THE EFFECT OF A NEW INTERCITY EXPRESSWAY BASED ON TRAVEL TIME RELIABILITY USING ETC DATA

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This paper describes a method of evaluating the level of service of road networks, based on the average travel time and travel time reliability using electronic toll collection (ETC) data. We focused on the variance in travel time under normal circumstances; thus, traffic accidents were removed from the database, and any effect of individual vehicle preference was excluded. We evaluated the travel time distribution based on the average travel time from ETC data for each 15-min interval. The level of service in an actual intercity highway network was analyzed using the proposed method. This analysis showed that the level of service fluctuated according to the road section analyzed, the month, and the time of day. These findings were confirmed by the shape of the cumulative distribution and indices of average travel time and travel time reliability. Using the evaluation method described here, the analysis also confirmed the change in travel time distribution between major interchanges after the opening of a new intercity highway route. Because a great change in the traffic conditions occurred, we analyzed the relationship between traffic demand and the level of service using detector data.

Key words: *level of service, travel time reliability, ETC data, intercity expressway*

INTRODUCTION

The reliability of transportation networks is an increasingly important issue for sustained economic growth and improvement in the quality of life around the world, as time is considered to be more and more valuable. Schedules and routes need to be able to accommodate unexpected events, such as accidents, natural disasters, or traffic flow fluctuations, with the minimum possible loss of operational efficiency.

Traffic fluctuates for various reasons, and the sources of the variability in transport service level can be categorized by the situation as recurrent or non-recurrent. Several indices have been proposed with regard to such situations. In non-recurrent situations, where large-scale disasters, serious accidents, or even terrorist attacks occur, traffic demand and traffic supply (capacity) may change. Under such situations, essential questions for the transport system are issues such as whether one can connect to a specific place or how much demand the degraded network can support. Connectivity or terminal reliability, capacity reliability, and flow decrement probability have been proposed as measures. Connectivity reliability[1] is defined as the probability that the specific pair of nodes are connected under given link-failure probabilities. Capacity reliability[2] is defined as the probability that the total transport network can afford to serve a predetermined demand level under given link-failure probabilities. Flow decrement probability[3] can be defined as the probability that the number of the people who cancel their trips is less than a predetermined amount.

In recurrent situations, where daily traffic demand may fluctuate, stable or punctual transport services are expected, and the question is whether drivers can arrive on time. Indices such as travel time reliability and encountered reliability have been proposed to evaluate the level of service (LoS) of transport in such situations. Travel time reliability is defined as the probability that a traveler can arrive at a destination within a given travel time threshold [4]. Encountered reliability is defined as the probability that drivers do not encounter congestion [5]. Recent analyses suggest that travel time reliability is an important criterion for route choice decisions [6],[7],[8],[9]. The evaluation of road infrastructure investments by the concept of travel time reliability is thus important. Although travel time reliability is an appropriate measure of road network reliability, long-term data collection is necessary to obtain distributions of travel times. Bates et al. [10] used experimental data to examine the diversity of travel time reliability. Among case studies, scheduling analyses have investigated changes in travel time reliability for rail travel and highway modes. Noland and Polak [11] conducted a field study of travel time variation based on stated preference (SP). They used a theoretical approach for discrepancies and considered the partial correlation between theoretical LoS and actual LoS. Stathopoulos et al. [12] discussed variations in traffic flow patterns using real-time traffic data for the urban area of Athens, Greece. They found that traffic flow characteristics were similar for all weekdays but showed relatively more variation during weekends and by time of day. Schurr et al. [13] applied a model of the design-speed profiles of vehicles approaching curve sections. Noland et al. [14] presented a model for simulating travel time uncertainty. In addition, from the user viewpoint, they validated scheduling choices based on traffic predictability, derived from expected cost and average travel delay.

Actual road section data have also been examined. Uno et al. [15] recently presented a methodology for evaluating both the average travel time and the travel time reliability, showing that the evaluation of travel time reliability based on the LoS of a whole road section is now possible. Levinson et al. [16] measured the effect of ramp metering using the fluctuation between the shortest and maximum travel times, based on data obtained from detectors. Chen et al. [17] presented the relationship between risk-taking route choice models and the effect on travel time reliability using a risk-averse approach. Emam et al. [18] presented a methodology for evaluating travel time reliability using a theoretical distribution according to traffic characteristics, based on detector data. Small et al. [19] reported commuting examples of the preference for a mean and variance of travel time and considered such issues with the traditional reliability indexes, by combining SP and revealed preference (RP).

Recent research on travel time has employed reliability indices [20] to evaluate the LoS of road transportation comprehensively, using traffic data obtained by various devices, such as detectors and automatic vehicle identification (AVI). van Lint et al. [21] proposed reliability indices derived from the median, 10th, and 90th percentile values. They confirmed the utility of the expression of differences in day-to-day LoS, such as distortion of travel time distributions. Franklin et al. [22] calculated the value of the travel time reliability adopting a cost-benefit analysis approach for 3 years of Stockholm's automatic travel time measurement data, dividing the duration to be analyzed into 15-min time intervals for the evaluation. Li et al. [23] explored the relationship between travel time reliability indices and the level of traffic demand using AVI data. Lyman et al. [24] examined the application of travel time reliability indices in LoS evaluations of sections.

As mentioned above, it is now technically possible to estimate variances in travel times using detector data, but obtaining precise estimates is difficult because a detector only observes traffic conditions at a single point, and the LoS of the whole road section may be different. Because many cars in Japan are equipped with electronic toll collection (ETC) devices, it is now possible to acquire travel time data between interchanges (ICs) using ETC data. In this paper, we propose a method of evaluating the LoS of a road network using ETC data to estimate travel time reliability. The LoS of an intercity highway network was analyzed empirically using these data to obtain the average travel time and reliability with the aim of quantifying the stability and the certainty of the road network according to travel time reliability indices. This methodology may be useful for evaluating effects of improvements in road networks, such as the construction of a new intercity expressway.

RESEARCH NETWORK AND DATA PROCESSING OUTLINE

The aims of this study were to develop a methodology for evaluating the LoS of road networks, to determine travel time reliability, and to evaluate the effects of a new intercity expressway on an existing expressway. Part of the Meishin Expressway, a major intercity expressway connecting Nagoya, Kyoto, Osaka, and Kobe, was selected for the test network. We focused our attention on the section from the Youkaichi IC to the Suita IC, a distance of about 80 km. The next section describes the evaluation of westbound LoS, which was selected because of the frequent congestion that occurs in that direction. Validating the methodology to evaluate LoS requires that the road sections being evaluated differ in terms of the number of lanes and the intensity of traffic demand. From the viewpoint of the availability of ideal travel time distribution, sufficient ETC data should be available for the sections being evaluated. Considering these requirements, we selected three sections of almost the same length: the sections from the Youkaichi IC to the Ritto IC (Sec.1), from the Ritto IC to the Kyoto-Minami IC (Sec.2), and from the Kyoto IC to the Suita IC (Sec.3). Figure-1 illustrates the sections evaluated to achieve the first aim of this study together with the network, including the new intercity expressway described below. We used 2006 ETC data to address the first study aim. Table-1 shows sample ETC volume data for March 2006 and the length of each section. A large volume of ETC data was available for calculating the average travel time and several indices representing travel time reliability.

