Variability of Travel Time Estimates using Probe Vehicle Data

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ABSTRACT

Accurate link travel time estimations obtained using probe vehicles are crucial to reliable dynamic route guidance systems. This study attempts to understand what level of travel time estimation reliability can be achieved from a given frequency of probe data. Hence the focus is on the variability of link/roadway segment travel time estimates for different data frequencies. Data is simulated to compare the variability of probe information; lower frequency probe samples are simulated by selectively deleting parts of higher frequency samples. The results suggest that higher frequency probe data do not always yield less variance in link travel time estimates, while lower frequency data have a smaller variance at links just before signalized intersections. On the other hand, the accuracy of roadway segment travel time estimates using low-frequency probe data appear little different from high-frequency data. Consequently, there is potential for the wide use of low-frequency data in route guidance applications.

KEYWORDS travel time estimates, variability, transmission frequency

INTRODUCTION

Probe vehicles have been regarded as a promising means of providing link travel times within signalized networks for DRGS (dynamic route guidance system), where loop detector data or vehicle occupancy data sometimes cannot distinguish vehicles making different turns at intersections (turn right, turn left, or straight ahead) and therefore provide unreliable link travel times for vehicles with different routes. The successful large-scale development of DRGS depends on highly reliable estimates of

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travel time. Thus, a lot of previous studies have investigated the expected reliability of probe travel time estimates. Sen *et al*. (1997) found that probe reports on link travel times are not independent and that the sample mean, however large the sample size is, never approaches the population mean. Hellinga and Fu (1999) concluded that the sampling bias in arrival time distributions and in the proportion of probes associated with each link departure turning movement will lead to a systematic bias in probe estimates.

Besides such problems with estimating link travel times that result from a biased sample distribution, one new problem with the application of probe data at low transmission frequencies has become, in a practical sense, a major obstacle preventing precise aggregated travel time estimates. A preceding study by the authors has already shown that the accuracy of individual probe reports of link travel time decreased sharply with increasing probe transmission interval (Liu *et al*., forthcoming). Moreover, even if individual probe reports of link travel time are perfect, the travel time for a particular link under identical traffic conditions is not necessarily the same because of heterogeneity in driving characteristics. For route guidance systems, it is more important to obtain accurate estimates of average travel time rather than individual probe reports. Therefore, it is necessary to know what level of reliability of travel time estimates can be achieved from a given frequency of probe data.

The accuracy of link travel time estimates obtained using probe vehicle data with different frequencies is one crucial indicator of data performance. It helps to make more cost-effective decisions for DRGS, because reducing probe transmission frequency to a reasonable level is an effective method of reducing the enormous operational costs and then increasing the probe penetration rate. This study focuses on comparing the estimates of travel time and their variability for different frequencies of probe data. The variability comparison is conducted from two standpoints in this empirical study: individual links and groups of links (roadway segments).

In the section that follows, the data used in this empirical study is described. Then individual reports of link travel time for probe data at different frequencies are examined. Subsequently, variability differences in link travel time and in cumulative link travel time (roadway segment travel time) are compared. The paper ends with our conclusions.

STUDIED ARTERIAL LINKS AND DATA COLLECTION

The test bed for this study was Hirokoji-Dori in the Imaike area of Nagoya, Japan. This is the main east-west urban arterial route directly to Nagoya station. A total of nine DRM (digital road map) eastbound links (Figure 1) were selected, measuring 877 meters in total length and with three lanes. All these links were numbered for easy and clear referencing. Link 5 is a very short link covering a main crossing at which the studied arterial route intersects with another main arterial road. There are a total of six traffic control signals within the studied links, operating in fixed-timed mode with cycle times ranging from 130 to 140 seconds.

Probe data collected in Nagoya from October 1st, 2002 to March 31st, 2003 were used for the empirical analysis. Among the 1,570 probe taxis taking part in the Nagoya

P-DRGS project, 90 with the highest distance-based frequency (at length increments of 50 meters) were selected for the research. The study was limited to weekday periods of four hours lasting from 20:00 to 24:00 so as to encompass relatively more samples. The four-hour period was divided into sixteen fifteen-minute aggregation time intervals to ensure that a reasonable number of observations were obtained for each of the links. Only trips passing through all the studied links were selected in order to avoid bias resulting from turning vehicles. Trips that had GPS errors or length increments greater than 70 meters were omitted. After filtering the data according to these criteria, a total of 438 trips remained in the study. The observed sample size for each fifteen-minute period ranges from 10 (from 20:15 to 20:30) to 46 (from 23:15 to 23:30).

