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EVALUATION OF PROBE VEHICLE SYSTEM BY USING MICRO SIMULATION MODEL AND COST ANALYSIS

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Abstract: The aim of this study is to discuss the feasibility of a system to collect traffic information using probe vehicles in a developing city in terms of cost efficiency. Firstly, the field test that applied five taxies as probe vehicles in Bangkok was conducted to identify their running performance and characteristics. Secondly, based on the result of field test, a micro simulation model was developed to verify the minimum number of probe vehicles that can ensure sufficient data collecting information from which reliable average travel time can be calculated. Finally, to estimate the cost of system, the amount of transmitted data from probe vehicles was calculated when probe vehicles collected traffic information dynamically applying the minimum number of probe vehicles. As a result, it was found that average travel time of all vehicles can be estimated in every 15 minutes at half of all road sections in Bangkok, if all taxis can be used as probe vehicles.

Key Words: Probe vehicle system, Minimum number of probe vehicles, Cost efficiency

1. INTRODUCTION

Although the system to collect traffic information in real-time such as the system using traffic detectors is imperative not only for traffic control but also for identification of traffic problems on an entire urban network, it has hardly been introduced in developing cities because of insufficient budget and/or technological background. The inadequate information based on the limitation of data collection system hinder not only operators from exercising better traffic management but also drivers from making proper driving decision. In the case of Bangkok, the traffic situations have currently been monitored by traffic detectors at 143 intersections on urban road networks and expressways, closed circuit televisions (CCTV), and manual reports from traffic policemen. However, they are not enough to clarify traffic situation of the whole Bangkok. Especially, the actual traffic situation on connected-and-unconnected minor roads (Soi) has never been observed.

Recently, the system to collect traffic information using probe vehicles is expected to be one of potential systems to effectively collect traffic information for the city where detectors have never been fully activated. Considering rapid growth of an urban area in a developing city, the system using probe vehicles which will pass through even newly opened road sections immediately seems to be more feasible. Also, using probe vehicles, it is expected that the spatial traffic information, such as OD data, route data and/or detailed travel time data can be obtained, which has been essential to analyze traffic situation in a developing city. Based on data from such probe vehicles, travel time at divided road sections can be calculated directly, which would be fairly more accurate than travel time which is estimated based on traffic volume and occupancy measured by traffic detectors.

However, there are several problems to use probe vehicles instead of detectors for traffic information collection as follows;

- The fundamental performances of the probe vehicle system, such as coverage area and frequency per each link, deeply depend on the running pattern of vehicles selected as probe vehicles and they would differ by size, network configuration, etc. Therefore, the vehicle, which can collect traffic information efficiently at the lowest possible cost, should be selected as a probe vehicle. But, it is difficult to reveal its performance unless field test is conducted.
- The required number of probe vehicles required to collect traffic information with high reliability should be obtained in order to estimate total cost of the probe vehicle system. This number cannot be revealed by a field test using very few probe vehicles, unless a full-scale test is conducted.
- Ascendancy of cost has to be verified on the basis of comparison with cost of other traffic information collection technology. For this purpose, cost per vehicle has to be calculated and total cost has to be estimated using the minimum number of probe vehicles. Especially, running cost per vehicle depends on amount of information to transmit from probe vehicle to a traffic information center. Moreover, the most effective transmission method should be clarified.

Therefore, this study discusses the feasibility of the system to collect traffic information using probe vehicles in a developing city in terms of cost efficiency. Firstly, the field test using five taxies as probe vehicles in 2002 at Bangkok was conducted to identify the performance and characteristics of movement of a prove vehicle. Secondly, using the result of field test, a micro simulation model was developed to obtain the minimum number of probe vehicles, that is, the minimum sampling size based on statistical sampling theory. Finally, to estimate the cost of the probe vehicle system, the amount of transmit data from probe vehicles was calculated when probe vehicles collect traffic information dynamically with the application of the minimum number of probe vehicles. Moreover, the costs of probe vehicle were calculated and compared by various transmission methods.

2. THE FIELD TEST OF PROBE VEHICLES IN BANGKOK

The field test to clarify the performance of the probe vehicle system was carried out for 39 days from 28th August to 13th November 2002 in Bangkok. Five sets of probe vehicle equipment were installed on five designated taxis belonging to a single cooperative taxi company. A set of equipment consists of data logger, a switch for dynamic state, and a GPS antenna, as shown in Table 1. All equipment was provided by the Association of Electronic Technology for Automobile Traffic and Driving or JSK in cooperation with ITS-Japan. The data logger is mainly used to store data such as latitude, longitude, time and other signals which are received by the GPS antenna, etc. The switch is used for identifying an existence of a passenger and detecting dynamic/static state. Since it is impossible to know whether a

Table 1. The Outline of Field Test

Period	Aug. 28 2004 - Nov. 11 2004
Probe Vehicle	Taxi 5 vehicles (Type:TOYOTA LIMO) 
Equipments	Data logger GPS antenna Switch for dynamic/static state   
Data	Location from GPS (Latitude, Longitude),Time,Passenger getting on/off
Running method	Regular driving on business

designated taxi stops for passenger getting on and off or by traffic congestion and/or traffic light/signals, taxi drivers were asked to push a button when a passenger gets on and off, and other events occur. The collected recorded data were then downloaded to a computer daily at the taxi company when each designated taxi returned to their company to switch drivers.