Table-1. Sample volume and section length

Section	Sec.1	Sec.2	Sec.3
Name	Youkaichi – Ritto	Ritto – Kyoto	KyotoMinami – Suita
Sample volume (number of vehicles)	148,256	424,441	1,460,125
Section length (km)	23.7	29.6	27.1

Detector	A	B	C	D
Section name	Ritto – Kusatsu	Kusatsu – Seta	Seta – Kyoto	Seta – UjiNishi (Keiji Bypass)

The second aim of this study was to use our methodology to evaluate the effect on the LoS of the existing Meishin Expressway of opening a new intercity expressway. The Shin (New)-Meishin Expressway has operated between the Kameyama IC and the Kusatsu IC since February 23, 2008. As shown in Figure-1, the Shin-Meishin Expressway connects the Kameyama IC on the Higashi (East) Meihan Expressway and the Kusatsu IC on the Meishin Expressway, providing an alternative route for users traveling from locations east of the Toyokawa IC to locations west of the Seta IC. It is reasonable to expect that changes in driver behavior, such as frequency of expressway use or route choice might occur. In particular, most drivers traveling from locations east of the Toyokawa IC to areas west of the Seta IC would be expected to take the new Shin-Meishin Expressway instead of the existing Meishin Expressway because of the shorter distance involved. The changes in the LoS of the existing Meishin Expressway were analyzed considering the concept of travel time reliability to support our second objective.

It is easy to imagine that the LoS is different between downstream and upstream sections with regard to junctions, such as the junctions between the Meishin Expressway and Shin-Meishin Expressway and between the Meishin Expressway and Keiji Bypass. Here, we focus on the level of service in Sec.2, including the junction where the traffic merges from the Shin-Meishin Expressway and Meishin Expressway and diverges to the Meishin Expressway and Keiji Bypass. To discuss the effects of junctions on the level of service, this study analyzed the cross-sectional traffic volumes (demands) observed by the detectors. In this study, four detectors, Detectors A to D (Table-1), were used to obtain traffic data. Detectors A and B are located upstream and downstream of the junction of the Meishin and Shin-Meishin Expressways, respectively. Detectors C and D are located downstream of the junction of the Meishin Expressway and Keiji Bypass. The hourly average and standard deviation of traffic volume are used as indices to evaluate traffic conditions later in this paper.

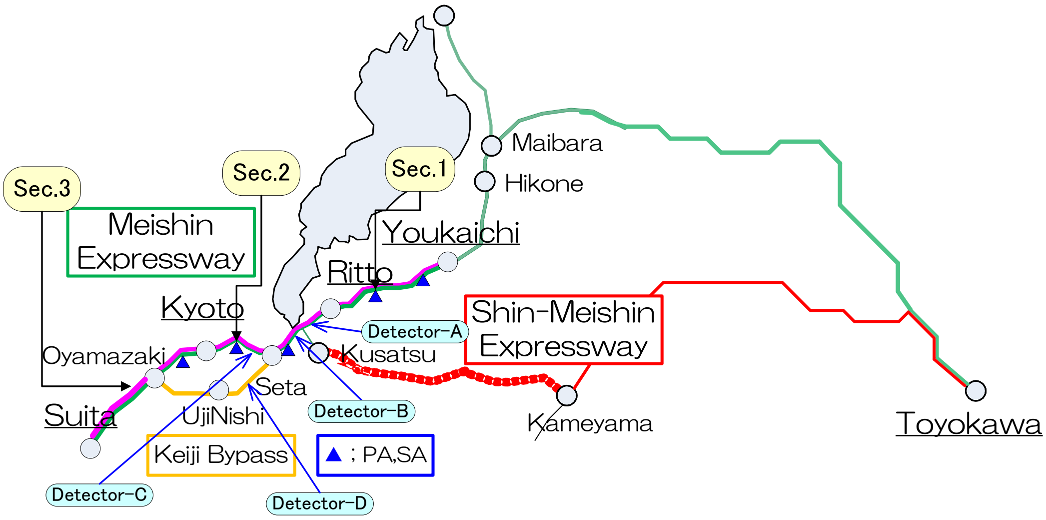


Figure-1. Network for analysis

We focused on the LoS during normal conditions, and ETC data that may have been affected by traffic accidents or delays due to road maintenance and repaving were removed from the database according to the daily reports provided by the expressway corporation. However, ETC data affected by congestion due to heavy inbound traffic were included in our analyses. The traffic conditions and corresponding LoS of the road network tended to change temporally within a day. To better manage traffic conditions and enhance the LoS of the expressway, it is necessary to evaluate the LoS of each road section based on the concept of travel time reliability and to identify periods of good or bad traffic conditions referring to the travel time distribution. Accordingly, this study groups the ETC-measured travel time data into 15-min intervals and uses the average travel time over each 15-min interval as an index to represent traffic conditions.

After excluding ETC data influenced by traffic accidents, road maintenance and repaving as mentioned above, some of the ETC-measured travel time data still showed inordinately long travel times compared with other data during the 15-min intervals (Table-2). Table-2 presents an example of observed travel time data from which data affected by traffic accidents, road maintenance, and repaving have been removed. As shown in this table, some extraordinarily long travel time data were still included in each 15-min interval. It is possible that these travel time data may include time spent on breaks at service areas (SAs) and parking areas (PAs). For a pure evaluation of LoS of road sections under normal traffic conditions, based on the concept of travel time reliability, it is reasonable that travel time data affected by the time spent on breaks should be excluded. Accordingly, we used a statistical and practical processing approach to exclude ETC data that might have been influenced by stops at rest areas, although discriminating between travel times affected by minor accidents without lane blockages and the times including rest stops is difficult. On the basis of the computed mean (μ) and standard deviation (σ) of travel time for the original ETC data, we assumed that travel time data for each vehicle outside the range of $\mu \pm \sigma$ were outliers and we removed such data from the ETC data set. The outliers were assumed to consist primarily of travel time data that included time spent on relatively long breaks at rest areas.

The following is an example of processing ETC data for Sec.3 in March 2006. The mean (μ) of all the ETC data for this section was 24.7 min, and the standard deviation (σ) was 22.8 min. Using $\mu + \sigma$ as a threshold to select ETC data suitable for evaluating the LoS in each 15-min interval, all travel time data exceeding 48 min in Sec.3 were removed as outliers (Figure-2). No outlier was selected by the lower bound $\mu - \sigma$ value in this section. Applying $\mu + \sigma$ as the upper bound resulted in removal of 4.4% of the data, probably corresponding to increased travel times caused by minor accidents or rest stops. Table-3 shows the amount of data removed and the sample size for each IC pair. Often, $\mu + 2\sigma$ is used as a threshold to filter outliers included in a data set. In Table-2, the dark-shaded and light-shaded travel times correspond to candidate outliers filtered by thresholds of $\mu + 2\sigma$ and $\mu + \sigma$, respectively. Realistically, it is difficult to imagine that traffic conditions on a certain section of a road network would change so drastically in a 15-min interval that travel times among vehicles would differ by 40 to 100 min in direct travel. Thus, a threshold of $\mu + 2\sigma$ did not seem appropriate for eliminating longer travel times due to breaks at rest areas. Considering this, we used $\mu + \sigma$ as the threshold for filtering.

Applying this procedure to filter outliers from the travel time data may lead to a bias in the travel time data. However, in this study, we adopted a common rule for filtering outliers from travel time data, and the sets of filtered travel time data may be valid for relative evaluations not only of LoS in 15-min intervals within days, but also for travel time reliability among road sections in the network.

