Study on the Cost-Effectiveness of a Probe Vehicle System at Lower Polling Frequencies

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One serious problem of continuous large-scale data collection with probe vehicle is the dilemma of balancing the cost economization and system reliability improvements. The polling frequency is found to be one of the major factors that determine the operation cost of a probe vehicle-based traffic data collection system. This paper focuses on evaluating the cost-effectiveness of a probe vehicle system at various space-based polling intervals, with the purpose of data collection on providing roadway travel time estimation at certain reliability. The proposed optimization framework concentrates on the least total operation cost through a combining consideration on the polling frequency and the required probe size, which gives a simple and valuable solution on the issue of cost-effective traffic data collection.

Keywords: *Cost-effectiveness, Probe vehicle system, Polling frequencies*

1. Introduction

Probe vehicles equipped with GPS receivers have been employed for travel time data collection for over a decade. While those data are widely used for ITS projects evaluation, the network traffic surveillance system solely based on probe vehicles is still rare. Generally the total cost for such a probe system over the entire network during the whole day might be too much to sustain, and therefore can not be afforded by ITS projects.

Currently the most significant factor that limits the wide spread of Advanced Travel Information System (ATIS) is still the lack of a cost-effective method of obtaining data that reflecting network travel conditions [1]. The cost-effectiveness of travel data collection is an important design issue that should not be ignored. A comprehensive data collection strategy should meet both acquirements of good accuracy and reasonable costs, under the consideration that the successful continuing deployment of ITS services depends on both the user expectation of system reliability and their willingness to pay.

To maintain a real time traffic data collection system based on probe technology, the outfit including in-vehicle GPS receivers and a wireless communication network between traveling vehicles and the information center are required. Currently, GPS receivers are configured as a part of in-vehicle navigation systems and are generally implemented in vehicles beforehand in Japan, therefore the main cost is the communication cost. Polling frequency is the uppermost factor to control the communication cost of an individual probe vehicle except those equipped with a corresponding in-vehicle device to record special event information [2]. In order to easily trace travel behavior and obtain realistic real-time network information, most of the ITS projects employed probe vehicles with relatively high polling frequencies, say, second-by-second. Generally speaking, high-frequency data obtained at high transmission cost are unaffordable and unnecessary. The polling frequency as a factor of influencing system operational costs has not yet attracted enough attentions.

The large-scale investment of Nagoya P-DRGS (Probe-vehicle-based Dynamic Route Guidance System) project during the last four years provides a unique opportunity for the evaluation of the system cost-effectiveness level. The experience of operating such a large probe system is valuable and helpful to other cities, especially those in developing countries, to make more efficient project planning. This study is conducted under the motivation of showing the potential of promoting the P-DRGS in urban area from a cost-effective aspect.

Cost-effectiveness of a probe system can be improved from several aspects, whereas this paper focuses on the trade-off between improving the estimation reliability of traffic information and reducing communication costs by decreasing the polling frequency. This paper begins with a review of the literatures on the cost-effectiveness of a probe vehicle system. Then the evaluation framework of optimizing these two factors is considered. This is followed by a description of the probe size estimation method and a hypothetical charge system. Subsequently the cost-effectiveness of probe data at various space-based polling intervals is examined. This paper ends with our conclusions and future research requirement.

2. Literature Review

The wide implementation of probe technology is regarded as a great progress in traffic surveys and traffic monitoring. However, ITS projects based on a probe system are still faced with the problem of data scarcity due to the lack of enough probe vehicles. Although some commercial dispatch systems have large numbers of vehicles that already cover the entire networks and seem to be highly cost-effective in traffic data collection, the common challenges in the application of these probes are their relatively longer polling intervals and the uncertainties in the link travel time measurements, which make the utilizing of such infrequent data difficult. Therefore, a comprehensive understanding on the cost-effectiveness of a probe system with the data at various polling frequencies is required before these commercial vehicles being put into routine service as probe vehicles.

Ishizaka *et al.* [3] examined the feasibility of a probe vehicle system to collect traffic information in a developing city in terms of cost efficiency. They gave emphasis on the cost problem by estimating the minimum required probe vehicles and by weighting the system cost associated with the amount of transmitted data, however, neither general conclusion on the cost-efficiency of data collection nor any clear recommendation on the selection of polling frequency was given. Moreover, a lot of researches have been conducted to overcome the problem of sparse data by data fusion [4], [5] or re-sampling [6].