In this field test, latitude, longitude and time detected from GPS signal every 5 seconds were recorded. To verify an accuracy of estimated travel time, a license plate matching survey was carried out at Din Daeng Rd. to obtain field travel time data. At same time, probe vehicles are directed to travel on the same road section and obtained the estimated travel time using the location data from GPS collected every 5 second. By comparing the travel time obtained by a probe vehicle and license plate matching survey, the travel time estimated by probe vehicles seems to be statistically accurate. And the 5-second interval was found suitable to record location of probe vehicles.

3. THE FUNDAMENTAL CHARACTERISTICS OF PROBE VEHICLE SYSTEM

To demonstrate geometrical coverage from where we can collect traffic information by probe vehicles, the links on which the probe vehicles ran during the experiment period are shown as

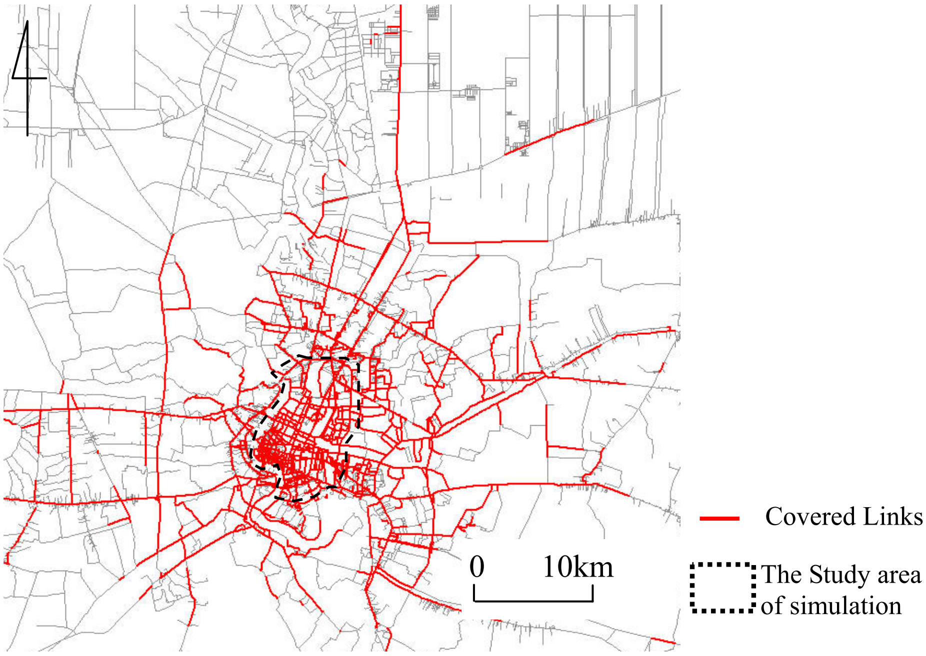

Figure 1. Coverage Area of Probe Vehicles

bold line in Figure 1. A percentage of links that was covered by probe vehicles within the Outer Ring Road was 90% and that within the Inner Ring Road was 93%. Since the Central Business District of Bangkok is included in the Inner Ring Road, five taxies are enough to collect sufficient traffic information. The percentage of links on each concentric circle, which was drawn at one-km interval around the taxi company, was calculated as shown in Figure 2. Thus, the percentage of links of main road is steady at 95 % within 15 km from the taxi company, although that of minor roads gradually declines with the distance from taxi company increases.

If traffic situation that is generally changing every moment is exactly observed, not only coverage but also frequency is essential point. Therefore, frequency, which shows the number of times that probe vehicles run through a link, has to be verified. This frequency was aggregated by distance from the taxi company, as coverage, and is shown in Figure 3. The highest frequency observed on roads around the taxi company was 289 times for the experimental period. Regardless of the road category, the frequency around the taxi company was high. Of course, in suburban area, frequency of vehicle running is high only on main roads connected to central area. Within 3 km from the taxi company, more than one time per day could be observed. However, the percentage of covered links cannot reach 100 % because rate of increase of covered links gradually reduces with increasing of data volume in Figure 4. As a result, it was concluded that detailed traffic situation of almost links in central area could emerge by only five taxies if collected data was stored. However, real time traffic situation in order to provide traffic information could not be observed by just five taxies.