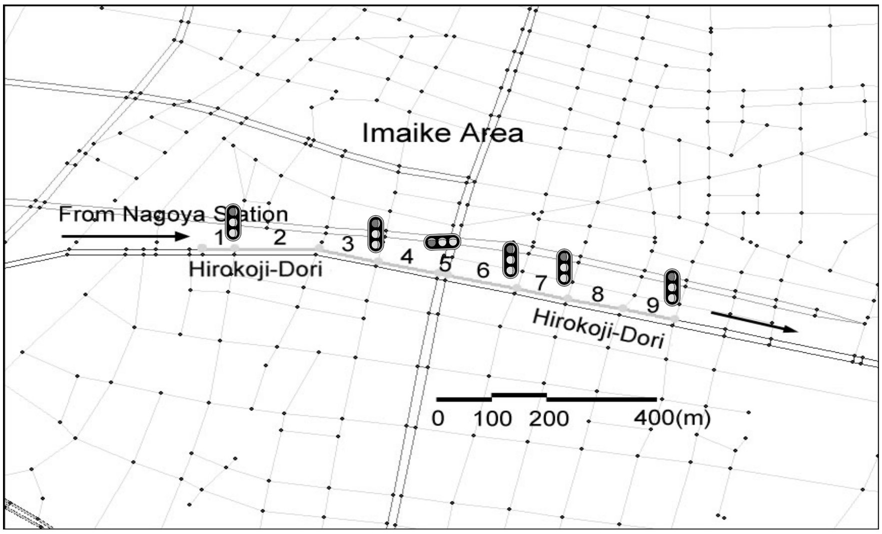


Figure 1. Studied arterial links

Lower-frequency data transmissions for each trip by each vehicle over the whole collection period were simulated by selectively deleting parts of records. A total of seven groups of data were simulated, with simulated transmission intervals ranging from 100 to 400 meters (abbreviated as 100m data, 150m data, and so on in this paper).

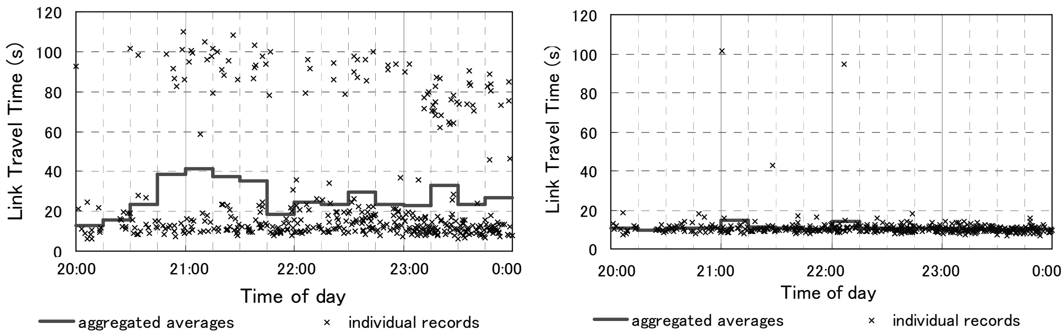
COMPARISION ON THE VARIABILITY OF TRAVEL TIME ESTIMATES

The aggregate mean of probe reports of link travel time can, in general, be seen as an estimate of travel cost. This type of information is widely used for route guidance and travel time forecasting. There are two possible methods of calculating individual link travel times from GPS point data: assuming uniform motion or uniform acceleration. The simpler uniform motion assumption is employed in this study, because it is difficult to judge when the speed of probe cars changes or where they stop using only position and time information. This is especially true for the lower-frequency data. Thus link travel time can be easily calculated by estimating the ingress and exit time under the assumption that a constant velocity is maintained between two adjacent GPS records. Details of this method can be found in Miwa *et al.* (2004).

It is important to understand the accuracy with which an aggregate travel time based on sampled data matches the aggregate travel time experienced by vehicles in general. Understanding the variability of vehicle travel times helps with understanding of traffic flows on urban networks. This section focuses on differences in the variance of travel time reports with different frequencies of probe data and attempts to understand the impact of probe transmission frequency on travel time estimates. Both link travel time and roadway segment travel time (including all 9 studied links) are examined.

