VALIDATION OF AN IMPROVED METHOD TO ESTIMATE EXPRESSWAY TRAVEL TIME BY THE COMBINATION OF DETECTOR AND PROBE DATA

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Abstract: In this paper, real world probe data are applied to estimate travel times on two urban expressway routes, one shorter and another longer, of Nagoya city Japan. The analysis of the estimation results of a shorter route shows that travel time estimation accuracy may improve accompanying the increase of probe report sample size, but turns out to be nearly constant when the sample size has become big enough. On the basis of this finding, a data fusion methodology to combine probe and vehicle detector section travel time estimates is developed. Via different methodologies, travel times of the longer route are then estimated by using ultrasonic vehicle detector data only, with different allocation densities; and the combination of different kinds of probe data and vehicle detector data as well. The analysis of the estimation results shows that sample size of probe vehicle data significantly influences the travel time estimation performance; however, even very limited probe data can also improve the travel time estimation accuracy on a network with low vehicle detector allocation density. This is especially encouraging to large cities of developing countries, where streets are almost always crowded with taxies and starved of fixed traffic information collection devices.

Key Words: probe vehicle, vehicle detector, travel time estimation

1. INTRODUCTION

In order to support traffic management and traveler information provision, it is necessary to adequately measure the current traffic conditions. Travel time data is very important in this context since it is a direct and also intuitively understandable indicator of the LOS (level of service) of traffic flow. In Japan, travel time information of urban and intercity expressways has long been provided to travelers through different media.

The worldwide commonly used expressway travel time estimation methodology is generally based on data obtained through vehicle detectors, which may belong to loop or ultrasonic ones, and can also be divided into either single (Petty, K.F. *et al.* 1998, Hellinga, B. *et al.* 2000, and Oh, S. *et al.* 2001) or double types (Coifman, B., 2002). Zhang, X. (1999) has provided an empirical comparison of travel time estimation methods using vehicle detectors. The most common characteristic of these estimation methodologies is that almost all of them depend on spot-speed data. Good accuracy may be expected only when the assumption that the traffic condition in the section is either homogenous or a linear combination of two nearby points is met. Thus it requires a high allocation density of vehicle detectors, which are expensive in both installation and maintenance, especially for transport infrastructure management agencies in developing countries.

Hence it has been suggested to use the combination of the limited yet high quality probe data in the accuracy improvement of the travel time estimation based on conventional detector data; such like Sano, Y. *et al.* (2000), Choi, C.K. *et al.* (2001), Wang, R. *et al.* (2002), Nakamura, H. *et al.* (2002), and Nanthawichit C., *et al.* (2003). However, the probe data used in these earlier studies are mostly simulation data or are from a handful test vehicles only, despite that the practical world is unavoidably much more complicated.

In 2002, a large scale Internet ITS Test has been carried on in Nagoya city. During this test, the daily driving data of 1,570 taxies have been collected. The contents of the data cover 29 types, including vehicle ID, realtime position, spot-speed, and so on. This test provides the authors a chance to examine the practical possibility of using probe data in travel time estimation, which is also the objective of the study.

The paper starts with an introduction of the probe data used in the study, before the proposed travel time estimation methodologies are discussed. After a description of the study expressway routes and its detector data, the relationship between probe travel time estimation accuracy and probe sample sizes is analyzed by using data from the shorter route and a data fusion methodology is then developed. Next the travel times of the longer route are estimated in two different ways; 1) detector data only – with different allocation densities and 2) the combination of detector and probe data while applying the proposed data fusion method. Through the accuracy comparison among the estimated travel time values, the method is evaluated from the practical viewpoints and suggestions are finally made for the future study in this area.

2. THE PROBE DATA AND THE ITERNET ITS TEST 2002

The Internet ITS Test was carried on from January 1 to March 31, 2002 by the Internet ITS Research Group. This agency is organized by the Ministry of Economy, Trade and Industry; the Research Institute at SFC of Keio University; Toyota Motor Corporation; Denso Corporation; and NEC Corporation.

The objective of the program is to evaluate the supporting communication and information technologies and the commercial potentials of the so-called Internet ITS. 1,570 taxies equipped with both GPS and two way communication systems were involved in this test. By using the next generation internet technology of IPv6, data were uploaded in realtime every 300m and/or every 550 seconds. When some events happened, e.g. the occupancy status of the taxies had changed, data would also be submitted. Every time more than 20 types of data can be submitted, this includes the taxi ID, current time, position, speed, taxi occupancy, and so on.

In this study, data from 1,418 taxies that had been offline map matched are used. Since a vacant taxi often shows a biased driving behavior, data from occupied taxies only are kept. For a typical weekday, these vehicles may report data for about 2,500 times from the interested urban expressway route.

