COST-EFFECTIVENESS IN PROBE VEHICLE SYSTEMS

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Abstract: The development of traffic data collection is promoted by IT technology. Probe vehicles are playing an increasingly important role in the field of ITS, and showing high ability for various ITS applications in the last decade. The overwhelming superiority of probe technology relies on a good coverage and a high penetration rate of probe vehicles. Although conceivable, the expectation of ubiquitous coverage of the entire road network is still far away from actual implementation nowadays. Through the review of current studies on the probe systems in ITS projects around the world, recent advances in probe technology are explored, following by an analysis of the impending obstacles or trade-offs that were faced by the extension of probe implementation. It is recognized that a cost-efficiency probe deployment scheme is of certainty to be the impetus of probe system evolution.

Key Words: Probe vehicle, Cost-effectiveness, Review

1. INTRODUCTION

Traffic surveys developed from conventional manual measurement to direct measurement through an impetus of IT technology, which makes the survey methods and mechanisms change rapidly. Turner et al. (1998) summarized the travel time data collection technologies of ITS projects in USA and provided guidance in the data collection, data cleaning and processing; as compared with other traffic data collection technologies, probe technology seems to be distinct because probe vehicles are already in the traffic stream for a different purpose when used for the collection of traffic condition data. Moreover, it provides a great possibility of monitoring the whole networks in real-time, while conventional traffic surveillance methods have no practical availability. It is therefore recognized that probe vehicle as a traffic data collection tool will be superior to most of the current technologies since the provided information are continuous, dynamic, full-coverage in space, and widely adaptable in kinds of applications.

The overwhelming superiority of probe technology relies on a good coverage and high penetration rate of probe vehicles. As compared with part coverage, the all coverage for a
probe system is much more cost-effective than the same extent of coverage for a fixed sensor system: the wider the coverage is, the more the investments can be saved. Furthermore a good coverage offers more valid information and hence provides more reliable estimation with respect to traffic condition. As a result, a probe system with wider coverage can easily win the trust of users and induce more potential users to become probes information providers. Turner et al. (1998) believed that probe systems are most cost-effective for collecting data within a large study area.

Although conceivable, the expectation of ubiquitous coverage of the entire road network is still far away from actual implementation nowadays. The problem that the cost constraint lacks sufficient considerations became urgent in the end of last century. In the last century probe technology was once used to be regarded as a research tool to evaluate the performance of traffic management systems rather than a practical tool that enables solutions to a set of transportation problems encountered by traffic user, and therefore should be as accurate as possible regardless of costs. As a matter of fact, probe technology was designed from the beginning to improve the cost-effectiveness of real-time traffic data collection. Even though some applications based on probe systems have been developed up to date, there are still some suspicions: if it is true that probe surveillance system is a cost-effective alternative to stationary sensors, why only a sprinkling of projects around the world is successfully implemented in a large-scale? How to enhance the feasibility of probe technology for offering more practical traffic solutions?

This paper attempts to answer these suspicions and investigate the cost-effectiveness in probe systems through a review of the existing studies on probe systems in ITS projects around the world. First, the improvement and advances in data collection, data accuracy and reliability, as well as the cost-effectiveness are explored. Then, attentions focus on the impending obstacles or trade-offs that were faced by the extension of probe implementation. This paper last proposes an optimization deployment strategy in order to enhance the cost-effectiveness of a probe system, along with an introduction of the potential data sources and future communication technologies that might improve the cost-effectiveness of probe systems.

2. RECENT ADVANCES IN PROBE APPLICATION

Over the past decade, probe systems implementation experienced a rapid extension through a drive of technology development and market promotion. The industrialization of advanced communication technology and location technology make the wide use of probe equipment in urban areas possible, especially after the Selective Availability (SA) of GPS by U.S. military was removed in 2000 and thus GPS satellite location service became free for civilian usage. Among the five types of probe systems listed in Turner’s report (Turner 1998), probes equipped with GPS receivers rank highly owing to lower operation cost per unit of data, higher flexibility, and higher accuracy. The other four probe systems include the automatic vehicle location (AVL) system, the automatic vehicle identification (AVI) system, the ground-based radio navigation system and the cellular geo-location system.

The required implementation technology for probes is not so complicated that a probe system can be easily integrated into the existing traffic management systems, while little investments of new infrastructures are needed. Two fundamental types of probe systems are being pursued around the world: freight trucks are most appropriate for data collection on the highways and in suburban areas, while in urban networks the traffic surveillance via taxi probes are
particularly adaptable. The overall traffic condition can be well traced through “averaging” the probe observations as long as no bias is observed or enough sample size is available. The traffic data of all probes are transmitted to a management center, and then transportation administrators can make easily some certain judgments on the traffic condition from high frequency reports and guide travelers to more efficient routes. This section reviews the advances of probe technology and improvement in practical implementation from existing studies both in theoretical research and in practical experiments.