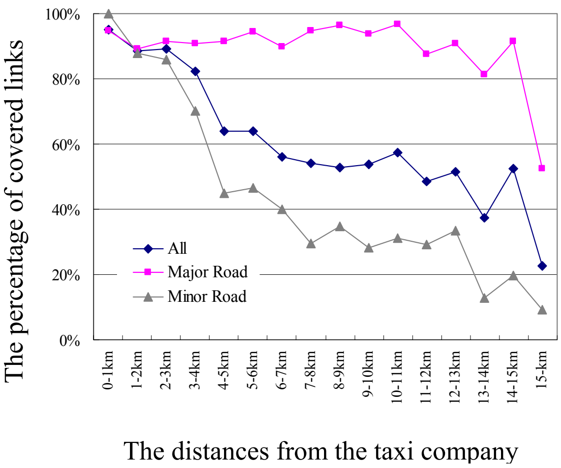

Figure 2. The Percentage of Links

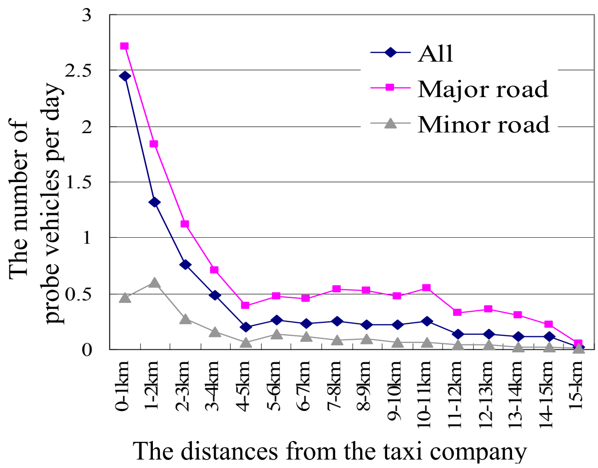

Figure 3. Number of Probe Vehicles that Passed though Links

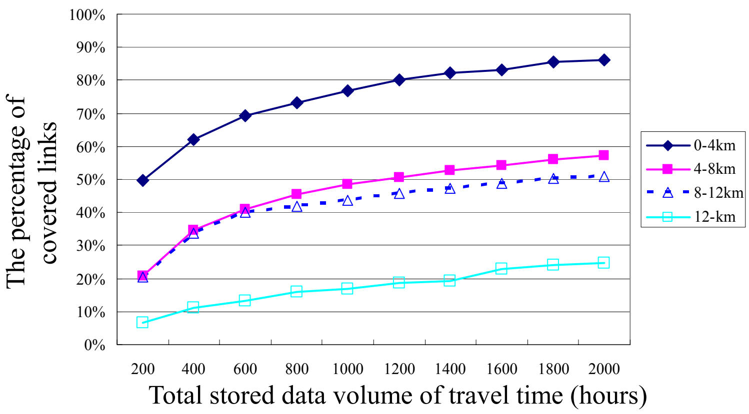

Figure 4 Trend of Percentage of Covered Links

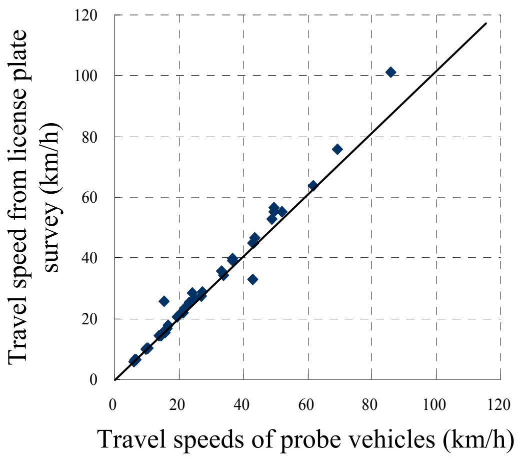

Figure 5. Travel Speed of Probe Vehicles and License Plate Survey

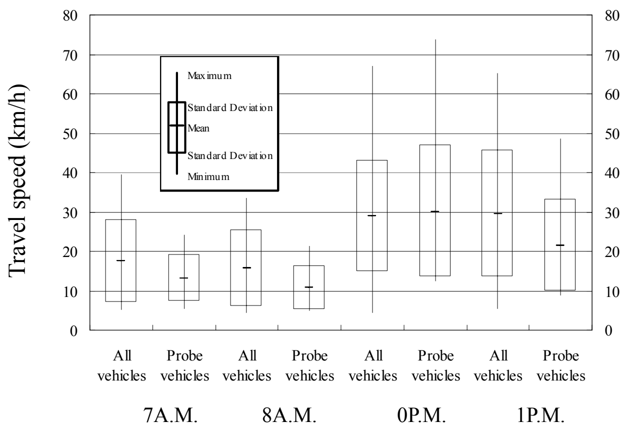

Figure 6. Standard Deviation of Travel Speed

The comparison of the travel speeds estimated by probe vehicles and calculated by the license plate survey is shown in Figure 5. Consequently, the travel speeds from probe vehicles were almost equivalent to actual speeds from the license plate survey. Therefore, the travel speed from probe vehicles can be used as actual travel speed. Since the travel speed from probe vehicles have been obtained from position data recorded at five-second interval, it implies that the method of recording position data with five seconds interval can be one of suitable configurations for probe vehicles.