Variability of Link Travel Time Estimates

Figure 2 shows the travel time reports and aggregated mean provided by 50m data for the link just before the main intersection (link 4) and the link just after the main intersection (link 6). The travel time reports for link 4 appear to form a bimodal distribution and range from 7 to 110 seconds, while those for link 6 are concentrated on around 10 seconds. These distributions indicate that some vehicles experienced stoppages or slowdowns at link 4 while almost all probes (all but three out of 438 samples) passed through link 6 without any delay. Only link 4 and link 6 are discussed in this section even though the investigation of link travel times was carried out for all studied links, because all other links can be categorized as one of these two types of link travel time distribution.

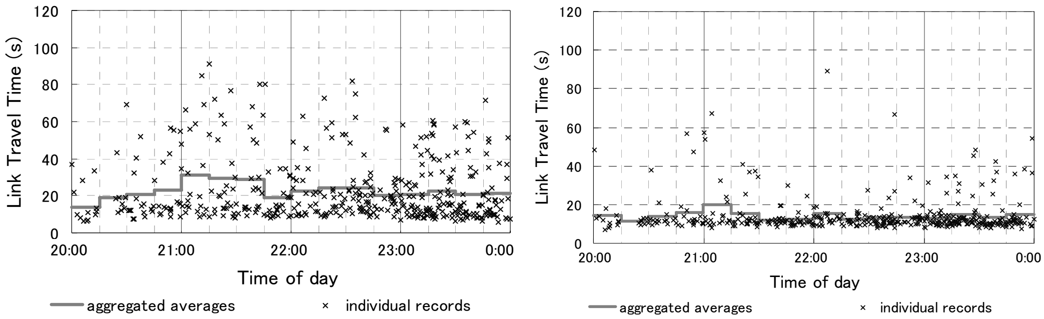


a) Link 4 b) Link 6

Figure 2. Link travel time estimates using 50m data

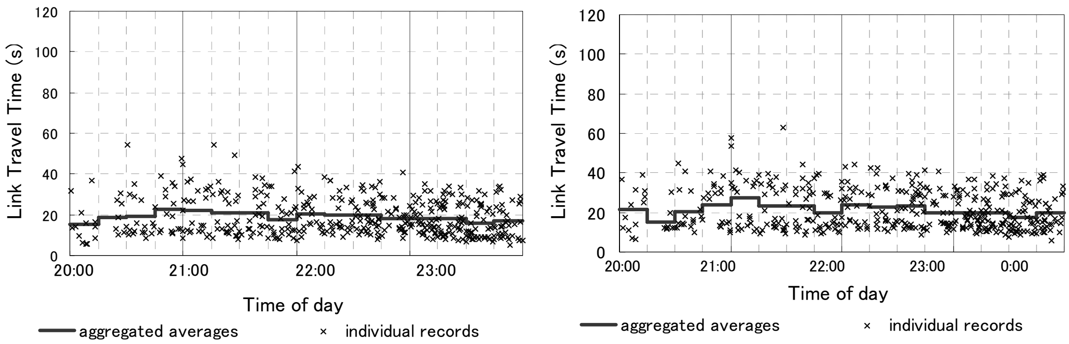
On link 4, most trips fell into one of two categories: long stoppage or rapid passage. This is reasonable, because of the limited length of queue and signals almost in phase with the upstream signal under the control of the green wave system. As a result, there is a clear division between vehicles that stop and those that do not. It should be noted that no probes stopped at this signal during the first two fifteen-minute periods, the ones with the fewest samples (only 15 and 10 samples, respectively). It can be understood intuitively that these probes represent an estimate that is far from the population average travel time because, by chance, they avoided delay at the signals. That is, the estimation error may be large even with high-frequency probe data, especially with a small sample size. Such errors can be reduced by increasing the sample size. However, the effect of unexpected delays at signals cannot completely be removed (Hellinga and Fu, 2002).