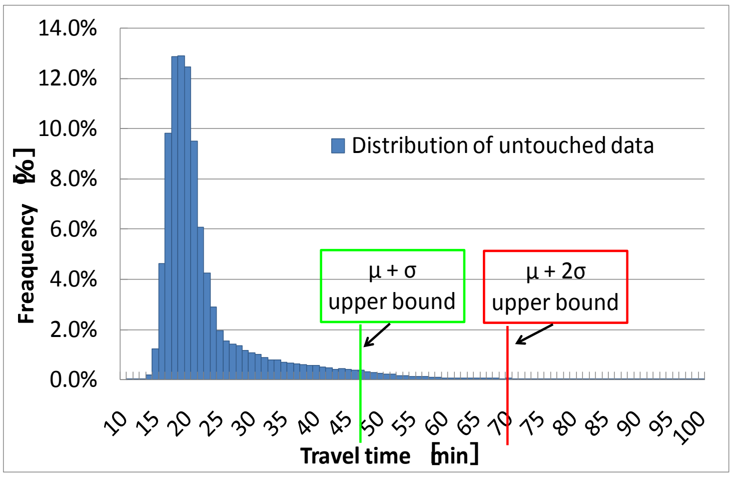


Figure-2. Original travel time distribution and the range of outliers for Sec.3, March 2006.
(Median = 20 min.)

Table-2. Example of observed raw travel time data including candidates of outlier

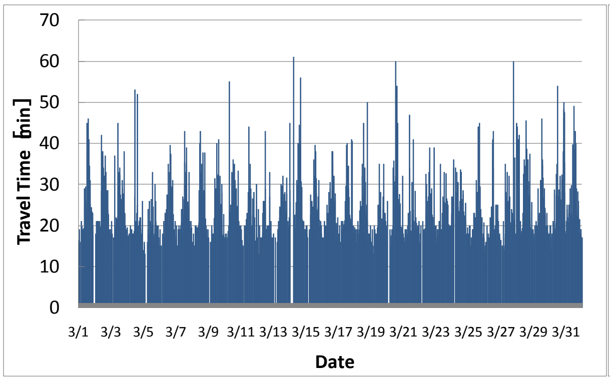
Day	Time			All sample	【2σ】 Data Filtered Percentage[%]	【σ】 Data Filtered Percentage[%]	Raw Data Ave.[min]	【2σ】 Data Filtered Ave.[min]	【σ】 Data Filtered Ave.[min]	Travel time[min] Outlier of $\mu+2\sigma$, $\mu+\sigma$									
3/1	11:45	~	12:00	61	4.92	11.48	29.38	24.89	23.35	100	···	88	···	50	46	···	19	18	17
3/2	11:30	~	11:45	54	9.26	14.81	30.83	25.04	22.30	97	···	79	···	64	41	···	17	17	17
3/6	11:45	~	12:00	57	8.77	15.79	32.35	27.10	24.04	98	···	76	···	57	48	···	19	18	18
3/7	11:45	~	12:00	41	7.32	19.51	30.61	26.18	21.64	95	···	71	···	48	43	···	18	18	17
3/8	11:30	~	11:45	72	11.11	13.89	31.24	24.69	23.23	92	···	74	···	70	46	···	18	17	17
3/10	12:15	~	12:30	53	15.09	20.75	33.34	25.67	24.05	83	···	71	···	55	41	···	18	18	17
3/13	12:30	~	12:45	63	12.70	20.63	33.51	26.60	22.78	92	···	71	···	57	42	···	18	18	17
3/14	11:45	~	12:00	63	9.52	12.70	30.32	24.68	23.76	96	···	70	···	48	47	···	18	18	18
3/16	12:00	~	12:15	57	12.28	21.05	33.47	25.42	22.24	97	···	71	···	48	38	···	19	18	18
3/20	11:45	~	12:00	65	13.85	20.00	34.43	26.79	24.23	100	···	71	···	55	47	···	18	18	17
3/20	12:30	~	12:45	71	11.27	18.31	31.52	24.76	21.81	100	···	71	···	50	47	···	17	17	17
3/21	12:15	~	12:30	47	8.51	10.64	31.34	26.23	25.69	95	···	79	49	47	47	···	17	17	17
3/27	11:45	~	12:00	65	9.23	16.92	31.54	26.00	23.15	95	···	72	···	50	45	···	18	18	18
3/28	11:45	~	12:00	61	8.20	13.11	29.28	24.36	22.85	97	···	70	···	48	47	···	18	18	17
3/29	12:00	~	12:15	56	7.14	10.71	29.48	25.06	23.44	100	···	70	···	65	47	···	18	18	18

Table-3. Data removed for each section (March 2006)

Section	Sec.1	Sec.2	Sec.3
Data size (number of vehicles)	13,045	37,887	132,722
Data removed (%)	502 (3.85)	2,938 (7.75)	5,821 (4.39)

An important characteristic of traffic on a road network is the time-dependent changes in traffic conditions and the corresponding LoS. This variable dictates the use of shorter unit time intervals to calculate travel times. However, shorter unit time intervals mean that fewer ETC data will be included in each interval, resulting in reduced reliability of the estimated travel time. We struck a balance between these tradeoffs and selected a time interval of 15 min. As already mentioned, the aim of this study was to evaluate the LoS of an intercity expressway under normal traffic conditions. This study also focused on the LoS that an *average* driver experiences, given that each driver's actual experience may vary due to differences in vehicle performance and driver attitudes or preferences. Thus, we considered the representative values that might be suitable for evaluating the LoS of road sections experienced by the average driver under normal traffic conditions: mean, mode, and median travel time.

Figures-3 and 4 represent the mean travel time as examples of representative values of travel time in Sec. 1 and Sec. 3, respectively. Figures 3.1 and 4.1 reflect the mean travel time with 5 min as the unit time interval. Figures 3.2 and 4.2 show a 15-min unit time interval. Additionally, Table-4 shows the frequency of unit time intervals during which no ETC data were observed. Figures-3 and 4 suggest that fluctuations in mean travel time in a unit time interval seem to be larger with a 5-min unit time interval due to there being fewer observations included in the unit time interval and outliers. Table-4 also suggests that with a 5-min unit time interval, a large number of unit time intervals have no ETC observations, compared with longer unit time intervals. To prevent instability in evaluating the LoS in each time interval due to the influence of outlier data with a smaller number of travel time observations, we adopted 15 min as the unit time interval for this study.



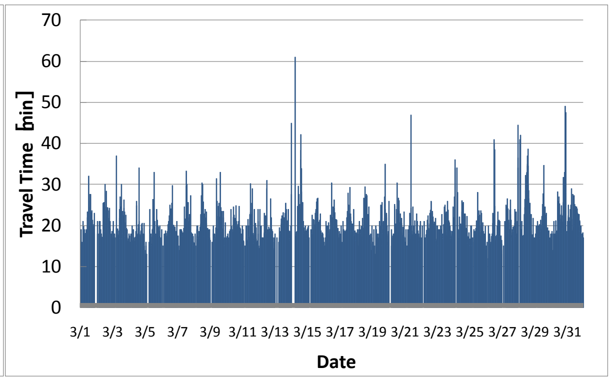
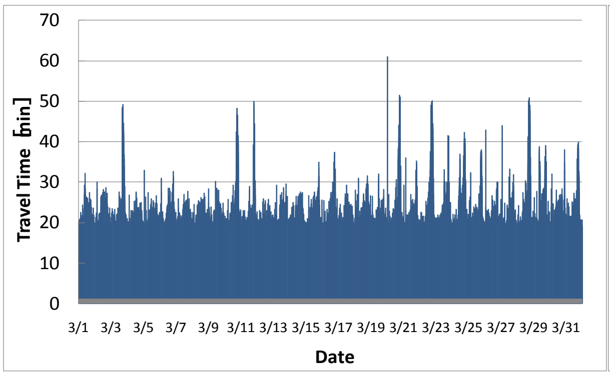


Fig-3.1. Mean travel times using a time interval of 5 min. (Sec.1, March 2006) Fig-3.2. Mean travel times using a time interval of 15min. (Sec.1, March 2006)