The standard deviation of the travel time of each hour and the average value of the travel time of probe vehicles are shown in Figure 6. The variation of travel speed was large in the case of probe vehicle stopping or not at intersections, especially during the daytime. However, compared probe vehicles with all vehicles, the same tendency of average speed and variation could be observed although there were few samples of probe vehicles. As a result of analyzing data of occupied taxis and vacant taxis with a video camera, the running state of a taxi did not affect travel time.

It was concluded that the probe vehicle system has potential to collect traffic information effectively and the configuration of probe vehicles such as interval for recording location is suitable. Therefore, this result can be inputted to develop following micro simulation model for evaluating the probe vehicle system. Based on the result of the field test, the OD matrix of taxis was made to represent driving pattern of the probe vehicles. All trips of taxies including the end of trips where passenger got on/off were aggregated into a distribution traffic volume. The taxi OD matrix made by averaging distribution of traffic volume was expanded by the number of taxi registration.

4. DEVELOPMENT OF MICRO TRAFFIC SIMULATION MODEL

Some previous studies attempted to estimate the minimum number of probe vehicles required to collect traffic information with high reliability. Boyce, Hicks, and Sen (1991) has estimated that the number of required probe vehicles should be 4700 to pass at least 50 percent of all links every 5 min for the North Shore network in Chicago and Srinivasan and Jovanis (1996) has estimated that it should be 3500 vehicles to collect traffic information at 80 percent of arterial and freeway links every 10 minutes for road network (432km^2) in Sacramento, U.S.A.. These studies used a traffic assignment method such as stochastic or dynamic assignment. Boyce, Hick, and Sen (1991) assumed that traffic information of the link has been collected if probe vehicles passed at least one time through the link. Since one time per link is not sufficient in frequency to estimate reliable average travel time, the results based on this assumption cannot show which reliable traffic information cannot be collected or not.

Therefore, statistical sampling theory, which can estimate the minimum sample size of probe vehicles required for estimating the average population, has been used by recent studies. If the number of probe vehicles exceeds the minimum sample size of each links, traffic information with high reliability can be collected by probe vehicles. The minimum sample size of probe vehicles is given by:

$$n = \left(\frac{t \times s}{\varepsilon} \right)^2 = \left(\frac{t \times c.v.}{e} \right)^2 \tag{1}$$

Where t is t-statistic from Student's t distribution for specified confidence level, s is standard deviation of travel time and ε is maximum specified allowable error. Coefficient of variation, $c.v.$ and relative error, e is given by:

$$c.v. = \frac{s}{\bar{x}} \tag{2}$$

$$e = \frac{\varepsilon}{\bar{x}} \tag{3}$$

If the sample size exceeds 30, the normal distribution can be used instead of Equation (1). This sample size is given by:

$$n = \left(\frac{z \times s}{\varepsilon} \right)^2 \tag{4}$$

Shuo Li et al. (2002) attempted to improve the methodology by adding an adjustment factor to equation (1). However, the modified methodologies have been lack of validation.

On the other hand, a micro simulation model has been accepted to use instead of the assignment methods because a micro simulation model can consider dynamic running pattern of each vehicle. Chen and Chien (2000) used the micro simulation model to estimate the minimum number of probe vehicles. However, the dynamic distribution of probe vehicles was not considered since the network consists of only one freeway and 5 intersections. Cheu, Xie, and Lee (2002) also used the micro simulation model for the road network of the Clemeti town area in Singapore. All of previous studies aimed at estimating the minimum number of probe vehicles and did not consider the difference of cost of each data transmission method. It is summarized that minimum sampling size is needed to be from 10% to 20%.

In this study, these basic statistical sampling theories were used to estimate the number of probe vehicles required for the road network of Bangkok. The entire road network of Bangkok is shown in Figure 7. The area shown by dotted line is the study area where 1896 links and 1310 nodes are located. OD demand of probe vehicles was configured as a part of taxi OD matrix that developed through the field test data. The other OD matrix was