Generally the submitted data have a

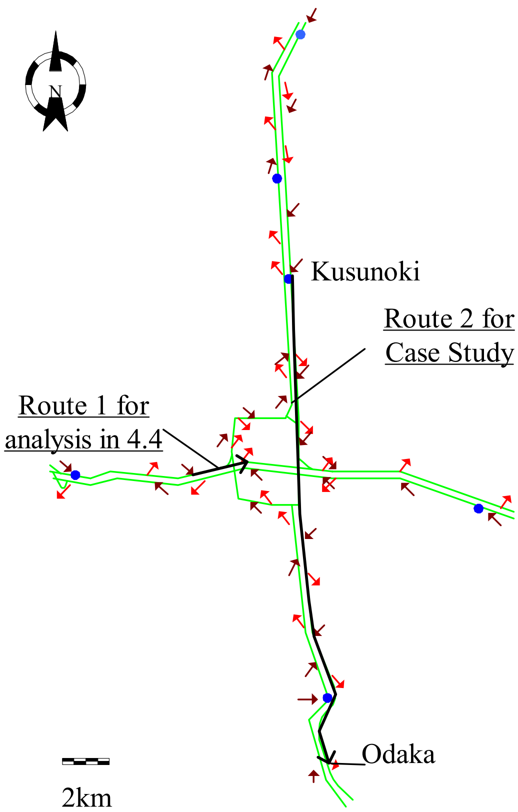


Figure.1 Study Routes on Nagoya Urban Expressway

Table. 1 Detector Allocation Densities in the three Scenarios

	Number of Sections	Number of Detectors	Average Section Length	Total Length
Scenario 1 (Det. High)	37	84	486m	17,970m
Scenario 2 (Det. Low)	13	29	1,382m	17,970m
Scenario 3 (Comb. TS/SS*)	13	29	1,382m	17,970m

* Two types of probe data are combined with detector data independently; see Chap.4 for detailed discussion.

tendency to be concentrated in the late night and early morning hours (22:00 – 4:00) when is the peak time to use taxies in the city of Nagoya with more than half of the total available data. A bigger sample size has significant advantage when using probe data. However, the peak period of taxi use is intentionally avoided in this study. This is because late night and early morning hours consist of less interest in the study of travel time estimation, if compared with morning/evening peak period in daytime.

3. THE STUDY NETWORK AND THE DETECTOR DATA

From Kusunoki to Odaka (southbound), one of the major routes of Nagoya urban expressway is navigated in this study. The total length of this route is 17.97km which can be divided into 37 sections with an average length of 486m. There are 7 on-ramps and 6 off-ramps along the way. All together 84 roadside ultrasonic vehicle detectors are installed in these 37 sections, i.e. one detector for each lane in a section while most sections consist of only 2 lanes, with a few exceptions. Most of the detectors of Nagoya Urban Expressway Networks are of single type. All the spot-speed data used in this paper are already estimated by the Nagoya Expressway Public Corporation (2001) using Equation (1), a statistical regression methodology.

$$v = \alpha e^{\beta Occ} \tag{1}$$

where v is spot-speed (km/hr), Occ is time occupancy (%), α (95.3) and β (-0.037) are parameters.

In this study, travel times are estimated under 3 different scenarios: 1) detector data only, and based on the original high detector allocation density (Det. High); 2) detector data only, and based on a loosened low allocation density around 1,400m (Det. Low); and 3) combination of detector and two types of probe data, i.e. probe travel speed (Comb. TS) and probe spot speed (Comb. SS). The detector allocation densities used by scenario 2 and 3 are different from the scenario 1. They are shown in Table 1, and the study network is shown in Figure 1.

Here in this paper, Scenario 1 (Det. High) is used as a benchmark to evaluate the performance of Scenario 2 (Det. Low) and 3 (Comb. TS and Comb. SS). The studies carried on by Nagoya Expressway Public Corporation and Nagoya Expressway Society (2001) have shown that the

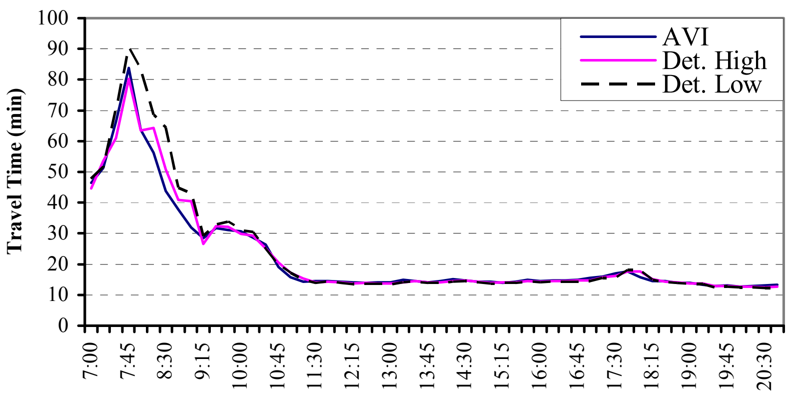


Figure 2. Comparison of Different Density Detector and AVI Travel Times (Oct. 23, 2001)

high detector density, or Det. High, travel times are very close to those measured directly via vehicle number plate matching technology. Thus Scenario 1 can be used as a benchmark. Figure 2 is an example of October 23, 2001. In this paper, vehicle number plate matching technology is referred as AVI (Automatic Vehicle Identification) technology.