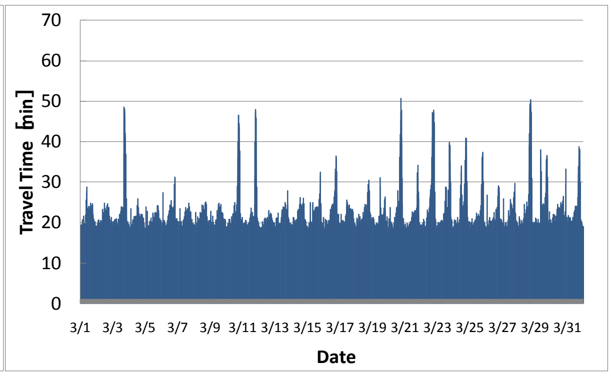


Fig-4.1. Mean travel times using a time interval of 5 min. (Sec.3, March 2006) Fig-4.2. Mean travel times using a time interval of 15min. (Sec.3, March 2006)

Table-4. Frequency of unit time intervals with zero ETC observations

Section / Time interval	Sec.1	Sec.3
5 min	3,686	23
15 min	623	0
60 min	48	0

Figure-5 shows the different distributions of each representative value: the mean, median, and mode of travel time in Sec.3. In Figure-5, each sample included in the distribution corresponds to a representative value of travel time with a 15-min unit time interval. When the travel time distribution was based on ETC data from which outlier data had been removed, most of the travel times were around 20 min, and the travel time distribution had a long right tail, indicating that the distribution included some relatively longer travel times due to the concentration of traffic demand. The distributions of both the median and mode tended to be located more to the left than the distribution of all ETC data, suggesting the possibility that adopting the median or mode of travel time as the representative value might lead to underestimating the LoS experienced by the average driver under normal conditions. In terms of the range of the distribution, the average travel time tended to coincide with the range of ETC data. Additionally, from the viewpoint of appropriately evaluating travel time reliability, we needed to adopt a representative value of travel time that was capable of capturing the long right tail of the travel time distribution measured by ETC. Thus, in this study, we used the average travel time based on 15-min intervals as the representative value for evaluating the LoS of road sections.

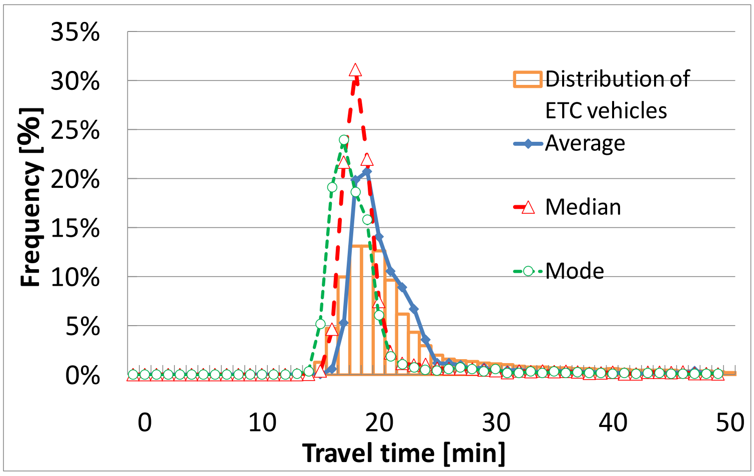


Figure-5. Distribution of ordinary ETC data and total representative values for Sec.3, March 2006.

The following additional data processing criteria were used.

- ✧ The travel time distribution was generated using the average travel time from ETC data for each time interval so as to exclude effects due to driver preferences and variation in individual driving. This index may be useful for evaluating the LoS of roadways from the viewpoint of road transportation management.
- ✧ A time interval of 15 min was selected to include a sufficient number of ETC data points. The average travel time should be computed using travel times obtained from ETC records for every 15-min interval on a certain day. The average travel time can be regarded as an index of the LoS for the time interval on that day.
- ✧ The time of day can be classified into time periods, such as morning commuting time, daytime, evening, and night, considering the features of traffic demand, because temporal changes in LoS by time periods according to the difference in traffic demand cannot be explicitly considered if all data are pooled for

analysis. Distributions of average travel time (ATT) were generated for four time periods; morning commuting time (6:00–9:59), daytime (10:00–16:59), evening (17:00–20:59), and night (21:00–5:59) to analyze differences in LoS by time of day.

✧ This study focused on three westbound sections; Sec.1, Sec.2, and Sec.3.

EVALUATION OF LOS BETWEEN MAJOR INTERCHANGES

We obtained the cumulative distributions of average travel time every 15 min for the three sections being analyzed. Because we wanted to comprehensively evaluate the temporal characteristics of LoS, we grouped the travel time data measured by ETC into 15-min intervals and obtained the average travel time over each 15-min interval as an index of traffic conditions. Figures-6, 7, and 8 show travel time distributions for March 2006. A cumulative distribution located toward the left side of the graph with a steep slope would indicate smooth and stable traffic service. In all expressway sections, the shape of the cumulative distribution of the average travel time for every 15-min interval during the morning (6:00–9:59) and night (21:00–5:59) were similar in that both distributions tended to be located towards the left, compared with the distributions during the day (10:00–16:59). This indicates that the travel time and its variation tended to be small both in the morning and at night. On the other hand, the variation in travel time was large, and the travel time reliability was lower, during the day (10:00–16:59), as indicated by the more gradual slope of the cumulative distribution curve and the fact that the distribution was located more towards the right. Moreover, the evening period (17:00–20:59) in Sec.3 had the poorest LoS in terms of both traffic smoothness and travel time reliability. This is seen in the gentler slope of the cumulative distribution curve, with the most gradual slope occurring at over 50% of the cumulative percentage of traffic.

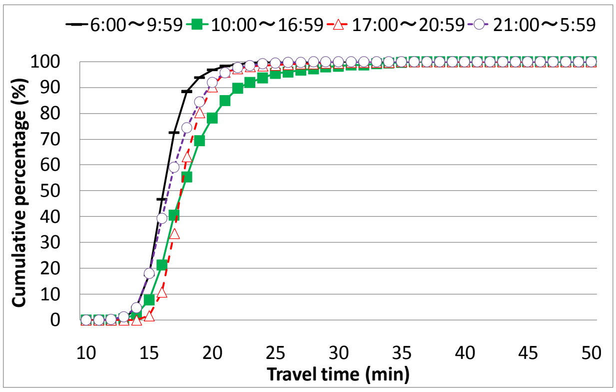


Figure-6. Cumulative distributions of ATT for Sec.1

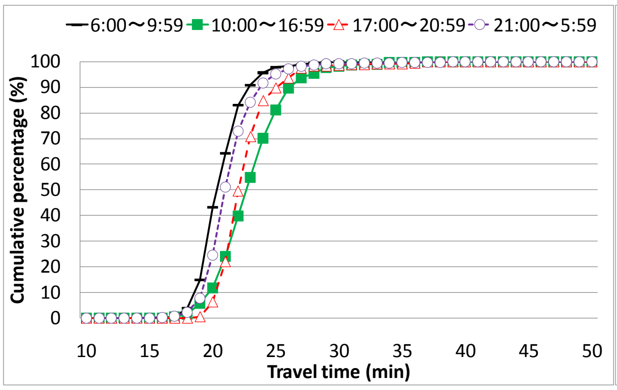


Figure-7. Cumulative distributions of ATT for Sec.2

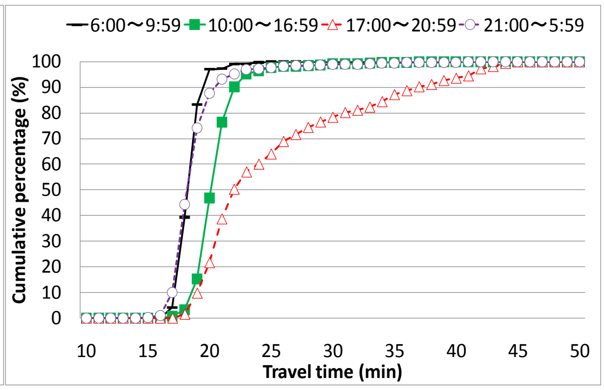


Figure-8. Cumulative distributions of ATT for Sec.3

The LoS characteristics of the three different sections based on the shapes of the cumulative distributions of average travel time are discussed below. The similarity in cumulative distributions of travel time across different time periods indicated that the Sec.1 seemed to provide drivers with relatively homogenous service in all time periods. The steepness of the cumulative distribution slopes indicated that the LoS of Sec.3 during both the morning and night seemed to be stable. This section has three lanes in the westbound direction and would thus be expected to provide drivers with reliable service compared with the two other sections, which have only two westbound lanes. On the other hand, the traffic demand in Sec.3 was relatively high. Indeed, enormous traffic demand tended to concentrate in this section, especially during the evening, and the LoS may deteriorate markedly when traffic demand exceeds the capacity of the section.