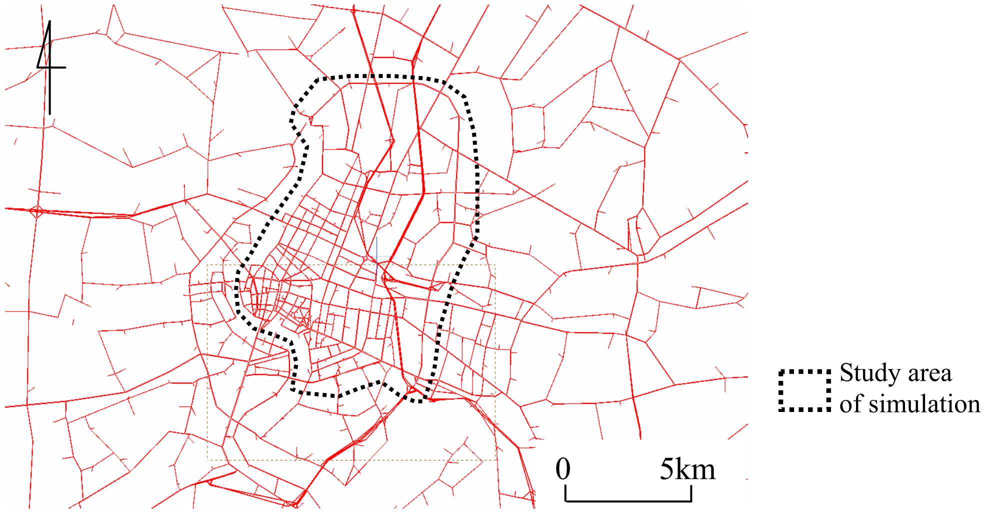

Figure 7. Road Network in Bangkok and Study Area

configured using UTDM (Urban Transport Database and Model Development Project) data, by OTP (Office of Traffic and Transport Policy and Planning). Total passenger car OD demand is approximately 2.3 million trips per day and total taxi OD demand is 0.7 million trips per day. PARAMICS version 4 was employed with original API program of sampling theory simulation which developed by authors. The simulation model was calibrated with travel time data which has been collected by probe vehicles through the field test in Bangkok. The detailed traffic situation described by Ishizaka et al. (2004) was referred. The traffic volumes at intersections, collected by Bangkok Metropolitan Administration or BMA were used.

To estimate the number of probe vehicles required, several simulation runs with the different condition were performed to calculate the number of links on which the required number of probe vehicles was attained. Probe vehicle OD demand was set 10%, 20%, 40%, 60%, 80% and 100% of the based taxi OD demand.

Transmission method to transmit probe vehicle data from a probe vehicle to traffic information center is focused in this study, because the running cost of probe vehicle heavily depends on the method and configuration of data transmission. For making clear comparison on cost by transmission methods, the developed traffic simulation model was used to estimate the cost. The constant transmission method and ST(short trip), SS(short stop) method are compared. The constant transmission method is method of transmitting data constantly at every 5, 10, or 30 second and the ST, SS method is the method of transmitting data when a probe vehicle starts to run, stops, or shifts to constant speed from acceleration and deceleration (Horiguchi, 2002). Because inflection point of the later method is used to estimate travel time, the reduction of data volume to transmit is expected.

5. RESULTS OF SIMULATION

5.1 The Required Minimum Number of Probe Vehicles for Reliable Travel Time Collection

The percentage of links that the minimum sampling size is satisfied during the simulation time, with respect to the percentage of probe vehicles, is shown in Figure 8. The percentage of