The researches of Wunderlich et al. [7] and Jung et al. [8], [9] measured the impacts of ATIS on on-time reliability from the aspect of ATIS investment guidance. They concluded that once ATIS reaches a level of error near or below 5%, benefit from further improvements can hardly outweigh the cost associated with these improvements. This signifies that the cost-effectiveness of ITS project investment is largely affected by the required (or expected) system reliability that is depending on traffic condition and travel demand of system users.

Attentions on the polling frequency have been initiated in previous studies but are still far away from enough. It is well known that the historical information of network traffic is also very important for a dynamic route guidance system, which depends on an adequate numbers of probe vehicles for providing reliable link travel time and speed (LTT/LTS) estimations. The travel time/speed estimates by Quiroga and Bullock [10], [11] revealed the trade-offs between sampling rates and the reliability of section speeds. However, previous studies on the minimum probe size generally ignored the impact of data polling frequency or just determined an acceptable polling interval intuitively.

Our previous research [12] investigated in detail the accuracy of map-matching and that of LTT/LTS measurements by using probe vehicle data at various polling frequencies. The most cost-effective polling frequency of one probe vehicle was judged by comparing the cost elasticity in response to the map matching accuracy and the LTT/LTS measurements accuracy. The accuracy per cost becomes the highest when the elasticity equals to one (unit elasticity). As a result, in Nagoya city the most cost-effective time-based polling intervals for one probe vehicle are 40s (from the aspect of map matching accuracy) and 10s (from the aspect of LTT/LTS accuracy). Furthermore, it is suggested that the cost-effectiveness of a probe system in a large scale can be improved by optimizing the combination of polling frequency and required probe vehicle numbers, i.e., probe size.

While maintaining safety and efficient transportation networks is regarded as the eventual objective of probe systems, the first step of cost-effective traffic surveillance with ubiquitous coverage is the key to achieve this long term goal. Turner *et al.* [13] believed that probe systems are most cost-effective for collecting data within a large study area compared to other traffic surveillance methods.

3. Cost-effectiveness Evaluation Framework based on Nagoya P-DRGS Experiment

3.1 Nagoya P-DRGS Experiment

P-DRGS (probe-based dynamic route guidance system) project in Nagoya, Japan is a remarkable probe experiment in Japan with the largest scale and the longest periods up to now. Nagoya probe experiment consisted of 1,570 taxis equipped with GPS receivers automatically reporting their locations through either NTT DOCOMO wireless network or Dedicated Short Range Communication (DSRC) network. Three types of probes were grouped according to the data transmission network and in-vehicle map matching capability of the vehicle, of which type II probe vehicles provided on-line map matched data thanks to an enhanced GPS receiver integrated with the in-vehicle navigation device. To date, P-DRGS consortium has successfully developed a web-based route guidance system - “PRONAVI” that can be visited through internet to provide multimodal traffic information and route guidance [14].

Probe vehicles in the Nagoya probe experiment mainly used two types of polling scheme: on a time interval basis (5s and 10s) and on a space interval basis (50m, 100m and 300m). The large-scale data collection makes the field trial research available.

The events transmission strategy is found to be a cost-effective alternative to the high frequent time-based or space-based transmission [15], [2]. However, there are still some demerits that limit this data transmission strategy for a large scale probe vehicle system. First of all, the required in-vehicle devices for measuring the vehicle condition and detecting exceptional status increase significantly the initial investments. Secondly, one large scale probe vehicle system should be faced with the dilemma between data missing due to communication channel congestion [16] and on the other hand unoccupied large capacity of communication channels for avoiding data missing.

Data fusion was employed in PRONAVI system, given that the existing VICS information from fixed roadside sensors might be complementary to probe information. Although this method is effective in improving the reliability of travel time estimates for some arterial links, the coverage area is not yet large enough. Therefore, we never stop looking for other available methods of enhancing the cost-effectiveness and extending the coverage area.

Among the 1,570 probe taxis participating in the Nagoya P-DRGS project, 90 taxis with the highest space-based frequency (at length increments of 50 meters) were selected for this study. Probe data collected in Nagoya from October 1st, 2002 to March 31st, 2003 were used for the empirical analysis. Only occupied taxi trips are examined for this study because they are proved to be better than vacant taxi trips in Nagoya in reflecting the traffic condition and route choice behaviors [17].

