Analysis of the Interrelationship Among Traffic Flow Conditions, Driving Behavior, and Degree of Driver's Satisfaction on Rural Motorways

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ABSTRACT

This study tries to assess the quality of service of a basic motorway section based on the driver's perception, which is one of the noticeable concerns in the discussion on the quality of service. A field driving survey in a rural motorway section is conducted in order to collect data on degree of driver's satisfaction under various uncongested traffic flow conditions. It is further analyzed how these measured values of degree of driver's satisfaction relate to the traffic flow conditions and driving behaviors, and the interrelationship among them is quantitatively described.

1. INTRODUCTION

The examination of the quality of service is an essential procedure in the planning and operational analysis of the traffic stream on highways. Whatever measure of effectiveness is used to characterize the quality of service, describing a traffic condition related to such perception of highway users as freedom to maneuver or comfort is one of the noticeable concerns.

In the discussion on the level of service in the HCM (TRB 1998), the users' perception of service quality is considerably described, as well as several operational variables. However, the individual driving behavior and comfort under a traffic flow condition are not necessarily expressed in a quantitative manner.

Japanese planning procedure for basic highway sections (Japan Road Association 1983, 1984) is basically similar to that of the American HCM 1965. Capacity analysis is started from the basic capacity under the ideal condition, and several adjustment factors are employed to estimate realistic (possible) capacity values. Three "planning levels" by classification of highways are prepared and the corresponding volume-to-capacity (v/c) ratios (0.75 to 0.90) are used. This corresponds to consideration of the LOS in the HCM, however, this is only for convenience and even concrete traffic flow conditions are not clearly described in each planning level. Thus, in reality, any concepts of quality of service are not appropriately considered in the Japanese procedure.

This study therefore tries to assess quantitatively the quality of service in a basic motorway section under uncongested traffic flow conditions, based on the degree of driver's satisfaction as an indicator which represents driver's perception. In order to collect data on driver's perception under various traffic flow conditions, a field driving survey in a rural motorway section is conducted. It is further analyzed how these measured values of degree of driver's satisfaction relate to the traffic flow conditions and driving behaviors.

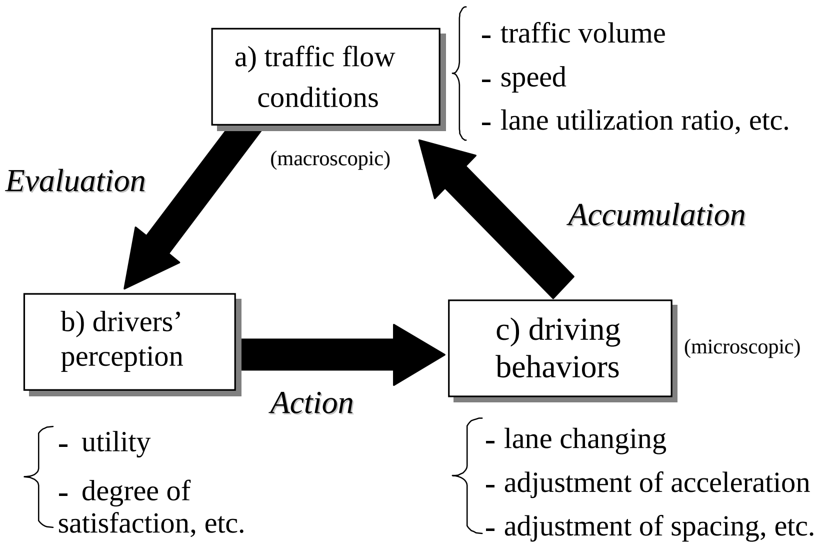

FIGURE 1 Assumed structure of "cause and effect" relationship between drivers' perception of traffic flow conditions and driving behavior (uncongested flow).