Next, the χ^2 test was used to assess whether travel time distributions for the four time periods were statistically independent. Table-5 shows the results of the χ^2 test in Sec.3. The numbers in Table-5 represent the probability that the null hypothesis, suggesting no statistical dependence between a pair of travel time distributions, can be rejected. To apply the χ^2 test, we classified the average travel time into five categories. In the case of Sec.3, travel time can be classified into less than 19 min, 19–20 min, 21–22 min, 23–24 min, and 25 min and above. The degrees of freedom = (5 - 1) = 4, and the 5% significance probability is 9.48. From this probability, it can be concluded that the travel time distributions among the four time periods within a day are statistically independent.

Table-5. Results of χ^2-test for independence of findings accordingly to daily time periods (Sec.3, March 2006)

	6:00-9:59	10:00-16:59	17:00-20:59	21:00-5:59
Morning(6:00-9:59)				
Day(10:00-16:59)	0			
Evening(17:00-20:59)	0	1.51 E-292		
Night(21:00-5:59)	4.23 E-79	0	0	

In this section, we analyzed the LoS characteristics of the three different sections using information obtained from the cumulative distributions of average travel time. Although these cumulative distributions seem to provide useful information for evaluating the LoS, the analysis itself tends to be subjective. In the next section, we quantify the LoS using travel time reliability indices.

TRAVEL TIME RELIABILITY INDICES

As mentioned above, the LoS in each section can be analyzed and evaluated in detail using a cumulative distribution of average travel time for each 15-min time interval. Although this is useful in analyzing the LoS of each section in detail, the cumulative distribution seems to have too much information for directly comparing the LoS between different sections and times of day. Thus, we used another approach to evaluate the LoS comparatively among road sections and time periods. This approach relied on two different indices to evaluate the LoS comprehensively from the viewpoints of average quality and variability (reliability).

Indices of travel time reliability considered in this study were the planning time (PT), buffer time (BT), buffer time index (BTI), and buffer time per distance (BT/Dist). PT is defined as the 95th percentile value of the travel time distribution for each time of day. BT is defined as PT - T_{avg}, where T_{avg} is the averaged value of the distribution of average travel time for the 15-min time interval. BTI is an index in which BT is normalized by the average travel time (BTI = BT / T_{avg}); BTI can thus be used to compare the LoS between road sections of differing lengths. The value of BTI is greatly influenced by the average travel time because of the way in which it is defined. As the distance between IC pairs increases, average travel time is necessarily greater, and BTI tends to be smaller. To exclude the influence of distance between IC pairs on the index in representing the reliability of travel time, we propose a new index, BT/Dist, defined as BT divided by the distance between IC pairs (BT/Dist = (T_{95} - T_{avg}) / section length). Figure-9 shows the monthly cumulative distribution of average travel time. Figure-10 shows the cumulative distribution of the average travel time in Sec.3 in March 2006 to indicate the relationship between the cumulative distribution and the indices above. Table-7 shows the corresponding computed results of these travel time reliability evaluation indices.

Figure-9 suggests that March, August, November, and December were less reliable, and June was the most reliable month in terms of travel time variability. Table-7 shows the travel time reliability indices for Sec.3. All the indices in June were the lowest of all the months shown in Table-7. The highest and second highest average travel time indices, T_{avg}, were in November (27.9 min) and March (26.2 min), respectively. In terms of average travel time, the LoS was poorest during November evenings. On the other hand, the LoS based on the reliability indices was relatively worse in August. Judging from the four indices of travel time reliability, in terms of travel time reliability, the LoS was poorest in August. This suggests that the LoS evaluated by the indices shown in Table-7 generally corresponded to the LoS represented by the original cumulative distribution of travel times shown in Figure-7.

It was also confirmed that the distribution shape was independent of month, as was shown using the χ^2 test for time of day. No difference between pairs of distribution shapes was found at the 5% significance level, except between daytime in June and daytime in December, and between morning in November and morning in December.

Table-6.1. χ^2 statistic for independence of findings according to month (Sec.3, 2006, morning: 6:00–9:59)

morning time	March	June	August	November	December
March					
June	6.56 E-03				
August	2.47 E-16	3.80 E-29			
November	3.09 E-07	4.28 E-16	4.11 E-29		
December	4.56 E-14	1.67 E-26	1.41 E-32	0.11	

Table-6.2. χ^2 statistic for independence of findings according to month (Sec.3, 2006, day: 10:00–16:59)

day time	March	June	August	November	December
March					
June	4.51 E-16				
August	1.34 E-20	2.01 E-58			
November	4.67 E-04	1.06 E-12	3.38 E-21		
December	3.92 E-07	0.05	2.56 E-47	6.03 E-06	

Table-6.3. χ^2 statistic for independence of findings according to month (Sec.3, 2006, evening: 17:00–20:59)

evening time	March	June	August	November	December
March					
June	0				
August	2.73 E-08	1.87 E-162			
November	3.47 E-16	0	2.64 E-36		
December	4.65 E-29	2.17 E-32	3.19 E-20	4.27 E-63	

Table-6.4. χ^2 statistic for independence of findings according to month (Sec.3, 2006, night: 21:00–5:59)

night time	March	June	August	November	December
March					
June	9.30 E-61				
August	1.60 E-12	3.21 E-22			
November	3.65 E-03	1.72 E-10	9.80 E-17		
December	0.02	4.41 E-03	7.98 E-24	8.93 E-11	

The LoS values between March and December were next compared in terms of travel time reliability. Although the BT value was similar in March and December (15.8 and 16.0 min, respectively), the LoS in December was poor compared with that in March in terms of travel time reliability based on the BTI index. In fact, a significant difference was found between March (0.606) and December (0.667) in BTI. On the other hand, the BT/Dist index had almost the same value in March (0.585) and December (0.591). Because of the way it is defined, the value of BTI is influenced strongly by the average travel time. This characteristic of BTI does not seem to be beneficial from the viewpoint of a pure evaluation of travel time variability. Additionally, the LoS of road sections with different distances must be analyzed and evaluated as separate cases. This indicates that the index representing the travel time reliability should be normalized by the length of the road section, so that the LoS for different-length sections can be compared directly. Thus, we selected the BT/Dist index to evaluate travel time reliability.

When we intuitively analyze and evaluate the LoS solely from the cumulative distribution shown in Figure-7, the LoS in November seems to be worse than in other months due to the shape of the cumulative distribution in the evening. However, this is not necessarily true when we evaluate the LoS in detail, based on the indices shown in Table-7. One reason for this discrepancy is that the average travel time in November tended to be longer than that in other months. Another reason is that the index for evaluating travel time reliability depends on the 95th percentile travel time. In future, we must investigate the possibility of introducing new evaluation indices based on higher-order information derived from the cumulative distribution, such as kurtosis or skewness. Kurtosis and skewness may provide better reliability indices to evaluate the LoS of a road section. These indices may better describe the cumulative distribution shape, which is not expressed well by current travel time reliability indices.