4. TRAVEL TIME ESTIMATION METHODOLOGIES

4.1 Route Travel Time Estimation Algorithm

In this paper, the route travel time from Kusunoki to Odaka is defined as the progressive sum of the consisting section travel times (Nakamura, H. *et al.*, 2002). Some times the method is also referred as time-slice travel time (Okada, T., 2001). From Figure 2, it is easy to find that there is almost no time lag between AVI travel times and time-slice detector travel times even though the data are of October 23, 2001 when a serious incident happened in the morning peak time. Time-slice travel time is defined as the progressive sum of section travel times here.

For an expressway route consisting of n sections, its travel time at time interval t_e, $TT(t_e)$, is calculated according to Equation (2),

$$TT(t_e) = \sum_{i=1}^{n} T_i(t_{ei}) \qquad (2)$$

where $T_i(t_{ei})$ is the travel time of the i^{th} section in the route at time interval t_{ei}, which is the time interval that the vehicles arriving the route entry during t_e are estimated to exit the link i. And t_{ei} should be equal or later to t_e. A Scenario 1(Det. High) example of October 23, 2001 is shown in Table 2. Attention should be paid that there are 37 sections for Scenario 1 and only 13 for Scenario 2 (Det. Low) and 3 (Comb. TS/SS).

Table 2. An Example of Route Travel Time Estimation (Unit: min)

Direction →

Time	Sec.1	Sec. 2	Sec. 3	…	Sec. 35	Sec. 36	Sec. 37	Route
9:15	0.24	0.61	0.62	…	0.82	1.01	0.38	26.48
9:30	0.3	0.89	1.25	…	1.08	1.03	0.36	32.39
9:45	0.32	1.22	1.22	…	1.14	1.23	0.45	32.16
10:00	0.2	0.43	0.49	…	1.21	1.1	0.39	29.92

4.2 Section Travel Time Estimation Methodologies Using Detector Data ($T_i^{\det}$)

During a time interval of 15 minutes, the original one-minute spot-speed and traffic flow data, which are collected from the m detectors on the m lanes of the i^{th} expressway section are used in the estimation of the section travel time ($T_i^{\det}$) by using the following procedure:

1. On the k^{th} minute in the time interval, the spot-speed observations from the m detectors on section i are firstly combined by using their weighted average; the weights are decided by the corresponding traffic flow rates of the same lanes, q_{ij_k}

$$v_{i_k}^{\det} = \sum_{j=1}^{m} q_{ij_k} v_{ij_k}^{\det} / \sum_{j=1}^{m} q_{ij_k} \qquad (3)$$

   where $v_{i_k}^{\det}$ (km/h) and q_{ij_k} are the spot-speed and flow rate observations from the j^{th} detector in the k^{th} minute;

2. The travel speed estimated from detector data $\bar{v}_i^{\det}$ (km/h) of the i^{th} section in the same time interval is then estimated by using the mean of the n one-minute spot-speed data $v_{i_k}^{\det}$.

$$\overline{v}_i^{\det} = \sum_{k=1}^{15} v_{i_k}^{\det} / 15 \tag{4}$$

3. The section length L_i (m) is finally divided by the detector travel speed data $\overline{v}_i^{\det}$ to estimate the detector travel time $T_i^{\det}$ (min) of this section at the time interval.

$$T_i^{\det} = \frac{0.06 * L_i}{\overline{v}_i^{\det}} \tag{5}$$

4.3 Section Travel Time Estimation Methodologies Using Probe Data (T_i^{probe})

As stated earlier in this paper, a probe vehicle can submit more than 20 types of data via every transmission. According to the different types of data applied, two methods are suggested in this study to use probe data in the estimation of section travel time. Method (a) uses the average probe travel speed, and Method (b) uses the average probe spot-speed.

The study urban expressway route is divided into sections with the same profile as of the Scenario 2 (Det. Low). In the i^{th} section, assumed the number of probe vehicles that had traversed through it is n^{probe}, and the j^{th} probe vehicle within them had submitted m_j^{probe} data reports during a certain time interval. Data of instantaneous speed, position and time are included in every probe data record.