2. METHODOLOGY

2.1 "Cause and Effect" Structure Between Traffic Flow Conditions and Driving Behavior

An assumed structure of "cause and effect" relationship between drivers' perception of traffic flow conditions and driving behavior, as shown in Figure 1, is considered in this study. The structure is cyclical. Under the uncongested flow conditions, a certain degree of freedom to maneuver is allowed, and each vehicle generates c) microscopic behaviors such as lane changing and acceleration/deceleration, according to b) degree of driver's satisfaction to the running condition. The accumulation of these microscopic behaviors further result in a a) macroscopic traffic flow condition. The major concern of this study is to quantitatively analyze the interrelationship among these elements. The macroscopic traffic flow conditions are observed by vehicle detectors and by video cameras. The data on the degree of satisfaction and the microscopic driving behavior are measured by conducting a questionnaire survey and a field driving survey to drivers, respectively, under various uncongested traffic flow conditions.

2.2 Field Driving Survey and Data Collection

Table 1 summarizes the field driving survey conducted in November 1998. The data were collected in a 9.3 km 4-lane rural basic motorway section between an on-ramp and an off-

TABLE 1 Summary of the Field Driving Survey

Objective	To collect data on the perception of drivers and to observe driving behavior under various uncongested traffic flow conditions
Road section	along Tomei Expressway Eastbound: Nagoya on-ramp to Miyoshi off-ramp (2-lanes, 9.3 km) Westbound: Miyoshi on-ramp to Nagoya off-ramp (2-lanes, 9.3 km)
Date and time	November 27, 1998. 5.30 a.m. – 11.00 a.m. and 2.00 p.m.– 6.30 p.m.
Subject for the survey	24 drivers (Staffs and students of authors' institute, Nagoya University)
Number of samples	105 travels
Collected data	a) Vehicle detectors (number of detectors: 10) - Traffic volume, spot speed, and time occupancy by lane. b) Questionnaire survey - Driver's evaluation of the traffic flow condition. - Attributes of the driver: age, length of driving experience, driving frequency, driving frequency on the motorways. - Vehicle attributes: vehicle type, engine displacement, vehicle age, mileage. c) Video cameras mounted on the test vehicles. - Travel time, number of lane changing, time of car-following situation by lane, elapsed travel time by lane, etc.