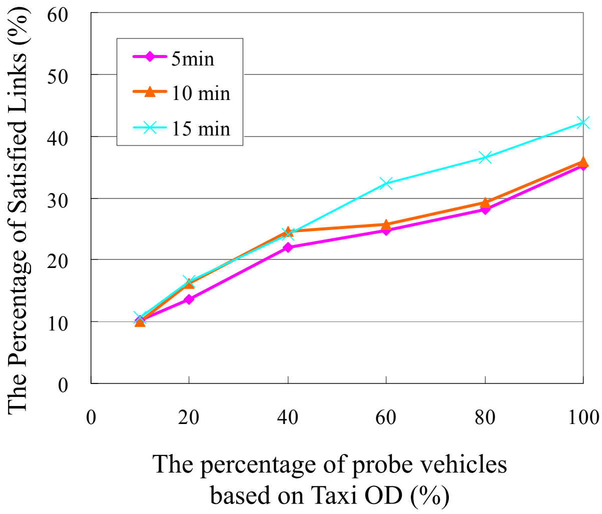

Figure 8. The Percentage of Satisfied Links

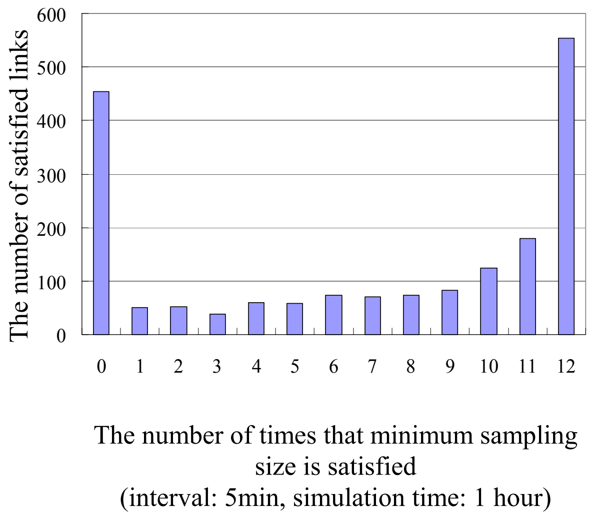

Figure 9. The Certainty of Data

links was increased with the percentage of probe vehicles. In this study, the percentage of probe vehicles was used instead of number of probe vehicles because over/underestimate of number of probe vehicles would be avoided. In other words, the OD oriented micro traffic simulation cannot identify the same vehicle which started from origin zone and stopped at destination, although it is worth that the simulation model for huge wide area is developed to evaluate it. Therefore, the percentage of probe vehicles was used to discuss the results. It is referred that the registered number of taxis, when OD data was collected, is approximately 70,000. The probe vehicle system could cover over 40 % of all links in the study area if all taxis were used as probe vehicles. In other words, even if all taxis were used as probe vehicles, it cannot cover 100% of links.

The certainty of continuously collecting traffic information in a link could not be shown in Figure 8, that is, it could not be shown which the probe vehicle system constantly collected traffic information of specified road section or not. The certainty of continuously collecting traffic information on the condition of 5-minute interval and one hour simulation time is shown in terms of the number of times that the minimum sampling size is satisfied in Figure

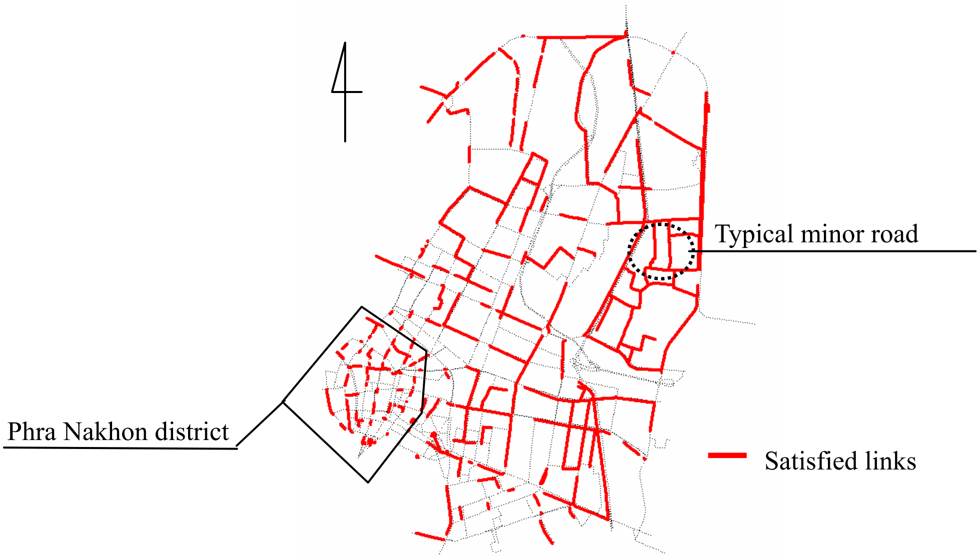

Figure 10. The Satisfied Links

9, in which horizontal axis represents the number of times and vertical axis represents the number of satisfied links. The number of links that the minimum sampling size is continuously satisfied during the simulation time, which is shown by the number of times equal to 12 on horizontal axis, is only 550. These links are called "satisfied links" thereafter. And the locations of these links are illustrated as bold lines in Figure 10. The above is the result of simulation applied on the condition that all taxis are probe vehicles. On the other hand, the number of links that the minimum sampling size could not be satisfied reached approximately 450 links. It is concluded that one third of links is continuously covered, the other one third of links is not always covered and the remainder is covered. Although the alternative traffic information collection system for two third links should be considered, this study focused on characteristic of two third of links to find a reason why two third of links were continuously satisfied.

In the terms of geographical distribution of satisfied links in Figure 10, regular relationship was not identified such as sequence of satisfied links about major road. There were not all major roads where the minimum sampling size was satisfied. And satisfied links weren't always connected with each other satisfied links. However, Figure 10 shows characteristics of satisfied links regarding specific road network configuration in Bangkok. A part of connected-and-unconnected minor roads (Soi) satisfied the minimum sampling size, which is shown by circle in Figure 10. Sois are specific roads in Bangkok and has never been observed due to absence of loop detectors. Therefore, this result is very significant even if satisfied links are part of Soi.

In addition, a part of satisfied links had not attained the certainty of continuously collecting traffic information because the distribution of probe vehicles was affected by traffic demand. Especially, old city area shown by polygon in Figure 10 is less stabile than other area. Few number of probe vehicles passed this area and length of links are supposed to be one of causes of this result. In other area, the certainty is supposed to be better than since each link has enough probe vehicles and its length is longer. The cause of this result is described in subsequent section. The impact of demand is shown by sensitivity analysis of traffic demand, which was explained in next paragraph. It was concluded that it should be carefully identified which link was satisfied or not.