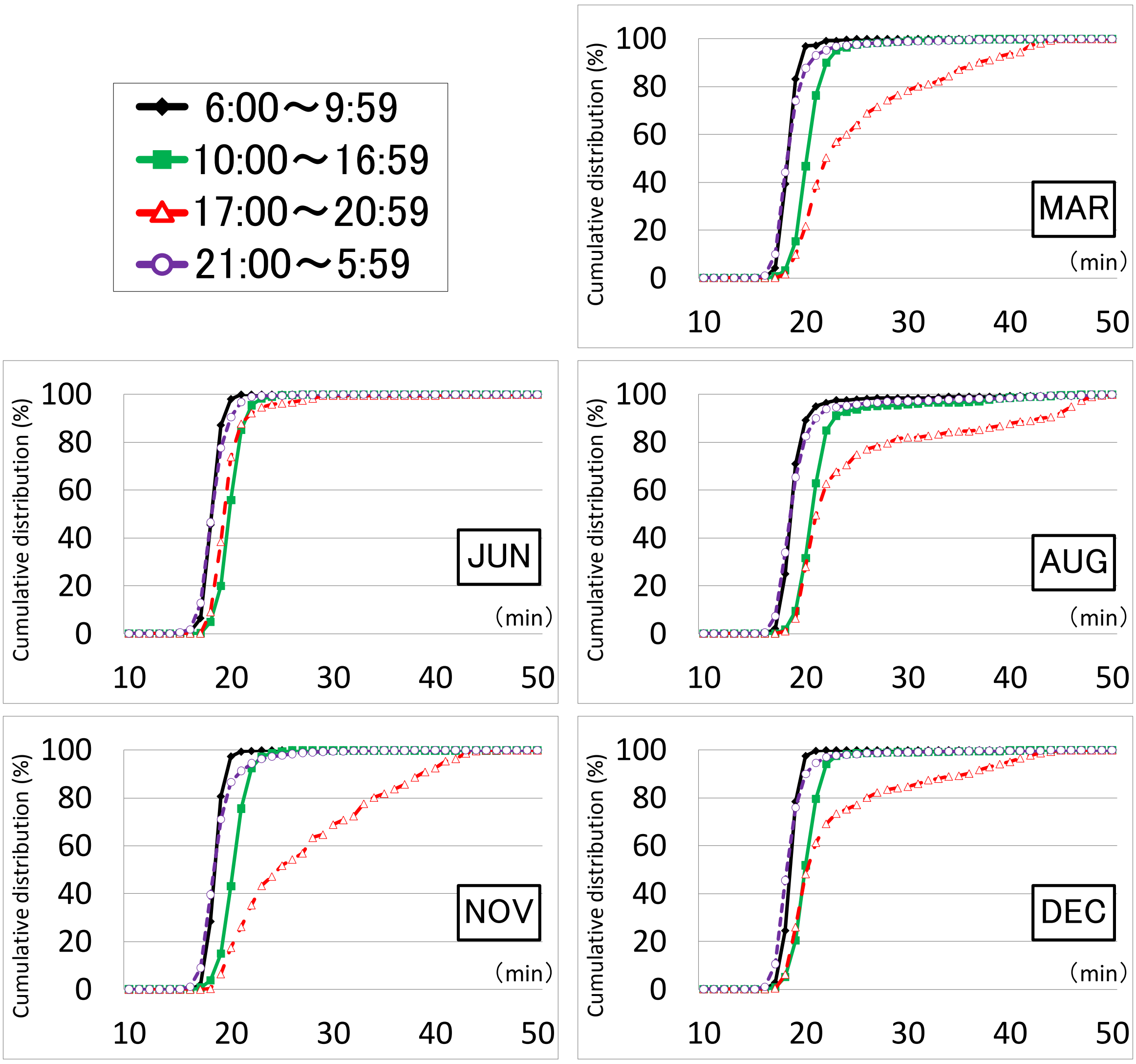


Figure-9. Monthly cumulative distributions of ATT for Sec.3, 2006.

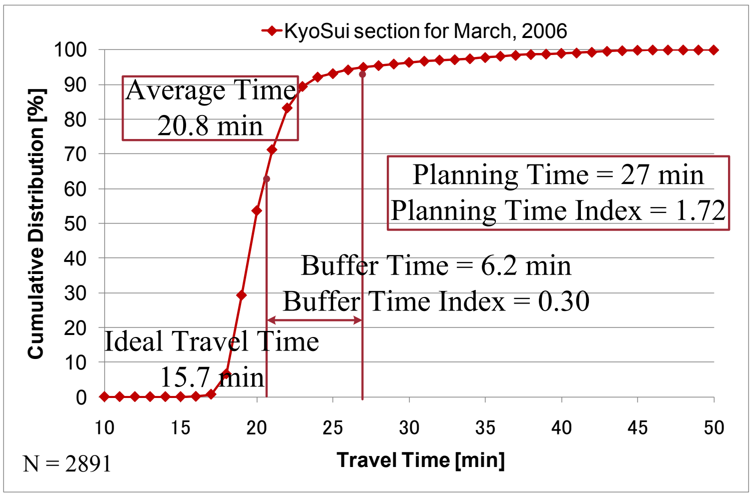


Figure-10. Travel time reliability indices for Sec.3, March 2006.

Table-7. Reliability indices by month for Sec.3, 17:00–20:59

	MAR	JUN	AUG	NOV	DEC
T_{avg}	26.2	20.8	26.0	27.9	24.0
$T_{95}(PT)$	42.0	24.0	47.0	41.0	40.0
BT	15.8	3.2	21.0	13.1	16.0
BTI	0.606	0.156	0.807	0.467	0.667
BT/Dist	0.585	0.120	0.774	0.482	0.591
IC Dist	27.1				

The LoS of the three different road sections were compared and analyzed as a case study to evaluate the LoS of road sections in terms of both average travel time and travel time reliability. Assuming two road sections, A and B, with the same distance and average travel time, it can be said that the LoS of section A is better than that of section B if the BT of section A is smaller than that of section B from the viewpoint of travel time reliability. Furthermore, assuming that road sections A and B have the same distance and BT, it can be said that the LoS of section A is better than that of section B if the average travel time of section A is smaller than that of section B. Clearly, the ideal situation in terms of LoS is defined as the road section that can provide travelers with a lower average travel time and higher travel time reliability. Judging from the simple example mentioned above, it is necessary to consider both average travel time and BT to properly evaluate the LoS of a road section.

As mentioned above, BT/Dist was used as an index to evaluate travel time reliability. The average travel time was also normalized by the length of the road section (T_{avg}/Dist) to enable a direct comparison of LoS for road sections with different lengths. Figure-11 shows a scatter chart of the relationship between T_{avg}/Dist and BT/Dist. Smaller values of these indices indicate better service levels. Each dot in Figure-11 corresponds to the LoS computed by both month and road section. For example, the red circle represents the LoS in Sec.3, and the 12 dots of each type represent the months included in the analysis.