Figures 3 and 4 show matching travel time reports and aggregated means for link 4 and link 6 calculated from probe data with 200m and 400m intervals, respectively. The enumeration of link travel reports and estimates derived from other simulated lower-frequency data is omitted in this paper because data for other frequencies follow the same trend as the 200m and 400m data.



a). Link 4 b). Link 6

Figure 3: Link travel time estimates using simulated 200m data



a). Link 4 b). Link 6

Figure 4: Link travel time estimates using simulated 400m data

Compared with the link travel time reports for these two links provided by the 50m data, those derived from 200m data contain some errors. These result from the methodology applied to measure link travel time. This methodology is based on the assumption of uniform motion between two adjacent GPS records and it smoothes out velocity variations during a travel sequence. Therefore, part of any delay incurred on link 4 is distributed possibly into the other links (such as link 6). The bimodal distribution of link travel times for link 4 is no longer clear, although the majority of trips that encounter a red signal can still be distinguished from those where there is no stop. The travel time reports for link 6 derived from 200m data appear to include more slowdown events than there should be. This is because link travel time is estimated based on a bidirectional displacement of travel time costs: from the observed link to others and simultaneously from other links to the one being observed. This trend is more obvious for probe data with longer intervals and at the longest interval there is no clear difference between the results for link 4 and link 6. Figure 4 reveals this extreme situation: there is no discernible boundary between vehicles that stop and those that do not and differences between fifteen-minute periods fade away.

Next, the variance of probe reports is examined. Figure 5 depicts the standard deviation for probe vehicle data at the three frequencies discussed. The standard deviation of the high-frequency probe data is much higher than that of the low-frequency probe data for link 4 during most periods, while the opposite is true for link 6. Examination of all 9 links shows that a higher variance is clearly associated with lower-frequency probe data only in link 5, link 6 and link 7, all of which are located at or after main intersections where few vehicle stoppages were observed. For other links, the variance of low-frequency probe data is relatively smaller in general. Average link travel times and probe report variance have similar trends with respect to aggregation period.

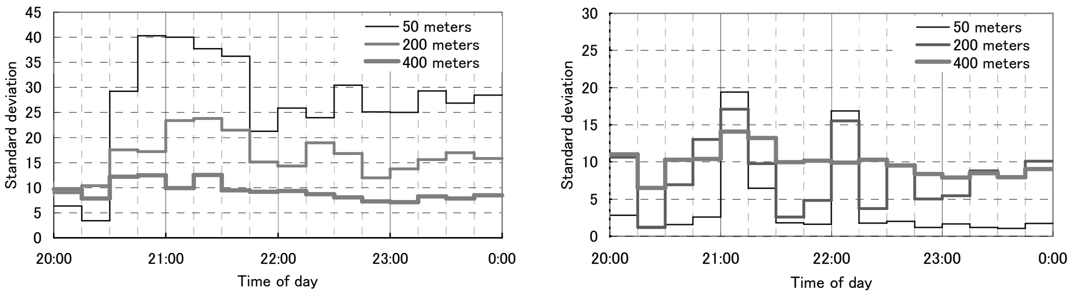


Figure 5. Variance in travel time reports for Link 4 (left) and Link 6 (right)

Although the 50m probe data may provide detailed information about individual vehicle movements in general, the aggregate mean value for each period hardly proves to be a reliable estimate of link travel cost in the case of link 4. Moreover, the great differences in estimates for link 4 between adjacent aggregation periods, as well as the large standard deviation, seem so strange that none of the estimation values can be treated as a generalization of traffic network conditions when it is taken into account that traffic must be relatively stable in the evening. Visually, the estimates provided by the 400m data and that have a relatively small standard deviation tend to be stable over time for a particular link.

One possible reason for the variation between fifteen-minute aggregating periods is that the period does not divide exactly by the signal cycle time (which ranges from 120 to 140 seconds). As a result, one period may include an excess single green phase together with several signal cycles while the next period might include an excess red phase as well as several signal cycles. Accordingly, sample distribution with respect to signal phase might be greatly different between aggregation periods.

Lower-frequency probe data do diminish the variance of link travel time reports for one link through a process of redistributing the travel cost from the link of interest to other links. This transfer of cost does help to reduce estimation errors resulting from the large variance in actual travel time experienced by each vehicle. It can be concluded that accuracy in link travel time estimates with high-frequency probe data is more sensitive to sampling error than in the case of lower-frequency data. As a result, the problem of inadequate probe sample size and subsequently great variability in link travel time owing to the complexity of signal delay time can be seen as one of the main obstacles to precise estimation using high-frequency probe data. On the other hand, for data with longer transmission intervals this obstacle disappears.

Variability in Roadway Segment Travel Time

An important practical issue then is to calculate the roadway segment travel time based on these link travel time estimates. In ITS applications, the travel time for a roadway segment is calculated by accumulating the link travel time estimates.