(a) Travel-Speed Method: While the instantaneous speed data from a probe vehicle are only a spot measure of the traffic situation, the position and time data from probe data reports may probably provide a line measurement; if and only if the probe can leave more than or equal to two data records on the section during a same time interval. In other words, probe vehicles may be regarded as *moving AVI systems*, rather than *moving sensors* (Nanthawicchit, C., *et al.* 2003) traveling in traffic flows. In this method, the time and position values of the first and last data reports from a very same probe vehicle in a same i^{th} section are at first used to calculate the *travel speed* of this vehicle in this section,

$$\overline{v}_{ij}^{probe} = \begin{cases} v_{ij}^{probe} & \text{if } m_j^{probe} = 1 \\ \dfrac{3.6 * (x_{im_j^{probe}} - x_{i1})}{t_{im_j^{probe}} - t_{i1}} & \text{if } m_j^{probe} > 1 \end{cases} \tag{6}$$

then using the mean of probe travel-speeds from all available probe vehicles to estimate the space mean speed of the section from probe data.

$$\overline{v}_i^{probe} = \frac{1}{n} \sum_{j=1}^{n^{probe}} \overline{v}_{ij}^{probe} \tag{7}$$

where $\overline{v}_i^{probe}$ (km/h) is the travel speed estimate of section i from the j^{th} probe vehicle; v_{ij}^{probe} (km/h) is the instantaneous speed data from a data report of the j^{th} probe; $t_{im_j^{probe}}$ (sec) and $x_{im_j^{probe}}$ (m) are the instantaneous time and position data also from the j^{th} probe's data reports in the section.

(b) Spot-Speed Method: the space mean speed of the i^{th} section $\overline{v}_i^{probe}$ (km/h) is firstly estimated using the harmonic mean of the instantaneous data from all available probe data reports in a time interval, as shown in Equation (8).

$$\bar{v}_i^{probe} = \frac{\sum_{j=1}^{n^{probe}} m_j^{probe}}{\sum_{j=1}^{n^{probe}} \sum_{k=1}^{m_j^{probe}} 1/v_{ij_k}^{probe}} \tag{8}$$

where m_j^{probe} is the number of the data records from the j^{th} probe; and $v_{ij_k}^{probe}$ (km/h) is the instantaneous speed data from the j^{th} probe's k^{th} data record in the i^{th} section.

After the space mean speeds are estimated through one of the above two methods, travel time of section i, T_i^{probe} (min), can be calculated by using Equation (9).

$$T_i^{probe} = \frac{0.06 * L_i}{\bar{v}_i^{probe}} \tag{9}$$

4.4 Data Combination Methodologies

(1) Analysis of Relationship between Travel Time Estimation Accuracy and Frequency of Probe Reports

When we want to combine probe and detector travel time estimates, the performance of probe travel time estimates under different conditions have to be taken into consideration. The accuracy of probe based travel time estimates depends a lot on the sample sizes of probe vehicle. The underlying reason behind is that the variance of the mean travel times obtained from n probe vehicles for a same expressway section over a certain time interval may decrease following the increase of n, or the sample size of probe vehicles at the interval.

Using two month data (February and March, 2002) on the Manba-Line of Nagoya urban expressway, travel speeds on the study route during the corresponding period are estimated at 15-min time intervals. Both of the two estimation methodologies, travel-speed method (a) and spot-speed method (b) are applied. The relationship between estimation accuracy and probe vehicle report frequency is then determined. The reason to use this route for accuracy analysis it that there are no under streets for this route and thus may simplify the map matching problem. The route is shown in Figure 3 and its position in the network is shown in Figure 1.

In this paper, mean absolute relative error (MARE) is used in this study to evaluate the performance of the estimations.