We first examined the difference in LoS according to the time of day. The LoS in the morning (6:00–9:59) and at night (21:00–5:59) were relatively good for all road sections, as shown by the fact that both T_{avg}/Dist and BT/Dist in all months tended to be small. It is clear that LoS in the evening (17:00–20:59) was poorest, especially for Sec.3, which was the worst of the three road sections analyzed. The distributions of dots for Sec.1 and Sec.2 differed from those of Sec.3. This suggests that Sec.1 and Sec.2 may be characterized by less time-of-day fluctuation in LoS than Sec.3. This also suggests that the LoS of Sec.3 was better than that of other sections except in the evening. Sec.3 has a minimum of three lanes in each direction, providing drivers with a better LoS than in the other sections with two lanes. However, it is also possible that heavy westbound traffic may degrade the LoS in the evening. This case study suggests that evaluating LoS using both T_{avg}/Dist and BT/Dist may be useful for direct quantitative comparisons of LoS between road sections and times of day.

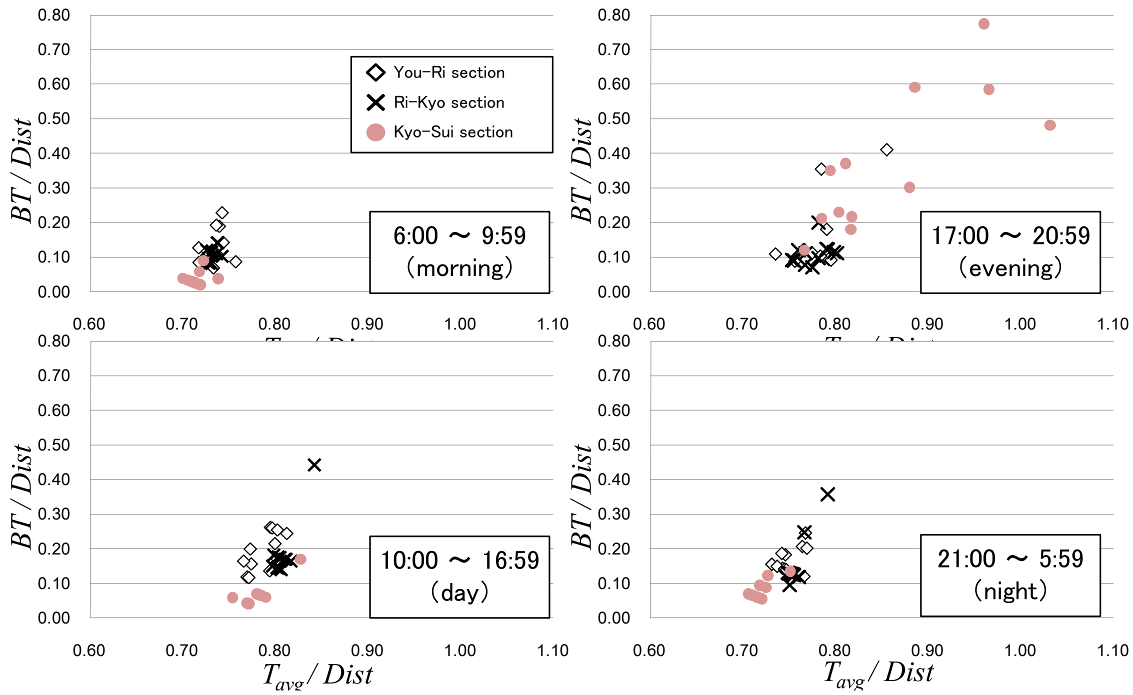


Figure-11. T_{avg}/Dist– BT/Dist plot for 2006.

EFFECTS OF A NEW INTERCITY EXPRESSWAY

This section analyzes the effects of the Shin-Meishin Expressway on the LoS of the existing network using the travel time distribution and some indices of travel time reliability. The effects of the Shin-Meishin Expressway were first evaluated based on the change in travel time of long-distance trips from areas east of the Toyokawa IC and west of the Suita IC. After the Shin-Meishin Expressway was opened, drivers traveling on the road network under consideration could choose either the existing Meishin Expressway or the new Shin-Meishin Expressway, as shown in Figure-1. Figure-12 shows the travel time distributions of the analyzed section before and after the opening of the Shin-Meishin Expressway. The present ETC system records the ICs through which each vehicle enters and exits and the corresponding date and time, but contains no information about the route taken between those ICs. Thus, the travel time distribution after the opening of the Shin-Meishin Expressway includes travel times on both the existing and new routes. The travel time of the road section between the Toyokawa and Suita ICs tended to be lower after the opening of the new Shin-Meishin route in 2008.

Although it is not possible to classify drivers into users of the Meishin and of the Shin-Meishin routes based on the information available, it does seem that the new Shin-Meishin route led to a significant reduction in the travel time of the analyzed road sections, including the existing Meishin route. Although the average travel time in 2008 decreased by about 20 min compared with the time in 2007, the reduction in PT (i.e., the 95th percentile travel time) was about 15 min, which was less than that for the average travel time mentioned above. Thus, the travel time reliability in 2008 appeared to be worse than it was in 2007. However, the LoS in 2008 was better than that in 2007, according to the travel time distribution shown in Figure-10. This illustrates the need for using several indices to measure the travel time reliability to evaluate the LoS of road networks accurately. Because Figure-12 is drawn using the travel time from actual vehicle travel time distributions, it may be expected to provide precise LoS for new road networks.

	μ [min]	σ [min]	BT[min]
2007	187.6	28.7	55
2008	168.4	30.6	60

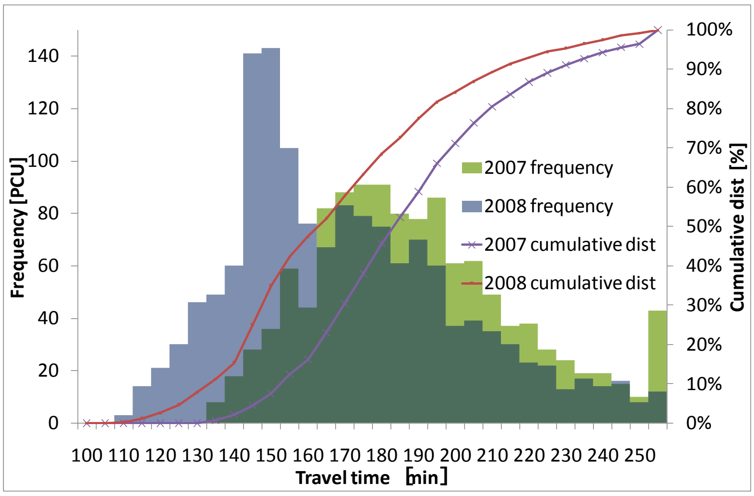


Figure-12. Comparison of travel time distributions in 2007 and 2008 for the Toyokawa to Suita IC section.

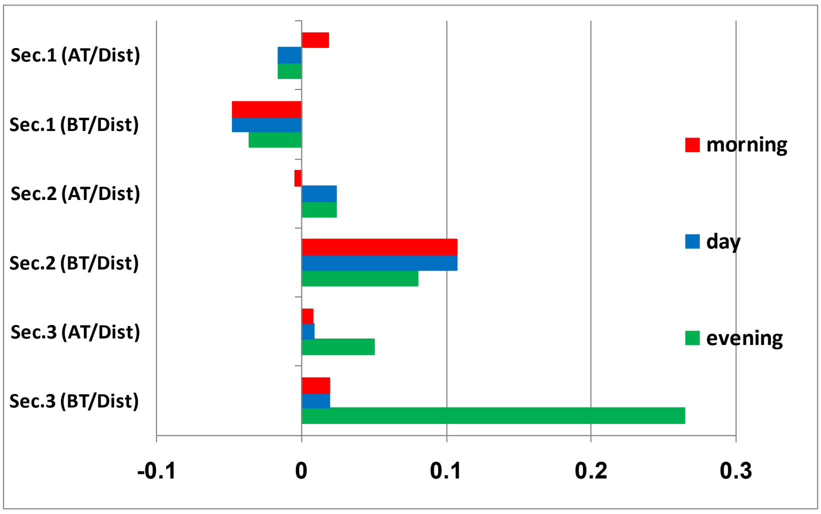
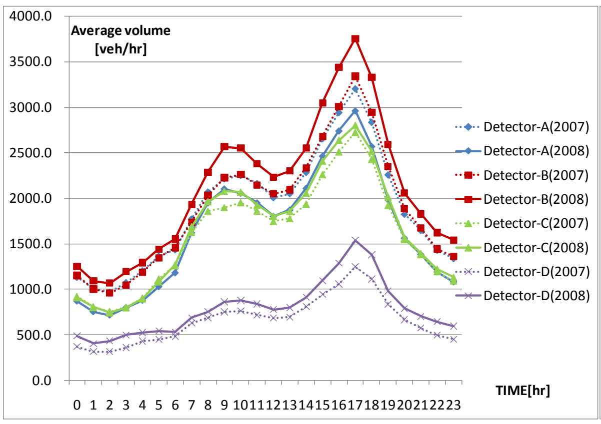


Figure-13. Differences in AT/Dist and BT/Dist between 2007 and 2008.