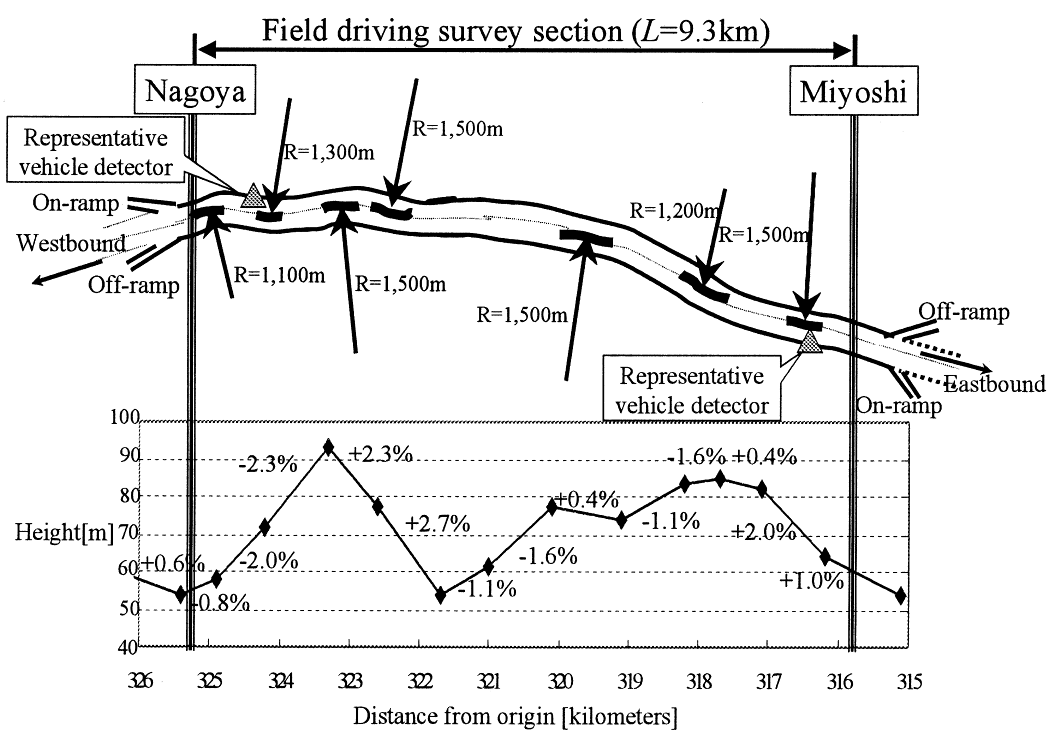

FIGURE 2 Geometric condition of the field driving survey section.

ramp along Tomei Expressway in Japan. Twenty-two subject vehicles traveled in turn, on both ways along this section (Figure 2).

A video camera was mounted on the navigator's seat of each vehicle to have the front views recorded. After every travel from the on-ramp to the off-ramp, the subject driver was made to answer the questionnaire survey given the traffic flow condition at the time of passing. Each traffic flow condition was evaluated using five classes, namely: "dissatisfied," "somewhat dissatisfied," "medium," "fairly satisfied," and "satisfied." During the time of the field driving survey, traffic streams were recorded by several video cameras located on a bridge beyond the section.

Figure 3 shows the traffic flow and speed variation data collected by a vehicle detector in the corresponding test section on the day of the survey. It can be confirmed from the figure, that the field survey was conducted under various traffic flow conditions from free-flow to near-capacity.

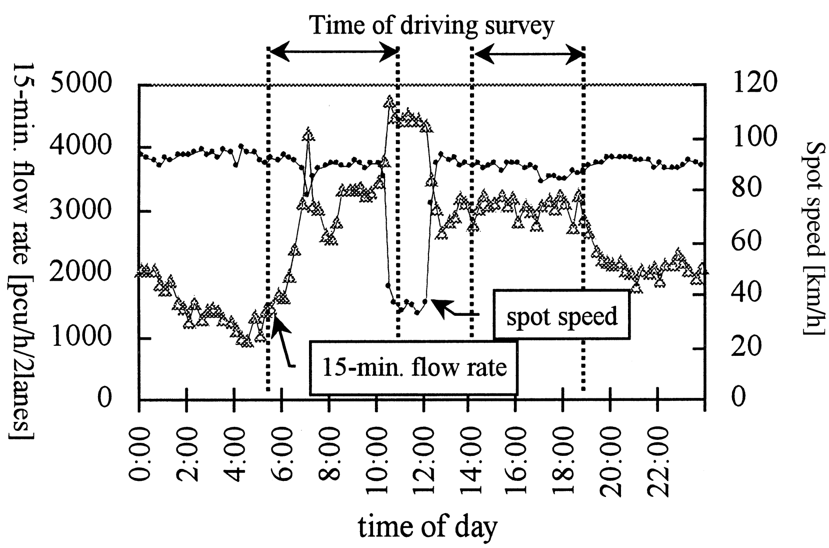

FIGURE 3 Flow rate and speed variation on the day of the survey (eastbound).

3. RELATIONSHIP BETWEEN DRIVING BEHAVIOR AND DATA ON TRAFFIC FLOW CHARACTERISTICS UNDER UNCONGESTED FLOW CONDITIONS

Under uncongested traffic flow conditions wherein motorists can afford to drive to a certain extent as they like, the degree of driver's satisfaction is revealed as driving behavior, and the accumulation of the driving behavior further reproduce a traffic flow condition. The number of lane changing, elapsed travel time by lane, and time of car-following situation obtained from the in-vehicle video tape recording (VTR) survey are the data collected for driving behavior. In Figure 4, the number of lane changing per 1 km is adopted to describe the microscopic driving behavior corresponding to the traffic flow rate, average spot speed, and lane utilization ratio, which are observed through a representative vehicle detector. The number of lane changing per 1 km is calculated by dividing the number of lane changing per one travel by the section length (9.3 km).

