

# Level-of-Service Measure of Road Traffic Based on the Driver's Perception

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## ABSTRACT

Currently used measures of level-of-service to evaluate the traffic condition of road sections are not necessarily linked to the perceived level-of-service by the drivers. The aim of this study is to propose a universal level-of-service measure of road traffic based on the drivers' perception of the driving environment. The measure is composed of aggregated driving utility, and the utility is estimated by the drivers' utility function with surrounding driving conditions. The analysis and modeling are conducted for merging sections where common driving behaviors are found in other types of road segments occur. The calibrated utility function based on a set of observation data shows a fairly good reproduction capability on the behavior of the observed drivers. This means that the proposed measure reflects the individual driver's perception of the level-of-service.

## 1. INTRODUCTION

The level-of-service of traffic of a road section is a concept to evaluate the service quality of road perceived by the drivers going through the road section. This concept was first proposed in the HCM of version 1965 (TRB 1965), and then defined by the six levels of A to F in relation to several traffic conditions in the HCM of version 1985 (TRB 1985). These measures of the level-of-service used there such as traffic density and traffic flow rate are not the level-of-service itself, but merely characteristics of traffic conditions which have rather a strong relationship to the level-of-service of the traffic, and not necessarily shows the quality of service perceived by the drivers. In addition, different measures used for roads or road sections of different types make it impossible to evaluate and compare the level-of-service between the road sections of different types. This inconvenience is due to using such traffic characteristics as substitutional measures (Kita and Fujiwara 1995).

Under the above background, this study reconsiders the present measures of the level-of-service of road traffic, proposes a new idea on the measure, and develops a model to calculate it. In Section 2, we discuss the necessary conditions for the measure of level-of-service after reviewing some past studies, and propose a new type of measure, which satisfies these necessary conditions, and the calculation method. In Section 3, we formulate the method to estimate the driver's utility by using the observed driving behavior data and the surrounding driving conditions. In Section 4, we describe a method to calculate the level-of-service measure by aggregating the driver's utility in the disaggregate level. A numerical example will be conducted to examine the adequacy of the proposed model in Section 5. The analysis and modeling are conducted for merging sections, because most common driving behaviors are found, e.g., acceleration, over-

taking, lane changing, which occur in other types of road segments such as basic freeway segments, weaving areas, multilane highways, and two lane highways, are also found in merging sections.

## 2. LEVEL OF SERVICE AND THE MEASURE

### 2.1 Study Review

Studies on the level-of-service, which is a concept to evaluate the quality of road service as perceived by users, were conducted intensively after its first introduction into HCM65. In HCM65, the level-of-service was described as the six classes from A to F in the combination of travel time and the ratio of traffic flow rate to the capacity, because travel time was recognized as a dominant factor of the service quality. However, these classes were not defined in a quantitative manner.

HCM85 introduced some new measures specific to different types of facilities, e.g., density for basic freeway segments and flow rate for ramp junctions. The levels-of-service were classified from A to F in relation to the range of corresponding measure. The measures of level-of-service adopted in HCM85, which describe the characteristics of traffic conditions under operation, include travel speed, traffic flow rate, and traffic density, for each types of roads as shown in Table 1.

These measures are useful to evaluate and compare the level-of-service of road sections of the same type. However, these measures cannot be used to evaluate the level-of-service over road sections of different types. In addition, these measures are merely traffic characteristics to describe the whole traffic condition with having the correlation to the level-of-service, but not clearly related to the conditions that each driver faces.