Figure 6 is a scatter plot of travel times for all 438 samples and the segment travel time estimates for the 50m, 200m and 400m data sets. Travel times vary from 50 to 300 seconds overall, but the majority range from 100 to 200 seconds. In fact, during the trip along all 9 links, almost all probes experience waits at one or two signals, while few experience three or more stops or no stops. It is differences in where and when stops are experienced that leads to the considerable differences in variance among probes with different data frequencies and between different links. It should be noted that the sudden fall in roadway segment travel times after 11pm results from a signal adjustment.

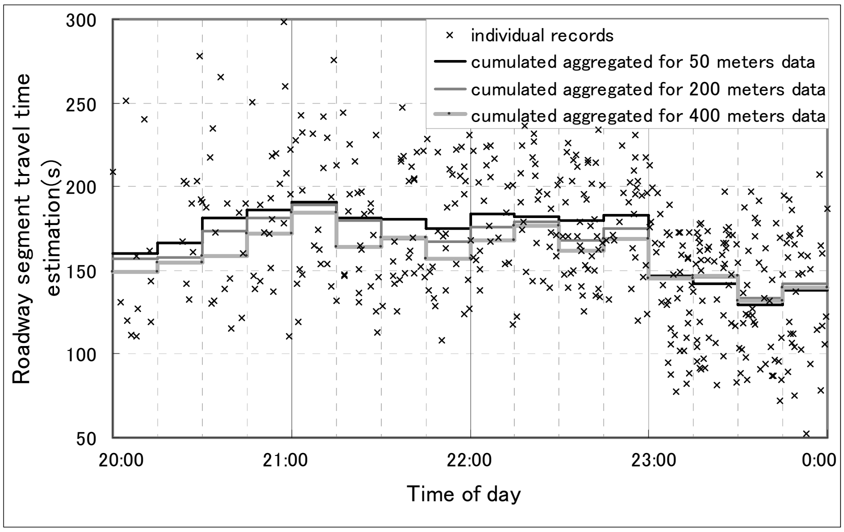


Figure 6. Aggregated average roadway segment travel times

The roadway segment travel time estimates derived from the three sets of probe data at different frequencies indicate that before 23:00 results based on the highest-frequency data are a little greater (ranging from 5 to 20 seconds) than those based on the lowest-frequency data. After 23:00, estimates using the three sets of data are almost the same. That is to say, during some periods the low-frequency data work as well as the high-frequency data, while at other times there is a small difference (as compared with the large difference in link travel time estimates).

This minor difference might be easily understood if roadway segment travel times were directly calculated from probe data at the different frequencies and then an average obtained. Using such a method, errors in segment travel time estimates from low-frequency probe data are determined only by the accuracy of segment ingress and exit times, both of which are determined by the two GPS records from before and after the ingress/exit nodes. Because ingress and exit nodes are in a normal distribution between these two points, the average error in segment travel time estimates should be a constant depending on transmission frequency and regardless of segment length. However, in this paper roadway segment travel times are calculated by accumulating link travel time estimates, so it may be thought that there would be considerable difference in accumulated segment travel times among different data considering the large differences in link travel time estimates.

The average time-distance diagram for all 16 accumulation periods and for all 8 datasets is shown in Figure 7. It is used to examine the cumulative average travel time along this roadway segment. The time-distance diagram of the lowest-frequency dataset, the 400m data, tends toward linear, as anticipated, while diagrams for higher-frequency datasets fluctuate about this line. The roadway segment travel times for the datasets are widely divergent at the end of link 2 and the end of link 7. Fortunately though, cumulative segment travel times at the main intersection are similar for all data, which means that using low-frequency probe data would have little external impact on route choice decision-making at these positions.