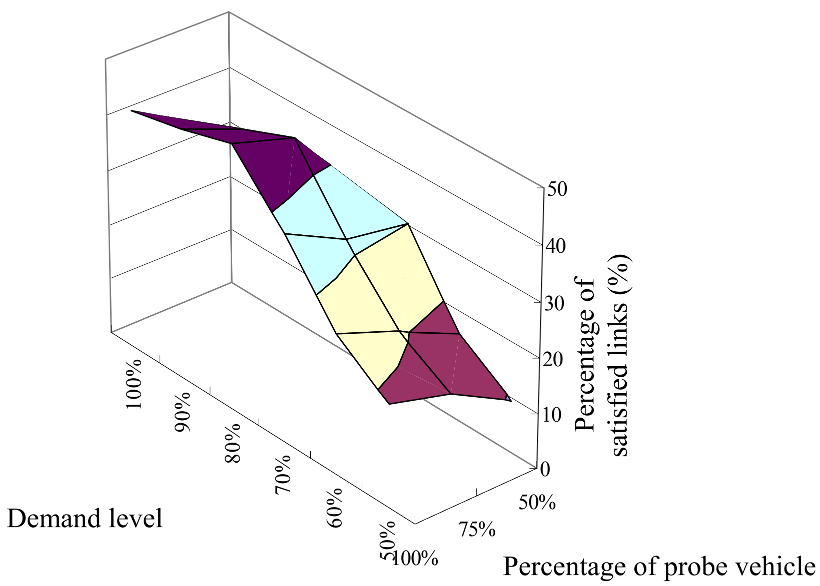

Figure 11. Sensibility Analysis

Although more realistic scenario such as other time period should be simulated, these simulations can be conducted because of lack of actual data for verification of simulation model. Therefore, sensitivity analysis of total traffic demand and percentage of probe vehicles was conducted. The traffic demand in morning peak hour, which was used a basis for other simulation periods in this study, is set 100%. It is shown in Figure 11 that the percentage of satisfied links is high in the morning period (demand level is 100%) and gradually falls down to the lowest point, when the demand level decreases. There are several reasons for the result. One is that traffic flow with 80% demand is very stable and critical speed to convert from congestion flow to free flow.

5.2 Comparison with Standard Deviation and Minimum Sampling Size and the Impact of Combining Links

It is worth discussing why the percentage of satisfied links shown in Figure 8 did not reach 50 %, even if all taxi OD demand are assumed as probe vehicles. If all links are satisfied, it is estimated that about 40 % vehicles are required because total OD demand is approximately four times larger than taxi OD demand. This figure is higher than previous studies. The result shown in Figure 8 was obtained under the worst scenario assumption that traffic congestion is the most serious, or the morning peak hours, in Bangkok. High variation of travel time and the number of times that probe vehicles could pass through each link within the interval is supposed to be one of the reasons. In the viewpoint of macro level regarding the latter reason, the impact of traffic volume was verified by sensitivity analysis as implied from Figure 11. And the latter reasons would also be verified using Figure 2, Figure 3, and Figure 4, although these figures are the result obtained by the field test of five taxis. Finally, the relationship between standard deviation of travel time and link length is shown in Figure 12. The data points in Figure 12 are classified in the terms of number of times that minimum sampling size is satisfied in each link. As this figure shows, standard deviation of travel time gradually decreased with link length. There are only data with high number of time that minimum sampling size is satisfied, in graph area where link length is over 1500 m. Moreover, it was shown through the field test in Bangkok that the standard deviation of actual travel time is high. Incidentally, when actual travel time data of Din Deang Road were used to calculate the minimum sampling size, the minimum sampling size is 214 vehicles at morning peak hour and 99 at daytime.