**TABLE 1 Measures of Effectiveness for Level-of-Service Definition  
(after TRB 1997)**

Type of Facility	Measure of Effectiveness
Freeways	
Basic freeway segments	Density (pc/mi/ln)
Weaving areas	Density (pc/mi/ln)
Ramp junctions	Flow rates (pcph)
Multilane Highways	Density (pc/mi/ln)
	Free-flow speed (mph)
Two-Lane Highways	Time delay (percent)
Signalized Intersections	Average control delay (sec/veh)
Unsignalized Intersections	Average control delay (sec/veh)
Arterials	Average travel speed (mph)
Transit	Load factor (pers/seat, veh/hr, people/hr)
Pedestrians	Space (sq ft/ped)

In contrast with this approach, Morrall and Werner (1990) sought their base to describe the level-of-service of traffic on the individual perception of drivers, and tried to evaluate the level-of-service of whole traffic by aggregating the individual perception over drivers. They computed the overtaking ratio (achieved number of overtaking/desired number of overtaking) of each driver in a given section of a two-way highway by using a simulation model. They found that the overtaking ratio widely decreased while the percentage of time delayed (delayed travel time/total travel time) was slightly increased under the condition of high percentage of time delayed. From this fact, they pointed out that the drivers must feel a decline in service quality even though the level-of-service defined in the delayed time ratio as the measure is the same.

The measure they used, overtaking ratio, is calculated by aggregating the overtaking ratio of each driver. What we should note here is the fact that the macroscopic measure and the aggregated microscopic measure that describes the driving condition faced by each driver show different behavior. This difference suggests to us that the level-of-service must be defined as an aggregated measure of microscopic driving conditions because the level-of-service is the quality of service perceived by drivers. However, there are a wide variety of measures that describe the microscopic driving condition perceived by each of the drivers. The measure, overtaking ratio, is merely one of them. For example, De Arzoza and Mcleod (1993) proposed to adopt the average travel speed as the measure of level-of-service. Since these measures including overtaking ratio are not the level-of-service themselves, it is important to clarify the reason why the measure is good as the measure of the level-of-service, when we select it.

According to the above discussions, the necessary conditions to the measure of level-of-service can be summarized as:

1. it can be used for evaluation and comparison of road sections of different types,
2. it is based on the description of microscopic driving condition of each driver,
3. it holds a base that the measure sufficiently reflects the drivers' perception of quality of service.

## **2.2 The Idea of the Proposed Measure**

To satisfy these necessary conditions, this study proposes a new measure based on the driver's utility. The level-of-service can be considered as the degree of driver's satisfaction of the driving conditions in a road section. This degree of satisfaction over the road section consists of the degree of satisfaction at each instance during the time from entry to exit of the section. The degree of satisfaction at an instance is formed of the driver's perception of the speed, the degree of freedom to maneuver, the degree of safety, etc. This can be understood as the driver's utility. If we can identify the utility function of drivers, which relates the utility and the influencing factors of driving conditions, we can estimate the driver's instantaneous utility corresponding to a certain driving condition.

One way to identify the utility function is to ask drivers directly their value of utilities or the degrees of satisfaction in driving under certain driving conditions and find a set of influencing factors that characterize the driving conditions. However, it is a tough work to find the relationship between the driver's perception on the overall level-of-service and

the facing traffic conditions because thousands of explanatory variables must be needed to characterize the experienced transition of local traffic conditions sufficiently. In case of braking down the local traffic conditions into those at each instance for reducing this complexity, then, we must know the driver's perception of level-of-service at every instance. Asking the driver's perception of level-of-service and record them at every instance is not easy.

Another way to identify the utility function of drivers is to analyze their driving behavior as the revealed preferences. If each driver takes the driving action with highest utility under a given driving condition, we can estimate the drivers' utility function by using the observation data on the driving behavior with applying the frame of discrete choice model (see, e.g., Daganzo 1981 and Kita 1993).