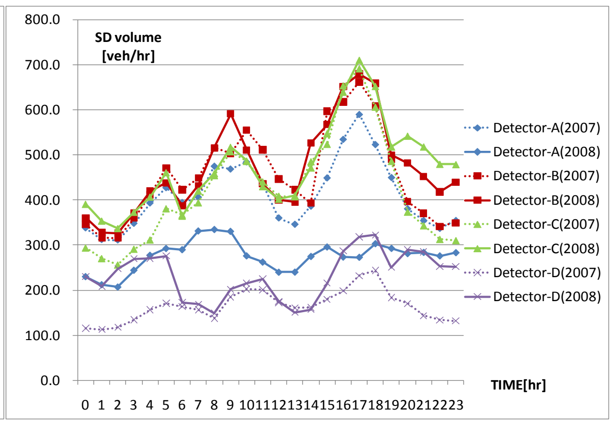


Figure-14. Average traffic volume for 2007 and 2008. Figure-15. SD of traffic volume for 2007 and 2008.

We next examined the difference in the LoS of the existing Meishin route before and after the opening of the Shin-Meishin route. Figure-13 shows the difference in AT/Dist (= T_{ave}/ Dist) and BT/Dist between 2007 and 2008. The difference in the indices was classified into three time periods: morning, daytime, and evening. A negative (positive) difference in an index indicates that the LoS improved (deteriorated). Figure-10 indicates that the 2008 LoS for the existing Meishin road may have shown some improvement. This seems to be true if we restrict our focus to the LoS of Sec.1 of the existing Meishin route. However, the LoS of Sec.2, including the junction between the Meishin and Shin-Meishin Expressways, deteriorated in terms of both AT/Dist and BT/Dist. This section seemed to be suffering from the concentration of traffic demand imposed by the merging of the existing Meishin route and the new Shin-Meishin route. Finally, the LoS in the evening in Sec.3 deteriorated markedly.

In this section, the changes in the level of service shown in Figure 13 are validated by the analyses of changes in hourly averages and standard deviations (SDs) of traffic volume estimated from data from Detectors A to D. Figures 14 and 15 show the mean and SD of traffic volume in 2007 and 2008, respectively. The mean and SD of traffic volume in 2007 and 2008 represent the cross-sectional traffic condition before and after the opening of the Shin-Meishin Expressway, respectively.

As shown in Figure-13, the LoS of Sec.1 improved after the opening of the new route. When we focus on both the average and SD of traffic volume, estimated from the data of Detector A in Figures 14 and 15, it can be seen that both tended to decrease from 2007 to 2008. It seems that this reduction in both the mean and SD of traffic volume may have been caused by the diversion of traffic, especially for long-distance travel, from the Meishin to the Shin-Meishin Expressway, which may have led to the apparent improvement in the level of service in Sec.1. Due to the concentration of traffic demand resulting from the merging of the existing Meishin route and Shin-Meishin route, the average traffic volume at Detector B tended to increase from 2007 to 2008. This suggests that the opening of the Shin-Meishin Expressway may have led to increased traffic demand in Sec.2, and thus the level of service may have deteriorated, especially in terms of travel time reliability, as indicated by BT/Dist (Figure-13).

Judging from the SD of traffic volume at Detector C, the traffic conditions tended to become more unstable. This tendency may be related to the deterioration in travel time reliability of Sec.3, the section further downstream of Detector C, in the evening in 2008. It seems that the increase in traffic demand (volume) in Sec.2 may also have caused an increase in traffic demand (volume) in the Keiji Bypass route, which diverges from the Meishin Expressway at a junction in Sec.2. Additionally, the SD of traffic volume at Detectors C and D tended to increase, especially from evening to midnight.

In this section, it can be said that the cross-sectional traffic conditions observed by the detectors may coincide with the level of service shown in Figure-13. That is, it was confirmed that the indices AT/Dist and BT/Dist are appropriate in evaluating changes in the level of service caused by the opening of the new intercity expressway.

CONCLUSIONS

We developed a method for evaluating the LoS of road networks from the viewpoint of both the average travel time and travel time reliability using electronic toll collection (ETC) data. Compared with conventional evaluations using only average travel times, the proposed method provides a detailed and exact evaluation of the LoS of road sections, considering variations in traffic service for different times of day and road sections. We evaluated the LoS and changes of travel time distribution between major ICs before the opening of a new intercity highway route (the Shin-Meishin Expressway) using the evaluation method established in this study. The changes in LoS between major ICs were also evaluated after the opening of the new expressway from the viewpoint of average travel time and travel time reliability. Although the LoS of most parts of the road network tended to improve with the opening of the new expressway, the LoS of some road sections seemed to deteriorate, due to a concentration in traffic demand. The following are our major findings:

1) This study established a methodology for evaluating the LoS in terms of travel time reliability using ETC data for an existing intercity expressway. To evaluate the LoS under ordinary traffic conditions, it was necessary to exclude outlier data, corresponding to time at rest stops and due to minor accidents. ETC data with travel times outside the range of $\mu \pm \sigma$ were regarded as outliers and were eliminated from the original ETC data set.
2) This study examined the average travel time in 15-min time intervals as the representative value for evaluating the LoS of road sections. The distribution of average travel times in 15-min intervals can be used for computing the indices used to evaluate the LoS including the mean value (μ), standard deviation (σ), PT, BT, BTI and so on.
3) In this study, we propose a new index, BT/Dist, to enable direct comparison and evaluation of the LoS among multiple road sections of different lengths. We suggest that both BT/Dist and T_{avg}/Dist be used to evaluate the LoS of road sections from the viewpoints of both average travel time and travel time reliability. We used case studies to confirm that the approach used to evaluate the LoS in this study can be valuable in determining the difference in the LoS for different road sections and times of day.
4) This study also evaluated the effect of the new Shin-Meishin Expressway on the LoS of the existing road network including the existing Meishin Expressway. It likely that the operation of the Shin-Meishin Expressway may lead to improvement in the LoS of the road network in general. Additionally, judging from analyses of cross-sectional traffic conditions observed by detectors, it was confirmed that the indices, namely AT/Dist and BT/Dist, were appropriate for evaluating the change in level of service caused by the opening of the new intercity expressway. The case study (using data only for the evening for 5 months) is not sufficient to justify use of BT/Dist. The effectiveness of this index needs to be verified in more detail with further relevant data in the future.

In future research, the ETC data used in the evaluation will be increased to cover a much larger road network. Additionally, temporal changes in LoS will be investigated using ETC data for additional years. Further investigation of how the LoS might be influenced by various factors, such as traffic demand, road structure, geometric design, and weather conditions, is required to contribute to better management of road networks.

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