From Figure 4[a], it is observed that the inner lane utilization ratio is low under the conditions wherein the 15-min flow rate is less than 2,000 pcu/h/2lanes, and the number of lane changing is also few; about 1 or 2 times per 10 km (Figure 4[b]). As flow rate increases to over 2,600 pcu/h/2lanes at which lane utilization ratios in both lanes are balanced, the vehicles change lanes frequently and the spot speed begin to decrease (Figure 4[c]). Speed at this condition is around 90 km/h.

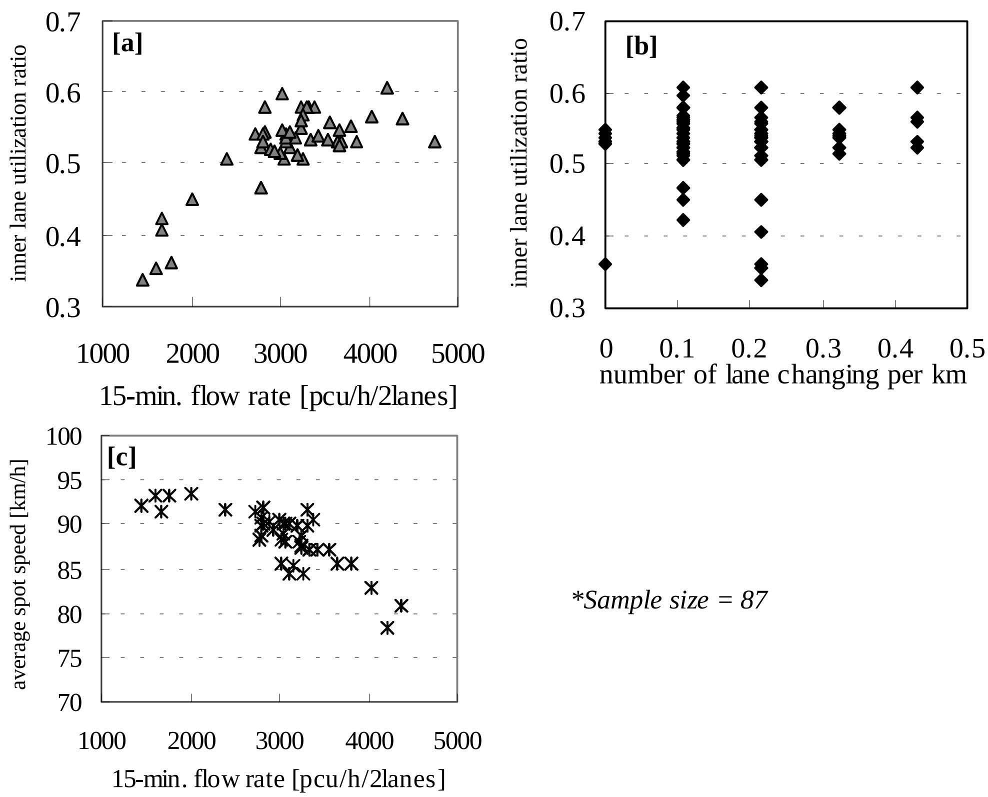

FIGURE 4 Relationship between traffic flow characteristics and number of lane changing.

4. QUANTIFICATION OF DEGREE OF DRIVER'S SATISFACTION AND ANALYSES ON ITS FACTORS

4.1 Quantification of Degree of Driver's Satisfaction by Method of Successive Intervals

Data on the degree of satisfaction, which are evaluated from five classes by drivers after driving, are abstract and discrete values. Moreover, the intervals between evaluation classes are not always constant. In order to resolve these inconveniences and to analyze these values quantitatively with traffic flow and driving behavior data, the results of the questionnaire are transformed to scores by applying the Method of Successive Intervals (MSI) (Masuyama and Kobayashi, 1989). This procedure is described as follows:

1) The cumulative ratio of the number of samples in each class i (P_i) is calculated (Figure 5).