Data at lower polling frequencies are simulated by selectively deleting parts of the records from 50m data. Eleven groups of simulated data with polling intervals ranging from 100m to 600m (abbreviated as 100m data, 150m data, and so on in this paper) are obtained for each trip by each vehicle over the whole collection period. Since all trip samples happened at the same time for data at various polling frequencies, the external influence can be ignored and the performance difference of data at various frequencies can be directly compared.

3.2 Cost-effectiveness evaluation framework

Probe was designed to improve the cost-effectiveness of traffic data collection and to extend traffic surveillance coverage to the entire network. The overwhelming superiority of probe technology relies on a good coverage and high penetration rate of probe vehicles [18]. In order to achieve large scale application, we proposed a comprehensive cost-effective deployment scheme [18], in which all contributors of probe systems, their functions in probe implementation and some uncontrollable factors affecting the cost-effectiveness level, as well as four controllable indicators which can

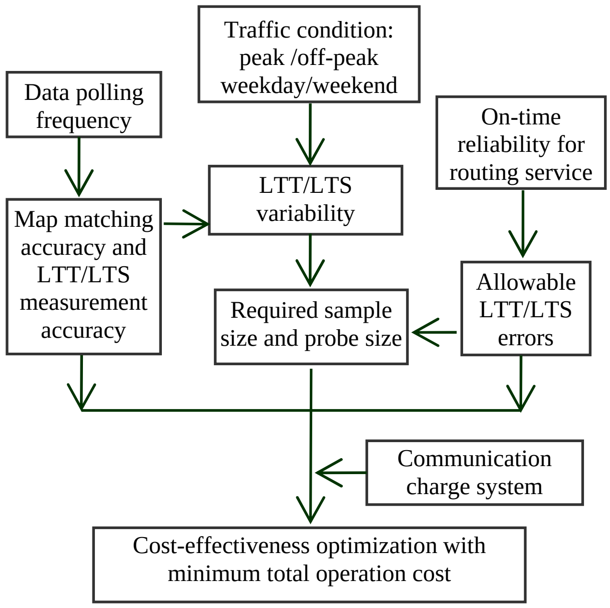


Figure 1. Framework of optimization between polling frequency and probe size

be optimized to enhance the system cost-effectiveness, are outlined. These controllable indicators include probe polling frequencies, required probe size, probe coverage area, and all required monitoring items, of which only the former two are considered in this study, given that the trade-off between polling frequency and probe size is of most urgency to be tackled and the available field data allow for such a study.

Figure 1 presents the optimization framework to achieve a balance between polling frequencies and the required probe size. While the effectiveness has different meanings for ITS projects with different purpose, the most important effectiveness indicator for a dynamic route guidance system is on-time reliability. High-frequency data are capable of generating more accurate traffic information [12] and therefore a relative smaller sample size can satisfy a certain level of LTT/LTS estimation reliability.

The optimal polling frequency is the one at which an ATIS spends the minimum total operation cost, which is the arithmetic product of probe size and the average cost for an individual probe. Probe size is the total required probe numbers for the whole network while sample size is the required probe observations for measuring individual links. Probe size should satisfy both requirements of enough sample size for LTT estimations and reasonable coverage area. In a given area, probe size should be theoretically in direct proportion to sample size if assuming probes are evenly distributed.

The required minimum sample size is determined by the allowable errors and the measured LTT/LTS variability, with the latter depending on the traffic conditions and the polling frequencies. Equation 1 is widely used for estimating the minimum required sample size at link level. It is based on the central limit theorem and on the assumption that the speed of vehicles in one link follows a normal distribution [19], [20]. Although such assumption is not always the case for urban arterials, this equation is widely used and expected to give a reliable sample size estimate [10]. The variability of LTT/LTS for various frequency data is first calculated, based on which the minimum required sample size can be estimated by assuming a given confidence interval and a certain maximum allowable error. According to the observed system reliability by Jung *et al.* [9], the maximum allowable error of ATIS in USA ranges from 14% to 21% according to cities and the time of day, below these levels of errors ATIS would provide positive travel reliability benefits on aggregate. A relative lower error level, 10%, is selected in this study as the system maximum allowable error for assuring positive user benefits. The minimum required sample size is given as:

$$n \geq \left(\frac{t_{a/2,n-1} s}{\varepsilon_{\max}} \right)^2 \quad (1)$$

where $t_{\alpha/2,n-1}$ means t-distribution statistic for $1-\alpha$ confidence interval with degree of freedom $n-1$; s means sample standard deviation; and $\varepsilon_{\max}$ means the maximum allowable error.