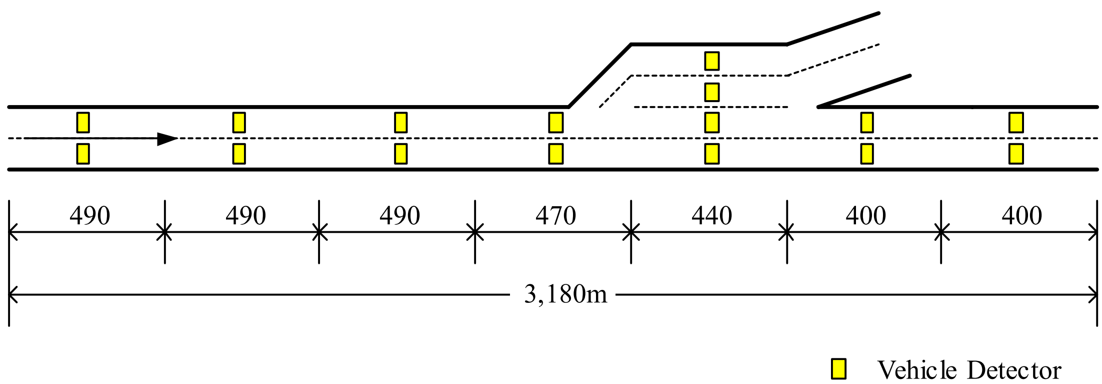


Figure 3. The Study Route on Manba Line

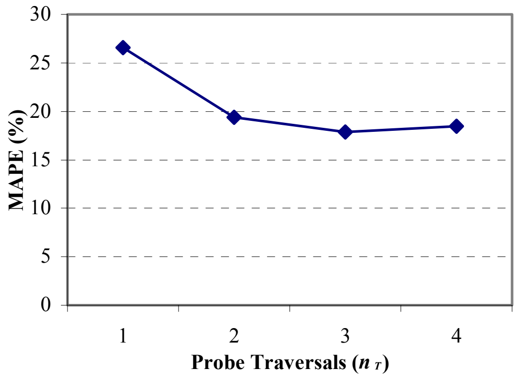


Figure 4. Relationship between MARE and Number of Probe Traversals (n_T)

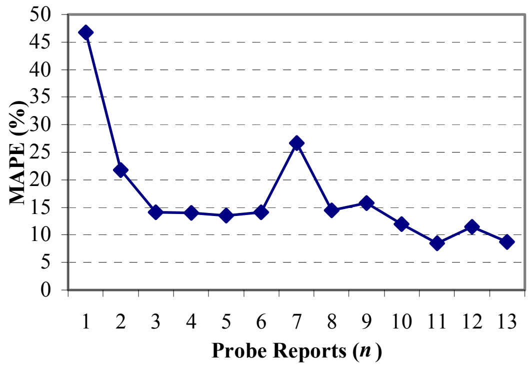


Figure 5. Relationship between MARE and Number of Probe Reports (n)

$$\text{MARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x_i - f_i}{f_i}\right| \tag{10}$$

where f_i is the i^{th} *true* value of the high density detector data (Det. High); x_i is the i^{th} estimated value, and n_T is the number of probe traversals and n the number of probe reports.

Since the probe vehicles involved in this study is only a very small fraction of the city's huge vehicle population. Very limited probe data reports and probe traversals were available. At 15-minute interval level, there were all together 5,664 time intervals during the 59 days, however 3,304 intervals among them were without even one single probe traversals.

Travel speeds of the left 2,360 time intervals with probe traversals are calculated with the two probe only estimation methods. The relationship between estimation MARE and sample sizes, which are the probe traversals or frequency of probe reports corresponding to the methods (a) and (b), is determined and shown in Figure 4 and 5.

From the two figures, it is very clear that estimation accuracy may improve with the increase of probe sample sizes n_T and n, but become steady when they are big enough. This result agrees with the conclusions of Sen, et al (1997).

(2) The Data Fusion Models

Here we assume, at a certain time interval, T_i as a travel time of expressway section i, T_{deti} as the section travel time estimated by single type detectors, and $T_{\text{probe}i}$ the section travel time estimated by probe vehicles. A common way to estimate T_i by combining both detector and probe data is to use the weighted average of T_{deti} and $T_{\text{probe}i}$, as the following formula:

$$T_i = (1-w)T_{\det i} + wT_{\text{probe}i} \tag{11}$$

where w is the weight assigned to probe based travel time estimates, and $0 \le w \le 1$.
From earlier discussion, we know that w is a function of probe reports number n, so we have

$$w = w(n) \tag{12}$$

As shown in Figure 5, the accuracy of probe only estimation is very poor when there are only 1 or 2 reports, and after 3 it will become kind of steady. Therefore, Equation (13) is proposed,

$$w = w(n) = \begin{cases} 0 & if\ n = 1; \\ 0.5 & if\ n = 2; \\ 1 & if\ n > 2. \end{cases} \quad (13)$$

5. TRAVEL TIME ESTIMATION RESULTS AND THE ANALYSIS

5.1 Travel Time Estimation Results

In order to evaluate the proposed methodologies, travel times from 7:00 to 21:00 of both February 2 (Sat.) and February 6 (Wed.), 2002 are estimated by using detector and probe data.