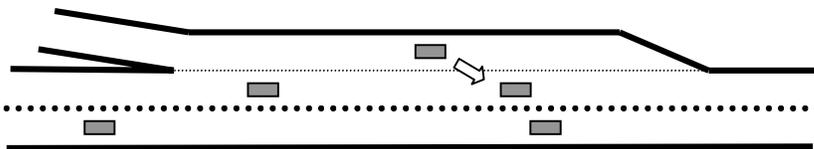
Once we can estimate the instantaneous utility of a driver to an instantaneous driving condition, then we can estimate the utility of the driver to the whole driving conditions through the road section by aggregating his/her instantaneous utilities over the driving time in the section, and also the utility of all the drivers to the whole driving conditions by aggregating the utilities of the drivers in the section. This aggregated utility is the proposed measure of level-of-service of this study.

Driving behavior and the influencing factors on it differ between types of roads. However, the utility resultant from the choice is universal regardless of the type of roads and choice behavior, so that the proposed measure can compare the level-of-service of roads of different types.

### 3. THE CHOICE MODEL OF DRIVING BEHAVIOR

#### 3.1 Assumed Road and Traffic Conditions

As mentioned above, the utility function can be identified by analyzing a set of observation data on the driving behavior in the road section. As shown later, we can see this in an on-ramp merging section of expressway, for example. Suppose an on-ramp merging section consists of one acceleration lane, one through lane, and one passing lane. The speed of merging cars is slower than that of through cars. So-called multiple merging, jointly merging of two or more cars into a gap, is not considered.



**FIGURE 1 Outline of Assumed Lane Configuration**

#### 3.2 Choice Behavior of Merging Car

A merging car always takes a choice of “merge” into the facing gap or “pass” it on the acceleration lane, and merge onto the through lane at the time of his/her first choice of

“merge” following after the repeated “pass.” Here, the driver of a merging car chooses his/her actions based on only the information at the time of decision-making. According to Kita (1993) and Kita and Harada (1995), TTC (Time to Collision) to the closest through car approaching from rear side,  $t_q$ , and the remaining length of acceleration lane normalized by the driving speed,  $t_l$ , are selected. TTC is a measure of collision risk defined as the ratio of the space headway to the relative speed of the consecutive two cars (Hayward 1972). The value 0 of TTC means collision occurrence. The driver feels maximum disutility in case of collision, and feels no desutility when the value of TTC is sufficiently large. By taking these characteristics, the utility function of the merging car can be formulated as follows,

$$\begin{cases} u_a = \lambda_1 t_q^{-1} + \varepsilon_a \\ u_b = \lambda_0 + \lambda_2 t_l^{-1} + \varepsilon_b \end{cases} \quad (1)$$

where  $u_a$  and  $u_b$  are utilities in case of choosing “merge” and “pass,” respectively,  $\lambda_0$  to  $\lambda_2$  are parameters; and  $\varepsilon_a$  and  $\varepsilon_b$  are random variable due to unobservable uncertain influencing factors. If the driver takes utility maximization behavior and the random variables follow independent and identical Gumbel distributions, the probability of choosing “merge,”  $P_a$ , and the probability of choosing “pass” are given as the following equations,

$$\begin{cases} P_a = \frac{\exp(u_a^*)}{\exp(u_a^*) + \exp(u_b^*)} \\ P_b = 1 - P_a \end{cases} \quad (2)$$

where  $u_a^*$  and  $u_b^*$  are the deterministic parts of  $u_a$  and  $u_b$ , respectively.

### 3.2 Choice Behavior of Through Car

A through car chooses either to “go (with the same speed),” “change lane (onto the passing lane),” or “slow down” against the foregoing merging car. The driver of a through car choose his/her actions based on only the information at the time of merging. According to the choice behavior of a merging car formulated in the preceding section, the selected influencing variables are TTC to the foregoing merging car  $t_q$ , and TTC to the closest rear side car on the passing lane,  $t_c$ , in the cases of “go” and “change lane,” respectively. In the case of “slow down,” the sum of TTC after deceleration for  $t_q$  and the current TTC,  $t_{c3}$ , is selected as the influencing variable.