A hypothetical charge system that determines the total communication charge for one probe vehicle is established, where the total communications charge is assumed to comprise two parts: basic charge per month and data transmission charge. Such a charging scheme is popular in Japan, and is also widely employed around the world. Here the data transmission charge is proportional to the polling frequencies, with an assumption of 1 unit cost for 600m data per month, that is, 2 unit costs for 300m data, 12 unit costs for 50m data, and so on. The ratio of data transmission charge to total charge ratio (D/T ratio) is used as an index to denote the different charge plan. The basic charge and total charge can be calculated for different plan. There consist of six levels of D/T ratios for 50m data, from 10% to 100%, with the higher D/T ratio means lower weights on basic charge. Table 1 lists the detailed basic charge and total charge for 50m data under different D/T ratios.

Table 1. Basic charge and total charge under different D/T ratios (unit: C)

D/T ratios for 50m data	10%	30%	50%	70%	90%	100%
Basic charge	108C	28C	12C	5.14C	1.33C	0C
Total charge	120C	40C	24C	17.1C	13.3C	12C

The detailed D/T ratios for data at various polling intervals are listed in Table 2 for better understanding the hypothetical charge system. Because the basic charge in actual world is constant for a certain charge plan, say, a given D/T ratio here, regardless of the polling intervals, therefore the resulted D/T ratios for data at various polling intervals are different. We use only the D/T ratios for 50m data as the denotations of the charging system in the rest of paper.

Table 2. Lists of the D/T ratios for probe data at various polling intervals

Polling intervals	D/T Ratios (%)					
50 m	10	30	50	70	90	100
100 m	5.26	17.65	33.33	53.85	81.82	100
150 m	3.57	12.50	25.00	43.75	75.00	100
200 m	2.70	9.68	20.00	36.84	69.23	100
250 m	2.17	7.89	16.67	31.82	64.29	100
300 m	1.82	6.67	14.29	28.00	60.00	100
350 m	1.56	5.76	12.47	24.95	56.19	100
400 m	1.37	5.08	11.11	22.58	52.94	100
450 m	1.22	4.53	9.98	20.55	49.94	100
500 m	1.10	4.11	9.09	18.92	47.37	100
550 m	1.02	3.81	8.47	17.75	45.43	100
600 m	0.92	3.45	7.69	16.28	42.86	100

4. Polling Intervals Optimization in terms of Cost-effectiveness

This chapter attempts to offer a solution of the best choice of polling intervals in terms of cost-effectiveness for a probe based route guidance system that are expected to provide predictions on route travel time with suitable reliability. Any kinds of data at lower polling frequency and with lower cost can be seen highly effective only if they can provide acceptable traffic measurements and reliable estimations.

Two levels of test beds were selected for this study: an arterial roadway segment and the road network within Nagoya downtown area. These test beds were selected allowing for the available data: with enough observations for LTT estimation. Individual links are not examined because large differences exist among links at different location [21]: the optimization at the individual link level based on average on-time reliability has little value. In this chapter, the calculated sample sizes are used in place of probe size to compare the costs between situations at various polling frequencies because of their directly proportional relationship as mentioned previously.

4.1 Optimization at segment level

The first level of test bed is the Hirokoji-Dori in the Imaike area of Nagoya, Japan, one of the main east-west urban arterials directly going to Nagoya station. A total of 9 DRM (digital road map) eastbound links (consisting of one intersection link, four links before one main intersection and four links after that) were selected, measuring 877 meters in total length. The samples were limited to four off-peak hours in weekday lasting from 20:00 to 24:00 in order to encompass relatively more samples for each of the links. Actually few occupied taxi trips before 20:00 were found in this area, one possible reason is that taxi drivers, as well informed through a dispatch system or just through their experiences, might be capable of avoiding the congestion during peak time.

A detailed study on the variability of LTT estimates has been conducted [21] and the results indicate that although high-frequency probe data have the advantage of accurately reporting experienced LTT, the aggregate mean hardly proves to offer a reliable estimate of link travel cost if without enough observations. Therefore an important issue is that how many observations are enough for LTT/LTS estimation.