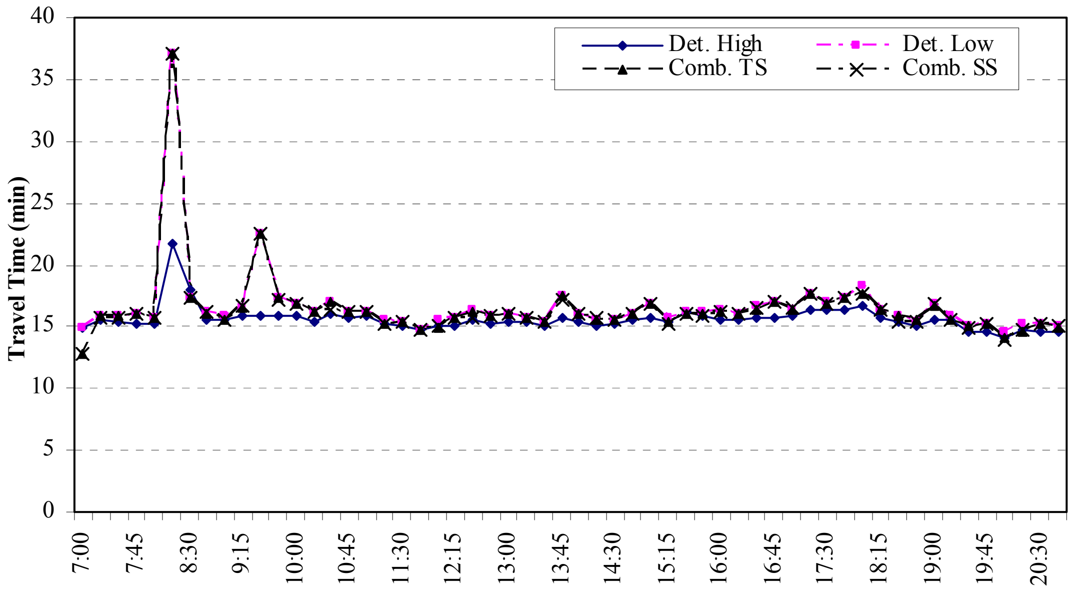


Figure 6. Travel Time Estimation Result of Feb. 2 (Sat.)

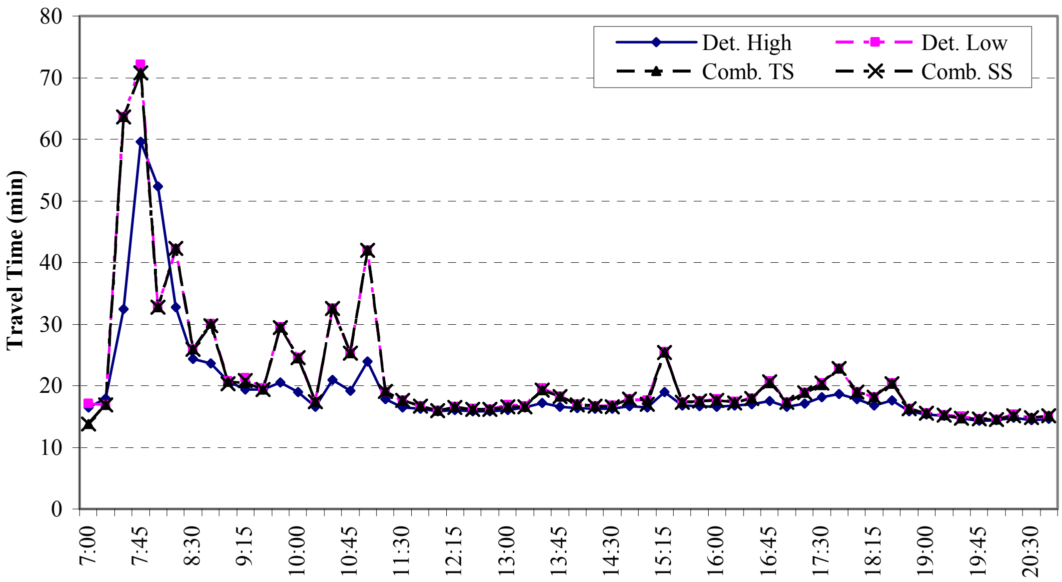
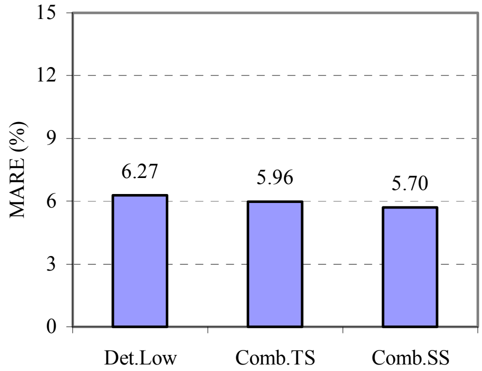


Figure 7. Travel Time Estimation Result of Feb.6 (Wed.)



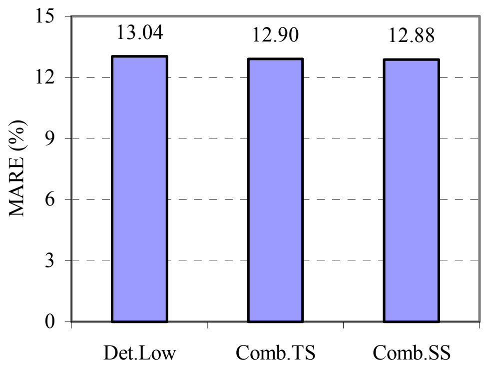


Figure 8. MARE Comparison in Feb.2 (Sat.) Figure 9. MARE Comparison in Feb.6 (Wed.)