2) P_i is transformed into standard normalized deviation Z_i, assuming that the values of degree of driver's satisfaction follow the standard normal distribution *f(x)*. Figure 6 describes this transformation using the cumulative distribution function *F(Z)*.

$$F(Z) = \int_{-\infty}^{z} f(x)dx \tag{1}$$

$$f(x) = N(0,1) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \tag{2}$$

$$Z_i = F^{-1}(P_i) \quad (i = 1, 2, 3, 4, 5) \tag{3}$$

3) The size of each interval, w_i is obtained by:

$$w_i = Z_{i+1} - Z_i \quad (i = 1, 2, 3, 4) \tag{4}$$

4) The scaled value (S_i) of degree of satisfaction is finally estimated by Equation (5), in which size of each interval w_i is considered.

$$S_i = \sum_{k=2}^{i} w_{k-1} + S_1 \quad (i = 2,3,4) \tag{5}$$

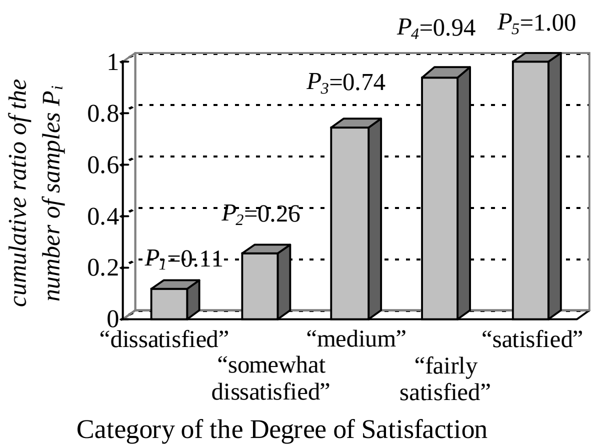

FIGURE 5 Histogram of degree of satisfaction.

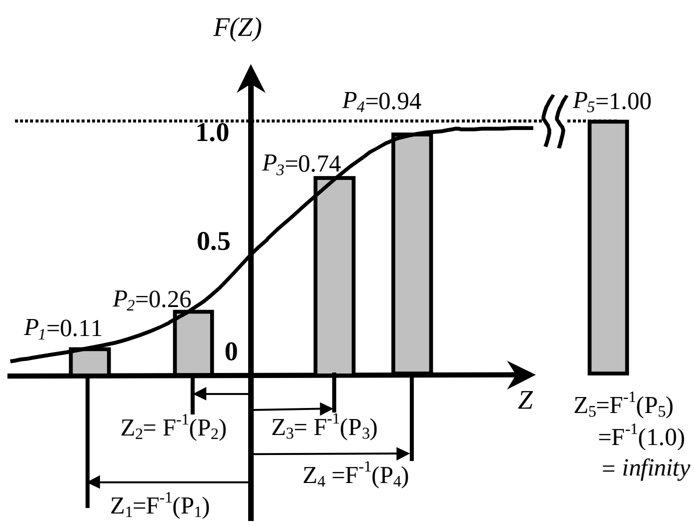

FIGURE 6 Transformation of P_i into standard normalized deviation Z_i.

The estimated values of each class of the degree of satisfaction, using the procedure above, are shown in Table 2. Furthermore, these estimated values are transformed into scores S_{100} whose scale is 0 at "dissatisfied" and 100 at "fairly satisfied", and are shown in the lowest row in the table. The score of "satisfied" is not shown here, since it reaches infinity by the MSI, due to $Z_5 = F^{-1}(P_5) = F^{-1}(1.0) = \text{infinity}$. From the result of Table 2, it is found that the interval between "somewhat dissatisfied" and "medium" is more or less greater than the intervals between the others.