The standard deviations of LTS for each 9 links are calculated by time of day. The average LTT value during aggregation periods (15 minutes) by 50m data is assumed as the population mean and accordingly the LTT estimation. The average LTS for all 9 links is 10.10m/s. The mean standard deviations are shown in Figure 2 and a logarithmic regression curve is drawn to make a smoothed estimation by assuring monotonic with increasing space intervals.

If the confidence interval is defined at 95% and the maximum allowable relative error is 10% of the average ground truth LTS, that is, $\varepsilon_{\max}$ equals 1.01m/s, the required minimum sample size in terms of LTS estimates at an aggregation period of 15 minutes can be calculated according to Equation 1 and are listed in Table 3. Thus, the total transmission costs imposed by local wireless transmission companies can be easily figured out.

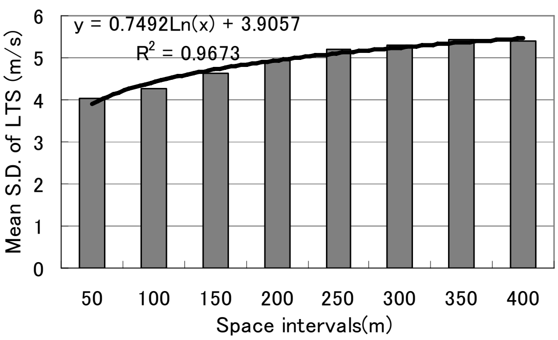


Figure 2. Mean SD of LTS for all 9 links

Table 3. Required probe size at various polling intervals at 9 links level

Space intervals (m)	**50**	**100**	**150**	**200**	**250**	**300**
Sample size	58	74	85	92	99	104
Space intervals (m)	**350**	**400**	**450**	**500**	**550**	**600**
Sample size	109	113	116	120	123	126

Results in Figure 3 shows that the total costs decreased constantly as polling intervals increase for cost systems with D/T ratios of 90% and 100%, which means that the longest interval (600m here) is the best choice with least cost. Similarly, the total cost increased constantly for systems with D/T ratios of 10% and 20%, that is, in such a case the shortest interval (50m) is the best choice. While for the other two charge systems with D/T ratios as 50% and 70%, the total costs experience a decrease followed by a constant increase, as a result, 100m is the best choice of polling interval for the system with D/T ratios of 50% and 300m is best for the system with D/T ratios of 70%, respectively. This result of optimization seems to be partially representative because only the variability of 9 links during off-peak hour is considered. Next section will address this issue at the level of network in Nagoya downtown area.

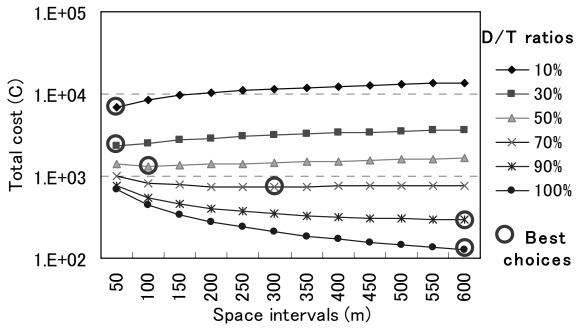


Figure 3. Best choices of space intervals at arterial segment level

4.2 Optimization at network level

Furthermore, Nagoya downtown area (Figure 4), which covers Nagoya Station, Fushimi, Sakae and Shin Sakae, is selected as the test bed at network level. This area extends 4km from west to east and over 1.6km from south to north, with an area of about 6.5km^2. This area attracts most of occupied taxi trips.

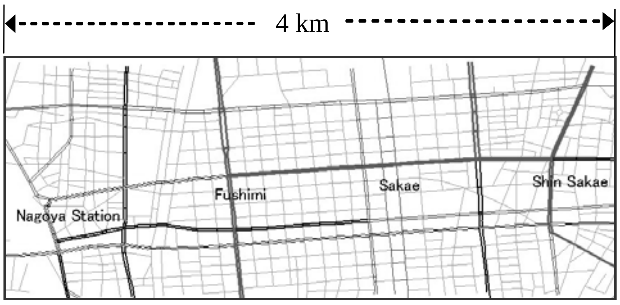
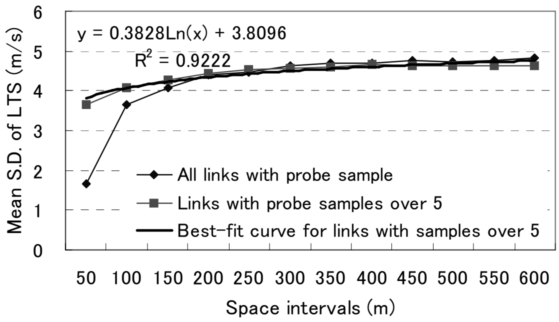