The estimation time intervals are 15 minutes for both days. The travel times are estimated under four different scenarios, namely the Det. High, Det. Low, Comb. TS, and Comb. ST. The estimation results are shown in Figure 6 and Figure 7.

In 2002, February 2 was an ordinary Saturday and February 6 was a Wednesday with an incident happened in the morning peak period. So no wonder it is found that the travel time patterns of the two days are obviously different. The nonrecurring congestion of February 6 is very obvious while the travel time pattern of February 2 is much smoother, except two extreme points in the morning.

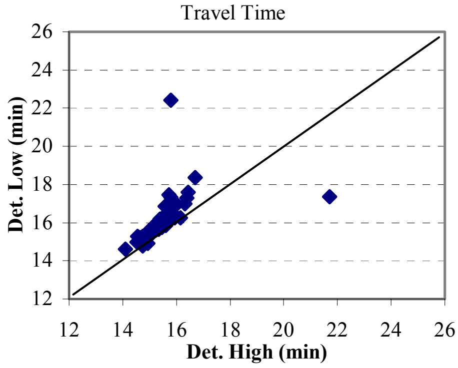
Det. High travel times are estimated by the original high allocation density detector data only. They are used as a benchmark in Figure 8 and Figure 9 to evaluate the estimation performances of the two combination methods, i.e. Comb. TS/SS.

This combination improves the estimation accuracy in February 2 (Figure 8), the estimation MARE is reduced to 5.96% (Comb. TS) and 5.70% (Comb. SS) from the 6.27% of Det. Low estimates. It is a 9.0% improvement. However, it gives slighter improved accuracy in February6 (Figure 9), probe data combination get 12.90% (travel-speed type probe) and 12.88% (spot-speed type probe) MARE, compared with the 13.04% of Det. Low travel time estimates. It is only a less than 1.3% improvement.

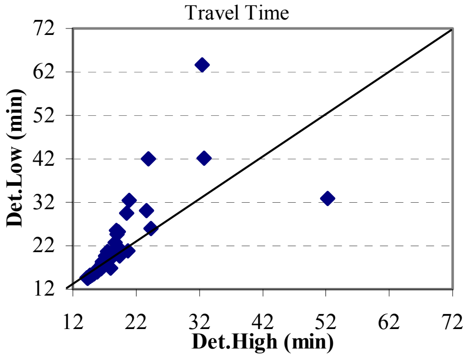
The other result is that there is barely difference between the combinations of the two types of probe data, travel-speed and spot-speed.

5.2 The Analysis of the Estimation Results

In both Figure 6 and Figure 7, Det. Low travel times, estimated by data from a loosened detector allocation density only, show a bias that is greater than the Det. High travel times. Figure 10 (a) and (b) show the distribution of Det. Low travel times in both February 2 and

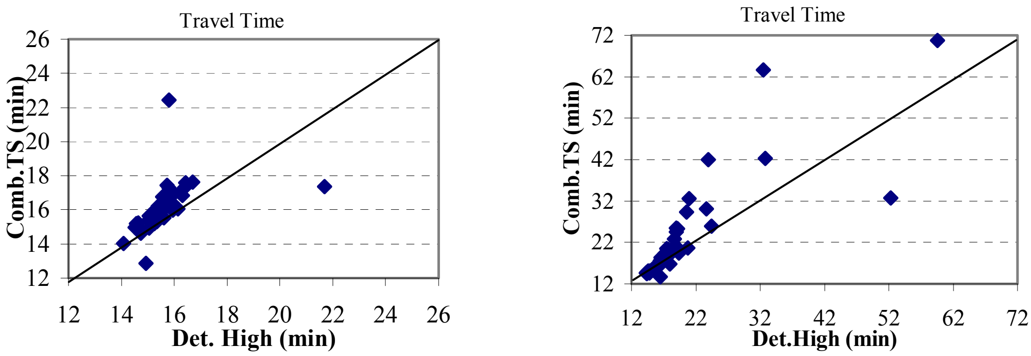


(a) Feb. 2 (Sat.)



(b) Feb. 6 (Wed.)

Figure 10. Bias Shown by the Det. Low Travel Time Distribution



(a) Feb.2 (Sat.) (b) Feb.6 (Wed.)