TABLE 2 Estimated Score of Degree of Driver's Satisfaction by MSI

Degree of satisfaction	Dissatisfied	Somewhat dissatisfied	Medium	Fairly satisfied
Estimated value by the method of successive intervals	$S_1 = 0$	$S_2 = 0.62$	$S_3 = 1.63$	$S_4 = 2.33$
0–100 score S_{100}	0	26.7	69.9	100

4.2 Analysis on the Factors Affecting the Degree of Driver's Satisfaction

In order to clarify the explanatory factors of the scored degree of driver's satisfaction, multiple regression analysis is conducted, using drivers' attributes, microscopic behavior indices, and macroscopic traffic flow condition data as explanatory variables. The estimated result is shown in Equation (6).

$$S_{100} = 1.46\times10^{2} + 26.8\times dex + 17.6\times freq - 2.19\times10^{-2}\times q_{15} - 20.9\times tfol - 5.23\times lchg \quad (6)$$

[t = 13.0] [4.6] [3.2] [–6.9] [–2.5] [–2.3]

(R^2 = 0.55, number of samples: 82)

where

- S_{100} = 0–100 scored satisfaction degree
- *dex* = driving experience dummy variable (1: < 2 years, 0: otherwise)
- *freq* = driving frequency dummy variable (1: = < once a week, 0: otherwise)
- q_{15} = 15-min flow rate [pcu/h/2 lanes] (observed by the representative vehicle detector shown in Figure 2)
- *tfol* = time ratio of car-following situation in outer lane (car-following time/travel time observed by the in-vehicle VTR survey)
- *lchg* = number of lane changing per one travel in the section (observed by the in-vehicle VTR survey)

From the significant parameter estimates, the following points are suggested:

1. the factor that most strongly affects the decrease in the degree of driver's satisfaction is the increase in the traffic flow rate;
2. as for driving condition, the number of lane changing and the elapsed time of car-following situation affect the level of driver's comfortability; and
3. a driver who has a shorter driving experience or drives less often tends to evaluate the traffic condition in a higher degree of satisfaction.

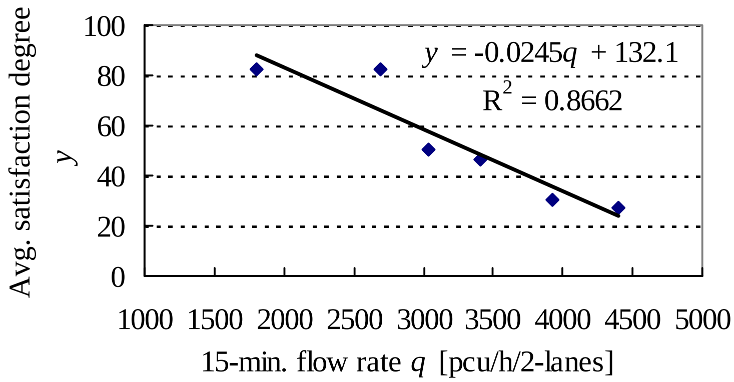

FIGURE 7 Relationship between traffic flow rate and average satisfaction degree under uncongested flow conditions.

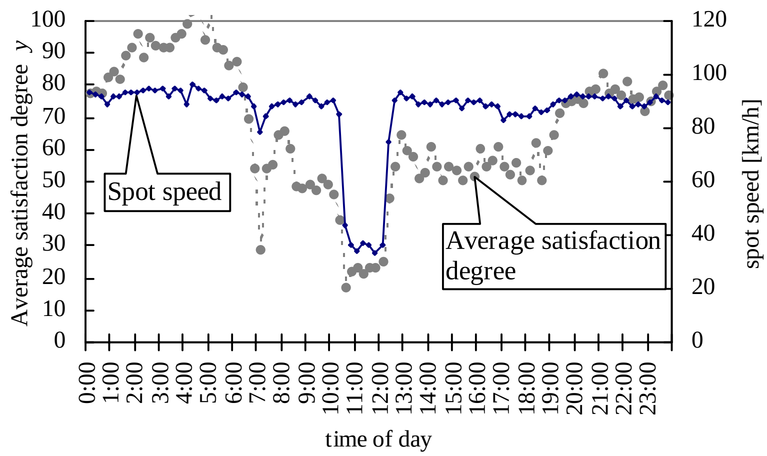

FIGURE 8 Variation of the average satisfaction degree and spot speed in the survey section (eastbound).