By taking these characteristics, the utility functions of the through car,  $U_1$  for “go,”  $U_2$  for “change lanes,” and  $U_3$  for “slow down” can be formulated as follows,

$$\begin{cases} U_1 = \mu_2 t_{c_1}^{-1} + \varepsilon_1 \\ U_2 = \mu_0 + \mu_3 t_{c_2}^{-1} + \varepsilon_2 \\ U_3 = \mu_1 + \mu_4 t_{c_3}^{-1} + \varepsilon_3 \end{cases} \quad (3)$$

where  $\mu_0$  to  $\mu_4$  are parameters, and  $\varepsilon_1$  to  $\varepsilon_b$  are random variable due to unobservable uncertain influencing factors. The probabilities  $P_1$ ,  $P_2$ , and  $P_3$ , that the through car choose the action “go,” “change lane,” and “slow down” are given as the following equations, respectively.

$$\begin{cases} P_1 = \frac{\exp(u_1^*)}{\exp(u_1^*) + \exp(u_2^*) + \exp(u_3^*)} \\ P_2 = \frac{\exp(u_2^*)}{\exp(u_1^*) + \exp(u_2^*) + \exp(u_3^*)} \\ P_3 = 1 - P_1 - P_2 \end{cases} \quad (4)$$

where  $u_1^*$ ,  $u_2^*$ , and  $u_3^*$  are the deterministic parts of  $u_1$ ,  $u_2$ , and  $u_3$ , respectively.

## 4. THE ESTIMATION MODEL OF LEVEL-OF-SERVICE MEASURE

### 4.1 Instantaneous Driving Utility

Above discussions are limited in the cases where a driver faces a situation to make a decision. As understood from the explanatory variables of the utility functions, driver’s utility depends on the traffic situation surrounding the driver. If the surrounding traffic situation changes along with the time, the utility of the driver changes, too, during the time of no choice. Let us call the driver’s utility at an instance as “instantaneous driving utility,” hereafter. It can be interpreted that the reason why a driver takes a different action from the current one at an instance is because the driver feels higher utility in taking the different action due to decreasing the utility to continue the current action no longer. The driver’s utility shown in the preceding section is formulated under the traffic situation at a certain instance, i.e., the instance of merging. The utility functions have to be rewritten as the function of time  $t$ , for taking into account the change of driving utility along the time passing.

### 4.2 Average Driving Utility as the Level-of-Service Measure

What kind of relationship is there between the driving behavior and the level-of-service of road section? The level-of-service perceived by a driver must have a strong relationship with the driving utilities at every instances in the road segment. Therefore, the level-of-service can be quantified by aggregating these instantaneous driving utilities in the section in some manner. The simplest way is to sum up the instantaneous driving utilities over all the driving time in the section. However, this simply summed up utility is not good to adopt, because it depends on the length of the road section and increases in proportion

with the length of road segment. We select the average instantaneous utility of chosen driving action over time as the measure of level-of-service in this study.

### 4.3 The Level-of-Service of a Merging Section

Suppose the situation where a merging car and a through car exist in an on-ramp merging section as mentioned in the last section. There can be two types of the level-of-service from the viewpoints of the merging car and the through car. We show the change of the driving utility of the through car to the merging car and the procedure to estimate the level-of-service measure of the section.

The merging car is assumed to travel on the acceleration lane with a constant acceleration, and then with a constant speed after becoming the same speed to the through cars. In this model, the merging car choose the driving action with higher utility, so that the driving utility of the merging car at the time  $t$ ,  $u(t)$ , is given as the higher utility between the utility in case of merging,  $u_a$ , and the utility in case of passing,  $u_b$ ,

$$u(t) = \max\{u_a, u_b\} \quad (5)$$

By applying Equation (1), Equation (5) is rewritten as,

$$u(t) = \begin{cases} \lambda_0 + \lambda_2 T_l(t)^{-1} & (0 \leq t < t_i) \\ \lambda_1 T_{c_1}(t)^{-1} & (t_i \leq t \leq t_L) \end{cases} \quad (6)$$

where  $t_i$  means the time of merging and  $t_L$  means the time of exit from the road section of the merging car.