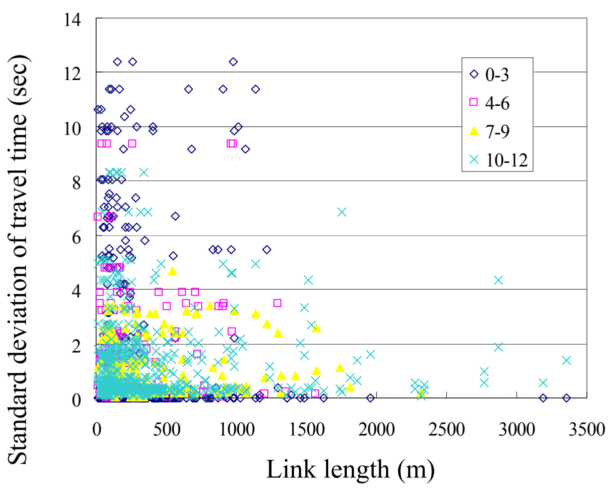

Figure 12. The Relationship between Standard Deviation and Link Length

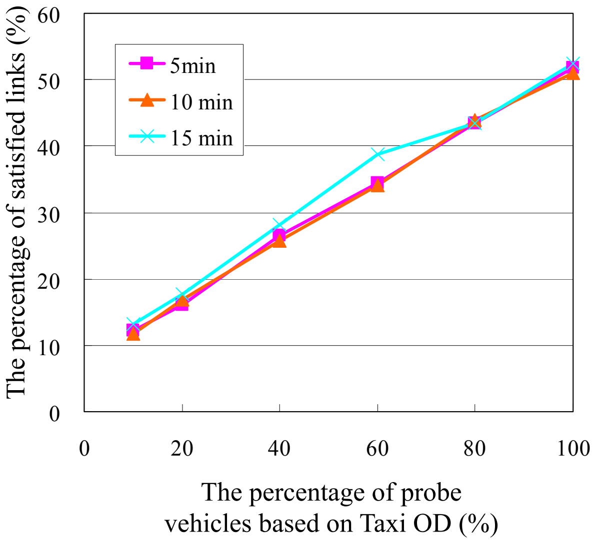

Figure 13. The Percentage of Satisfied Links in case of Combined Links

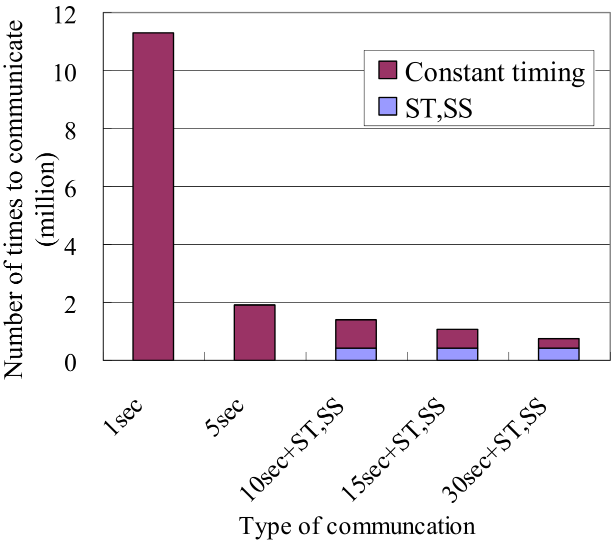

Figure 14. The Difference of Number of Times that Data Was Transmitted

Therefore, it is concluded that the reliability of probe vehicle data can be enhanced by reducing the variation of travel time by combining links with same performance. To verify the influence of link length, the number of required probe vehicles was calculated again by using combined roads from 1896 links to 960 links, that shown in Figure 13. The other conditions excepting road length are the same as the condition of simulation shown in Figure 8. Compared with Figure 8, the percentage of satisfied links at most didn't change with a few amounts of changing percentage of probe vehicles. On the other hand, the number of satisfied links changed by high percentage with changing of percentage of probe vehicles. This is the reason for the number of probe vehicles which passed a link for an interval was decreasing.

It is described in this paragraph that why standard deviation of travel time is high. These causes mainly lead probe vehicles not satisfying the minimum sampling size of probe vehicle per link. One cause is a long cycle length at signalized intersections with peculiar traffic light system in Bangkok, which causes long waiting time on queue. And random phase and random green time length make traffic flow high variation. Although it is impossible to improve actual traffic situations and the traffic signal system, making link length longer should be attempted to smooth the variation of travel time. Especially, in the peak hours, police men control signal timing in Bangkok. The variation of travel time might be higher than in this micro simulation model.

5.3 Comparison of Data Transmission Methodology

The number of times to transmit data to a traffic information center was calculated with assumption of simulation configuration: percentage of probe vehicles was 50% and interval was 10 minutes as illustrated in Figure 14. Considered with results of reliability of travel times that depicted Figure 5 of section 3, 5-second interval seems to be suitable for data collecting in the term of cost efficiency and amount of data adequacy. Although the ST, SS method can reduce the number of times to send data, further study which can enhance the accuracy of travel time and efficiency of data collection, should be conducted.

6. CONCLUSION

The percentage of probe vehicles was calculated by using the developed simulation model. It is concluded that it is possible to continually collect traffic information by using probe vehicles in 40% of links in Bangkok. If some links with same characteristic of travel time is combined, probe vehicle system can cover 50% of links. On the other hand, the probe vehicle system couldn't cover 50 % of all links in the study area even if all taxies are used as probe vehicles. Therefore, it is significant to consider how to collect traffic information of these links. The prediction technique using both traffic volume and probe vehicle data should be considered. However, current probe vehicle system technology cannot observe traffic volume unless communication technology between all vehicles is added. Therefore, some detectors should be installed on the links where probe vehicles don't pass every time. The suitable combination will be studied in further study, because there are some loop detectors in Bangkok.

As the results of simulation, costs of each transmission method were quite different. It was concluded that 5 seconds interval is enough to record travel time with high reliability and the ST, SS method can reduce the number of times to send data to a traffic information center. In this study, running costs of probe were considered by using the amount of data under the assumption that cost depends on the amount of data. Although this is effective way to evaluate, total costs including invest and running cost should be considered after actual cost to transmit data is set.

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