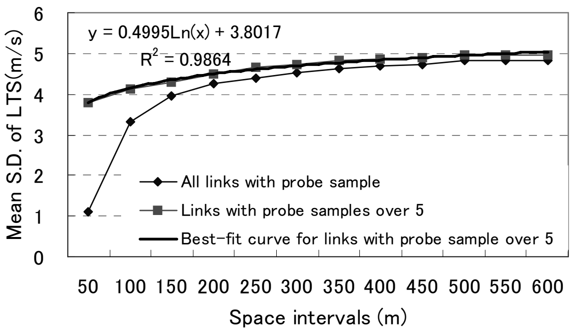
Figure 4. Test bed at network level (Nagoya downtown area)

The average variability of LTT/LTS estimates at network level reflects the whole traffic condition. The mean standard deviations of LTS of all links in Nagoya downtown area for 12 groups of data at various polling frequencies are calculated. Here, the LTT estimation from 50m data is assumed as the average population LTT, which can then be used to calculate the mean standard deviations of LTS for all links during whole 96 periods. For each dataset at a certain polling interval, the same regression model [14] of LTT complementation is used for making LTT table. Mentioned that the bias of data absence at congestion links due to taxi drivers' route choice and the problems of discordance between the aggregation time and signal cycle times [22] can not be overcome by this method.

Two situations of A including all links and B including links with no less than 5 probe samples are examined simultaneously, by considering that LTS estimation from smaller samples can be hardly representative of the population average value. Results in Figure 5 show that the standard deviation of situation A appear to be much smaller than that of situation B for data at higher polling frequencies whenever in weekday or in weekend, while little difference can be found if polling intervals are longer than 200 meters.



5-a) Weekday



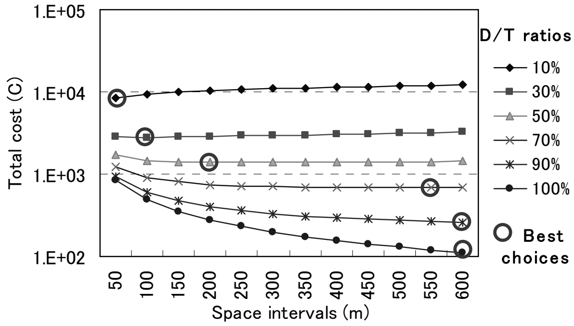
5-b) Weekend

Figure 5. Mean standard deviations of LTS for Nagoya downtown network

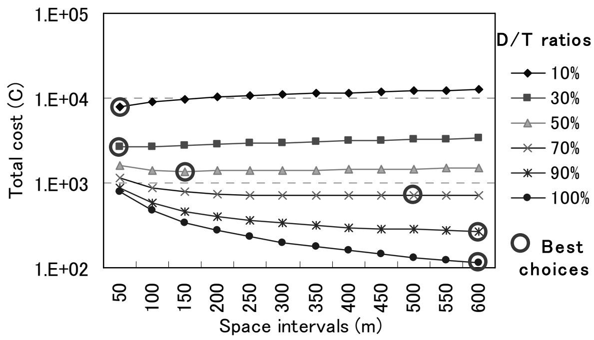
Table 4. Required probe size at various polling intervals at network level

Space intervals (m)	**50**	**100**	**150**	**200**	**250**	**300**
Sample size (weekday)	71	81	88	92	96	99
Sample size (weekend)	66	78	86	92	96	100
Space intervals (m)	**350**	**400**	**450**	**500**	**550**	**600**
Sample size (weekday)	101	104	106	108	109	111
Sample size (weekend)	103	106	109	111	113	115

Then, the minimum required sample size is calculated for both weekday and weekend (Table 4). Same as the arterial roadway segment level, the minimum sample size at network level is calculated with the same confidence interval of 95% and the same maximum allowable relative error of 10%. The observed average LTS values are 8.88m/s and 9.23m/s for weekday and weekend, respectively. Figure 6 shows the results of total cost and best choices of space intervals at network level. The optimized polling intervals with the least cost are outlined in Figure 7 for the six charge systems with different D/T ratios.