Denote  $v_0$  as the initial driving speed at the entrance of the road section,  $\alpha$  as the acceleration, and  $v_j$  as the speed of through car. Now, let the speed of the merging car at the time  $t$  as  $V_i(t)$  ( $= \min\{v_0 + \alpha t, v_j\}$ ), the running position as  $R_i(t)$ , the time of merging as  $t_i$ . TTC to the closest rear-side through car at time  $t$ ,  $T_{c_1}(t)$ , and TTC to the end of merging lane at time  $t$ ,  $T_l(t)$ , are described as the follows,

$$T_l(t) = \frac{(L - R_i(t))}{V_i(t)} \quad (7)$$

$$T_{c_1}(t) = \frac{gv_i + \{R_i(t) - R_i(t_i)\} - v_j(t - t_i)}{v_j - V_i(t)} \quad (8)$$

where  $L$  in Equation (7) is the length of acceleration lane, and  $g$  in Equation (8) is the time headway between the merging car and the closest rear-side through car.

The average driving utility,  $\bar{u}$ , can be obtained by using  $T_{c_1}(t)$ ,  $T_l(t)$ , and  $t_L$  as

$$\bar{u} = \frac{1}{t_{L_i}} \left[ \int_0^{t_{i_i}} \{\lambda_0 + \lambda_2 T_l(t)^{-1}\} dt + \int_{t_{i_i}}^{t_{L_i}} \lambda_1 T_{c_1}(t)^{-1} dt \right] \quad (9)$$

This  $\bar{u}$  is the level-of-service measure proposed in this study.

While  $T_{c_1}(t)$  in Equation (8) is formulated in the case that the through car chooses “go,” the similar way of formulation can be made in the cases of “change lane” and “slow down.” The average driving utility of the through car can be formulated in a similar manner, too. The level-of-service of a merging car with multiple through cars can be estimated by measuring the utility in taking the driving action that maximizes the driving utility against all the through cars. Furthermore, in case of existence multiple merging cars, level-of-service measure can be given by estimating the average driving utility of each merging car.

## 5. A NUMERICAL EXAMPLE

To check the performance of the proposed model, we conducted some numerical examinations. The observed video data recorded at Ichikawa I.C. of Keiyo Expressway, Chiba, Japan, in 1988 is used. The westbound on-ramp merging section has the similar lane configuration mentioned in the Section 3.1 with the acceleration lane of 220 m. The traffic is rather heavy but with smooth merging.

Table 2 shows the estimated parameter values of utility functions,  $\lambda_0, \lambda_1, \lambda_2, \mu_0, \mu_1 \dots$  by using maximum likelihood estimation. Smaller TTC, a more dangerous situation, corresponds to the situation with lower utility. Hence, the parameters of the inverse of TTC must be negative. Under the condition that the values of other explanatory variables are same, “merge,” “keep lane,” and “keep speed” may be preferred than “pass,” “lane change,” and “slow down,” respectively. Hence, the pass constant, lane change constant and slow down constant must be negative. All of the estimated parameters have proper sign. The log-likelihood ratio is 0.49 for the behavior model of merging cars and 0.31 for the model of through cars. These statistics show that the proposed model has fairly good replication ability on the driving behavior of the observed cars. If a driver chooses the action with the highest utility at every instance that corresponds to the driver’s perception on the level-of-service at the instance, this result means that the proposed measure well describes the drivers perception on the level-of-service.