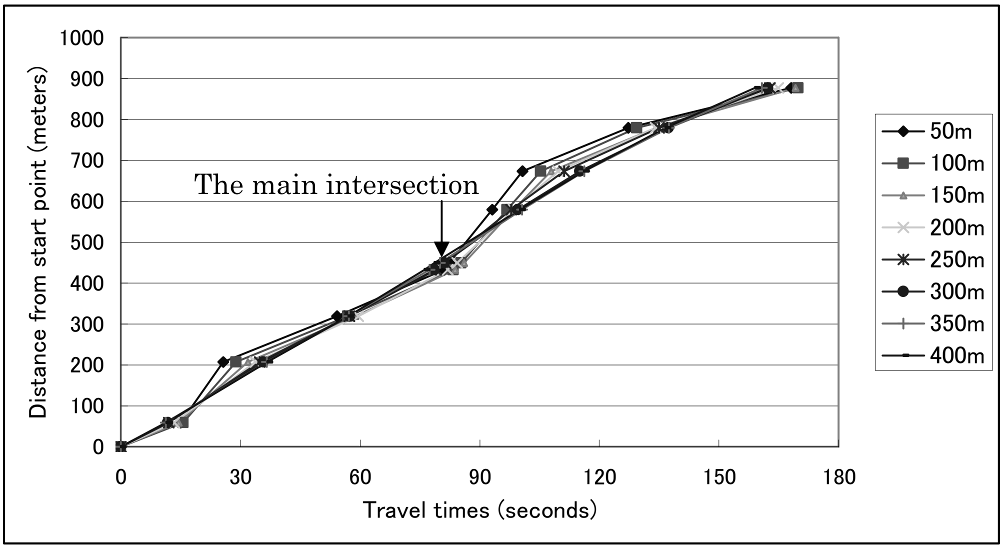


Figure 7. Time-distance diagram for all probe data at different frequencies

It is easy to understand this result from the differences in link travel time estimates: probe data at lower frequencies tend to underestimate travel times on some links where many delays are observed while others are overestimated. By accumulating roadway segment travel times, the major differences are smoothed and overall travel times tend to be similar.

Furthermore, the average standard deviation of roadway segment travel time estimates for all 16 time periods can be calculated using equation 1, where p is the total number of periods; T_i is the actual roadway segment travel time reported by probe i; and $\overline{T_j}$ means the aggregate travel time mean for link j. As shown in Table 1, the results suggest that the original 50m probe data and all the simulated lower frequency probe data offer almost the same accuracy.

$$\sigma = \frac{1}{p}\sum_{p}\sqrt{\sum_{i=1}^{n}\left(T_i - \sum_{j=1}^{9}\overline{T}_j\right)^2 / (n-1)} \qquad (1)$$

Table 1. Average standard deviation of roadway segment travel time estimates

Data interval (m)	50	100	150	200	250	300	350	400
Standard deviation	40.1	40.0	40.2	40.8	41.1	41.3	41.9	42.1

It is clear that if there are enough samples then low-frequency probe data can be used for route travel time estimates without too much loss of accuracy compared with high-frequency probe data. This could affect great savings in the transmission costs. Furthermore, more probes can be employed for a given budget if lower transmission frequencies are adopted, resulting in a higher probe ratio and more reliable estimates according to the population average value.

CONCLUSIONS

The objective of this study was to investigate the reliability of travel time estimates achieved from a given frequency of probe data. The focus was on the variability of link/roadway segment travel time estimates when data with different frequencies is used. Variance of the sample mean was adopted as the main criteria for identifying the value of low-frequency data in link-based travel time estimates.

Although high-frequency probe data have the advantage of accurately reporting experienced link travel times, the aggregate mean hardly proves to offer a reliable estimate of link travel cost. Sometimes it cannot be treated as a generalization for traffic network conditions if the sample size is small. Such estimation errors can be reduced by increasing the sample size. With lower-frequency probe data, the large variance in each link is reduced through a process of travel cost redistribution. This helps to reduce estimation errors arising from the large variance in experienced travel times by different vehicles. It can be concluded that accuracy in link travel time estimates for high-frequency probe data is more sensitive to sampling error than for lower-frequency data.

Segment travel times are more important than link travel times for travelers. It is found that the accuracy of roadway segment travel time estimates obtained using low-frequency probe data may not be as poor as the individual link information obtained. Roadway segment travel time estimates obtained by aggregating estimated link travel times do vary according to the frequency of the data used, but the variance is much smaller than the differences in individual link times. Fortunately, the cumulative segment travel times at the main intersection are similar for all data, which means that low-frequency probe data have little external impact on route choice decision-making at this main intersection. In summary, low-frequency data would possibly support segment travel time estimates with the same accuracy as obtained from high-frequency data, or at least with little degradation. However, the ability to successfully apply low-frequency probe data depends largely on the accuracy with which such infrequent data can be map-matched to the right position in the network.

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