5. EVALUATION OF HIGHWAY QUALITY OF SERVICE BASED ON DEGREE OF DRIVER'S SATISFACTION

5.1 Traffic Flow Rate Versus Average Satisfaction Degree Under Uncongested Flow Conditions

In the previous chapter, it was shown that the degree of driver's satisfaction is strongly affected particularly by the traffic flow rate, even though explained by various factors. Here, the relationship between traffic flow and degree of satisfaction is analyzed in order to estimate the average score of satisfaction degree y under general uncongested flow conditions. To alleviate the dispersion of plots on the plane of 15-min flow rate q versus score of satisfaction degree y due to other affecting factors (*ex.* attributes of the subject), the raw data are categorized into each 500 pcu/h/2lanes traffic flow rate and the scores are averaged by category. Figure 7 shows the q-y plots. These averaged plots are used for the regression analysis and the result is as follows:

$$y = -0.00245q + 132.1 \qquad (R^2 = 0.8662) \qquad (7)$$

Equation (7) makes it possible to estimate the traffic flow rate values corresponding to every degree of driver's satisfaction. The variation of the average score of satisfaction degree estimated by Equation (7), as well as the spot speed variation observed by a representative vehicle detector in the section on the day of survey, is shown in Figure 8. This suggests that the average satisfaction degree does not always correspond to the spot speed, since it is a period-of-time and section-of-space parameter and should rather be related to the travel speed in the section.

5.2 Level of Service Setting Based on Average Satisfaction Degree and Referred Traffic Flow Condition

Assuming that every classification of the average satisfaction degree, which reflects traffic flow condition (e.g., "medium," "rather satisfied," …) is used as the threshold of level of service, the corresponding *v/c* ratio values are estimated. The estimated *v/c* ratios are summarized in Table 3, in combination with several indices, which represent macroscopic and microscopic traffic characteristics. This table makes it possible to specifically refer to concrete driving conditions at each class of the average satisfaction degree. For example, drivers begin to feel somewhat dissatisfied, when the inner lane utilization ratio is over 0.52. Under this condition, drivers follow the leading vehicle for about a half of the total travel time and they make overtaking 1.9 times per 10 km on the basic motorway sections.

TABLE 3 Interrelationship Among Average Satisfaction Degree, Traffic Flow Characteristics, and Driving Behavior

Average satisfaction degree	Macroscopic characteristics				Microscopic characteristics		
	v/c ratio	Speed difference between two lanes [km/h]	Inner lane utilization ratio	Time occupancy in outer (inner) lane [%]	Travel speed [km/h]	Time ratio of car-following situation	Number of overtaking [/km]
Fairly satisfied	0.28	>19	0.30	6(3)	>100	0.20	0.16
Medium	0.60	>18	0.52	8(6)	>96	0.47	0.19
Somewhat dissatisfied	0.85	>14	0.57	11(12)	>91	0.75	0.15
At capacity	1.00	>4	0.52	26(29)	>64	0.92	0.13

5.3 Comparison with Conventional Set of *v/c* Values

In Figure 9, the estimated *v/c* values, to which each of average satisfaction degree corresponds, are compared with the conventional values set by LOS in the HCM and Japanese Planning Level. For the calculation of *v/c* ratio, a uniform capacity value of 4,600 pcu/h/2lanes is used for the entire 9.3-km section, since the variation of the geometry can be considered little in the section. LOS B (*v/c* = 0.44) of HCM is positioned at "medium," and LOS C (*v/c* = 0.66) corresponds more or less to "somewhat dissatisfied." On the other hand, the majority of drivers feel "somewhat dissatisfied" under the traffic flow condition of *v/c* = 0.75, which is applied to almost all of the Japanese intercity motorways as Planning Level 1 in the design procedure.