Figure 11. Bias Shown by the Comb. TS Travel Time Distribution

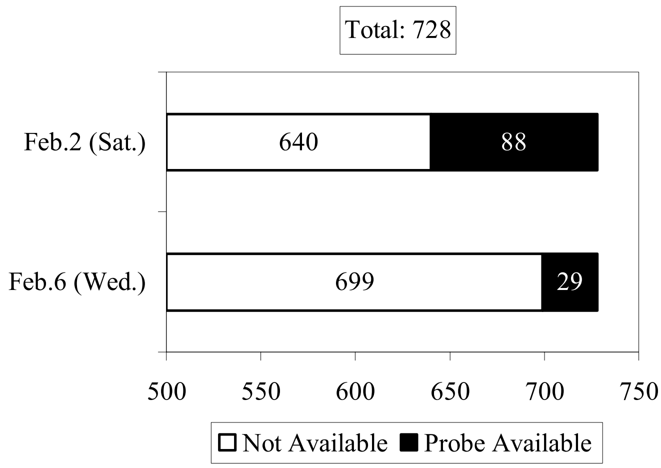


Figure 12. Comparison of Availability of Probe Data Section Travel Time

February 6. While on both days bias is observable, on February 2 this bias is extremely obvious. The simulation data of Nakamura, H. *et al.* (2002) showed the complimentary relationship between probe and vehicle detector section travel times, they then concluded that it was the reason why combination of even a few probe data could also improve the estimation accuracy. This conclusion is also proved by the real world probe data used in this study by the comparison between Figure 10 (Det. Low) and Figure 11 (Comb. TS). As shown in the Figure 10 (b) and the Figure 11 (b), the bias of Det. Low travel times is improved by combination of travel-speed type probe data, even though the latter gives only slight better estimation accuracy. And this improvement of bias is also obvious with the February 2 data by the comparison between Figure 10 (a) and Figure 11 (a).

Observation accuracy of detector and probe data may affect travel time estimation accuracy in the probe data combination methods. In February 2, a serious incident happened on the study route and aroused a serious congestion. Low allocation density occupancy type vehicle detectors may give much poorer estimation accuracy under such situation, and the fluctuation is very obvious as shown in Figure 7. On the other hand, sample sizes of probe data influence directly probe data's performance in the estimation of travel time (A. Sen, *et al.* 1997). Since taxi usage tends to significantly decrease when serious congestions happen on urban expressways, much few probe data are available in February 6, 2002. The time interval used in this study is 15 minutes. So there are all together 728 section travel time data during the estimation time spanning from 07:00 to 21:00, i.e. 56 data for each of the 13 sections. As shown in Figure 12, there are 88 available probe section times in February 2, compared with the 29 data of February 6 (Wed.). The poorer observation accuracy from both detector and probe sides may be a reasonable explanation of the better performance of probe data combination in February 2.

In the Internet ITS Nagoya Test, the probe vehicles were supposed to submit data every 300m or 550sec. It means that the traffic flow condition is relatively stable among different data submission. This is probably an explanation of the better performance of the spot-speed type probe data.

6. CONCLUSIONS

In this paper, a theoretically simple and practically applicable methodology is proposed to combine real-world probe data with vehicle detector data in the estimation of travel times on an urban expressway route in Nagoya, Japan. The real-world data estimation justifies the simulation result of Nakamura, H. *et al.* (2002). They found that complimentary relationship existed between probe data and vehicle detector data. It is also found that the combination of probe data may improve the estimation accuracy significantly when the sample size of probe vehicle is large enough. For instance, in February 2, 2002, when probe data were available for 12.1% of the total 728 section travel times, the estimation MARE is reduced as much as 9.0%.

Two types of probe data usage are investigated to estimate urban expressway section travel time. Probe travel-speed is estimated by using the submitted probe position and time data, while probe spot-speed data are direct submitted data. Their estimation results show no significant difference in accuracy, because the data submission interval is quite short in the Nagoya test. In future estimation work, attention should be paid when the similar short intervals can not be expected.

Real world probe vehicle data collected by the Internet ITS Nagoya Pilot Program, the relationship between travel time estimation and probe sample size is analyzed. It is found that the estimation accuracy will be significantly improved accompanying the increase of probe sample size n, before it is lesser than 3. After that, the elasticity of MARE to n will tremendously decrease. It proves the early researchers theory analysis that the estimation accuracy will not improve significantly accompanying the increase of sample size when it has been big enough. This is very important for the design of MPR for a practical probe vehicle system.

Based on this finding, a data fusion model that incorporates probe travel time estimates with detector estimates is developed. In the model, probe and detector estimates are assigned different weights according to the sample size of probe vehicle.

GPS central control and navigation network is now rapidly spreading in taxi fleets of some big cities in Asian developing countries. It is reported that such a network with more than 2,000 taxies has been settled in Beijing by May 2002 (http://www.zgjtb.com/gb/content/2002-05/15/content_4250.htm). This study's practical applicability in developing cities is obvious.

In future, more work needed to analyze quantitatively the relationship between estimation accuracy and the current traffic flow conditions. A more accurate data combination method based on this quantitative relationship is very interesting. And finally, all the work in this paper is under offline situations. How to simulate the real online situation is of great use to the practical prospect of the methodology.

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