6-a) Weekday



6-b) Weekend

Figure 6. Best choices of space intervals at network level

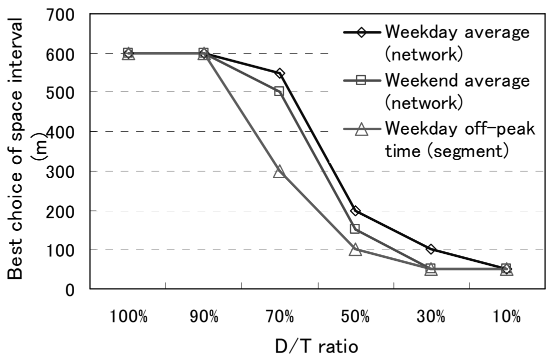


Figure 7. Optimal polling intervals under different D/T ratios

For the D/T ratio of 50%, the best choices of polling interval are 100m, 150m and 200m for weekday off-peak time, weekend average and weekday average, respectively. Under the same level of reliability expectation, the best choice of polling frequency for a dynamic route guidance system in weekend is higher than that in weekday, because the mean LTS variability in weekend is a little greater than that in weekday. However, the actually required reliability in weekend may not be as rigorous as that in weekday. Therefore the best choice of polling frequencies can be reduced intuitively according to required reliability.

It should be noted that although 600m data presents the least total data transmission cost for the situation of D/T ratio of 100% and 90%, it can not be regarded as the best choice of polling intervals, because data at far longer polling intervals would require smaller total data transmission cost than 600m data does (absolutely for D/T ratio of 100% and possibly for D/T ratio of 90%). On the other hand, the best polling intervals should satisfy the requirement of map matching accuracy under the consideration of all information can not be obtained until the original probe data are correctly map matched in the DRM network. Therefore, the most cost-effective choice of transmission intervals from aspect of map matching should be the longest choice according to different D/T ratios. Please refer to Liu *et al.* [12] on the optimal polling intervals for map matching accuracy.

These results indicate that only the communication charge system with D/T ratios ranging from 50% to 70% can recognize practically the superiority of lower frequency data to higher frequency data from the aspect of cost-effectiveness.

The effects of map matching accuracy and coverage area are not considered in this paper. The minimum required probe size for lower frequency data should be larger if taking map matching accuracy into account because map matching errors resulting from probe data at lower frequency might lead to more uncertainty in LTT/LTS estimation, while on the other hand larger probe size for lower frequency data offers large coverage area that makes up a defect of higher estimation errors. It should be also mentioned that the calculated probe size is an average value based on the LTT estimates, which should be multiplied by some coefficients to obtain the total size if assuming that probe vehicles distribute evenly in the downtown area.

5. Conclusions and Future works

In order to improve the cost-effectiveness of a probe vehicle system in traffic data collection, this paper attempts to search the optimal polling frequency by weighting increasing polling frequencies against expanding probe vehicle size. The framework proposed in this paper is a part of a cost-effective deployment scheme of our previous study. This paper offers an evaluation example for a probe based route navigation system and provides a solution on the issue of cost-effective polling frequencies.

The evaluation framework considers the influence factors including traffic condition, travel time estimates reliability (based on travelers' requirements), and transmission charge system (communication agency). The variability of travel time estimates is examined at two levels: roadway segment and network in a given area. Then the reliability and variability of travel time estimates achieved from a given frequency of probe data are used to optimize the polling intervals and required probe size under a hypothetical transmission charge system.

The optimized polling interval for a probe system that provide the same level of estimation reliability (with 95% confidence interval and maximum allowable errors of 10%) is that with least total data transmission costs. The lower frequency data can recognize superiority to higher one in cost-effectiveness only when the D/T ratios are among the interval of 50% to 70%. For the D/T ratio of 50% for 50m data, the best polling interval is between 100m to 200m in Nagoya depending on traffic condition.

Note that 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. Therefore the longest interval of the best choice of polling interval should be no longer than the optimal polling interval for map matching. Future research will consider the cost-effectiveness issues at the entire network level and the error propagation from map matching.

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