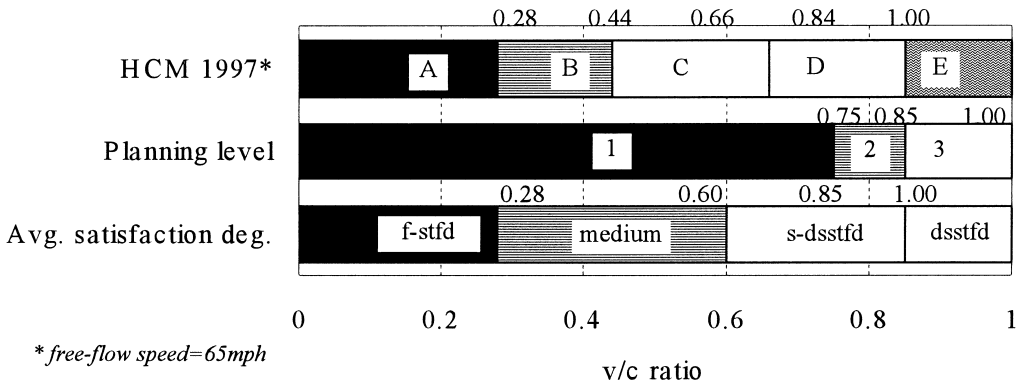

FIGURE 9 Comparison of *v/c* values based on average satisfaction degree with conventional values.

5.4 Trial Estimation of Required Number of Lanes by Average Satisfaction Degree

Finally, the required number of lanes is estimated, for the section which the survey was conducted, as a case study employing the *v/c* ratio based on the average satisfaction degree. For calculation, values of AADT = 94,111, K = 0.072, D = 0.564, which are observed in the survey section, are used. Table 4 summarizes the result.

It is found that the survey section should be widened to 12 lanes (6 lanes in each direction), so that drivers may evaluate the traffic flow condition as "fairly satisfied." Thus, it cannot be helped investing enormously, if highways are designed employing the *v/c* value that is set only from a viewpoint that assures higher satisfaction degree of drivers.

TABLE 4 Required Number of Lanes by Average Satisfaction Degree—A Case Study in the Field Survey Section

Average satisfaction degree	Conventional Planning Level	*v/c* ratio	Required number of lanes (for one direction)
Fairly satisfied		0.28	12 (6)
Medium		0.60	6 (3)
	1	0.75	6 (3)
Somewhat dissatisfied	2	0.85	4 (2) = actual

6. CONCLUSIONS

In this study, traffic flow conditions in a basic intercity motorway section were evaluated from the viewpoint of the driver's perception, and the interrelationship among traffic flow conditions, driving behavior, and degree of satisfaction was clarified. It was found that the factor that most strongly affects the degree of driver's satisfaction was traffic flow rate. The number of lane changing, the elapsed time of car-following situation, and the driving experience also affects the evaluation of traffic condition.

In addition, setting the level of service based on the average satisfaction degree was tried and was compared with the conventional ones. The result may suggest that the current traffic condition in Japanese motorways hardly satisfy the drivers, however, further intensive surveys and analyses are required for this discussion.

It is considered that degree of driver's satisfaction must be also affected by geometric conditions. However, sensitivity to this effect could not be analyzed adequately, since the field driving survey was conducted in only a certain basic motorway section. It is still necessary to clarify the relationship between driver's perception and geometric conditions, as well as the generalization of the study in employing varieties of samples in various attributes. Furthermore, evaluation of congested traffic flow, which is more important in the operational analysis, should also be investigated.

ACKNOWLEDGMENTS

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