**TABLE 2 Estimated Results**

Parameters	Estimated value	t-statistic	log-likelihood ratio
“pass constant” ( $\lambda_0$ )	-0.48	-0.41	
TTC to the rear-side car ( $\lambda_1$ )	-10.18	-4.16	0.49
Remaining distance of acc. Lane ( $\lambda_2$ )	-11.88	-2.16	
“Lane change” constant ( $\mu_0$ )	-2.64	-3.87	
“Slow down” constant ( $\mu_1$ )	-2.62	-4.46	
TTC to the merging car (“go”) ( $\mu_2$ )	-27.23	-4.73	0.31
TTC to the rear-side car(passing lane) ( $\mu_3$ )	-16.57	-2.80	
TTC to the merging car (“slow down”) ( $\mu_4$ )	-3.6	-2.00	

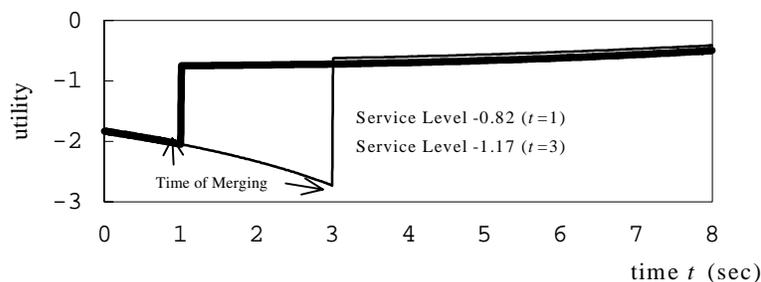
The next examination estimates the level-of-service perceived by a merging car in the situation where a through car and a merging car run in a merging section. The through car is assumed to choose the driving action of “go” against the merging car in a similar manner in the preceding section. Average speed of merging cars at the entrance of merging section is  $\bar{v}_0 = 16(\text{m/sec})$ , average acceleration is  $\bar{a} = 0.38(\text{m/sec}^2)$ , average speed of through cars is  $\bar{v}_j = 21(\text{m/sec})$ , and the length of acceleration lane is  $L = 140(\text{m})$ . Under these conditions, the performance of driving utility of the merging car, which merges into a gap of  $g = 3(\text{sec})$  between through along time is demonstrated on Figure 2.

The thick solid line shows the case where the time of merging is  $t_i = 1$ , and the fine solid line shows the case of  $t_i = 3$ . The average driving utility is  $-0.82$  for  $t_i = 1$ , and  $-1.17$  for  $t_i = 3$ . This figure shows that the longer time of acceleration carries a higher driving utility after merging because of having a safer merging with high speed, when merging into the gap of same size. On the other hand, we can understand that merging car tends to take earlier merging to avoid higher disutility due to approaching to the end of merging lane.

The definition of the level-of-service of a driver passing through a road segment is as the average of the utility of actions, which are chosen by the driver as the action with having the highest utility among the alternatives at every instance, over time. Discrete choice model calibrated from observational data guarantee the good correspondence between the chosen action and the action with the highest utility estimated by the calibrated utility function, if the model is properly composed and calibrated. The high value of the likelihood ratio shows the adequacy of the proposed discrete choice model. Hence, the proposed measure reflects the drivers perception of the level-of-service, if the definition is acceptable.

## 6. CONCLUSIONS

This study proposed a new type of level-of-service measure to evaluate the performance of road traffic condition based on the driver’s perception. The model developed here showed a method to identify the driver’s utility function, formulate the level-of-service measure, and estimate the value of measure in a systematic way. The calibrated utility function based on a set of observation data shows a fairly good reproduction capability on the behavior of the observed drivers. This means that the proposed measure reflects the individual driver’s perception on the level-of-service. Through the numerical examples, the performance of the proposed measure looks reasonable and reflects the change of geo-



**FIGURE 2** Computed service level.

metric design variables and traffic characteristics. While the modeling in this study is focused on merging sections, the proposed concept of utility-based measure is applicable to other types of facilities in common. Though the present model on the level-of-service measure is simple, this approach can give a new framework to evaluate the quality of service of road traffic with a theoretical base.

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