2.1 Data Collection through Probe Vehicles
Accompanied with the wide employment of GPS and GIS technology, traffic data collection through probe vehicles has entered a new epoch characterized by automated collection, electronic format, successive collection and broadest coverage. It has been recognized that significant benefits can be gained from such kind of real-time traffic data: improving traffic management, prompt identification of incident location, more efficient and environment-friendly travel route guidance, and so on. Besides the basic information such as location and time, more information can be collected to meet the needs for all kinds of application projects: traveling speed, wiper operation, weather (air temperature / precipitation), fuel consumption, engine rpm, turn signals, and so on. To date, traffic data collection practice through probe vehicles can be categorized into several types according to the research motivation, for instance, traffic monitoring and congestion detection, travel time estimation and short-term prediction, investigating travel behavior, trip OD distribution and dynamic OD prediction, real time route guidance or navigation, and so on.

The Internet ITS consortium operated one of the largest worldwide probe systems in Nagoya from 2001, Probe-vehicle-based Dynamic Route Guidance System (P-DRGS). This project had approximately 1,570 taxis equipped with GPS receivers for automatic reporting their locations from January, 2002 to June, 2004. Based on these historical traffic condition data, a web-based route guidance system, named as “PRONAVI”, has been successfully developed (Morikawa, et al. 2007). Real-time information is obtained from a relatively small percentage of vehicles and VICS system. In order to maintain such a great probe system, a large amount of communication costs are required and therefore only few ITS projects in the world can afford. The large scale implementation of a probe vehicle system with its surveillance coverage over the entire metropolitan area is rare. ITS projects on a probe system basis are still faced with the problem of data scarcity due to relatively small probe size.

Two types of polling schemes are widely employed for a probe system: time-interval polling and space-interval polling. Generally speaking, time-interval polling provides superior feasibility due to the less missing data, while the space-interval scheme is more efficient since almost all GPS reports can be treated as useful data (Liu, et al. 2007b). Although frequent probe reports provide more information, it is found that an adaptable lower polling frequency would help to improve the cost-effectiveness of probe data collection (Liu, et al. 2006a). It should be mentioned that because those “passive” probe taxis that have their destinations and favorite routes are beyond the controlling of system administrators, therefore the distribution in space at any time is also uncontrollable to some extent. With respect to one system that aims to monitor part of networks, say, only the main arterials, the observations at other road links provide less usefulness.

2.2 Accuracy and Reliability of Probe Information
The wide implementation of probe vehicles in traffic survey and traffic monitoring domain is considered a great progress due to the induced accuracy improvement. For instance,
performance measurement, such as travel time and speed, congestion and delay time at signalized intersection, can be directly measured rather than making estimates through the conventional fixed sensors. Moreover, different vehicle turns (turn right, turn left, or straight ahead) at intersections can be distinguished and therefore more reliable short term traffic condition can be estimated and predicted.

The successful large-scale development of probe system in traffic surveillance fields depends on higher reliability of real-time travel time estimates. Eisele and Rilett (2002) measured the accuracy of AVI in Houston, Texas, against probe vehicles. They found that for the corridor studied, the AVI measured travel time for individual probe vehicles matched their true travel time within 2%. However, for an ATIS application, reported travel time depends on sufficient market penetration to keep estimates up to date and to smooth variations between drivers. Jung et al. (2002) applied the Heuristic On-line Web-linked Arrival Time Estimation (HOWLATE) methodology in a large scale evaluation of a prospective pre-trip notification based on ATIS in two cities over 15-month period. They summarized that ATIS benefits are overwhelmingly from improvements in trip reliability and minimally from improvements in in-vehicle travel time.

However, in the dense urban network environment, great uncertainties are always inevitable. Sen et al. (1997) found that probe reports on link travel time are not independent and that the samples 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. In order to overcome this problem, a lot of research have been conducted by data fusion (Hellinga and Gudapati, 2000; Choi and Chung 2001; Wang and Nakamura 2003; Wang et al. 2006) or re-sampling (Vasudevan et al., 2004).

Chen and Chien (2001) compared the travel time measurement on path based with that on link based and concluded that travel time prediction on path based is always better in reliability than that on link based. Similarly, Li et al. (2007a, b) suggested that a selection of relative longer road link (divided by arterial intersections) would help to remove possible biases and achieve higher reliability on link travel time estimation. Furthermore, an estimate of probe queuing time due to various probe access distribution is necessary, rather than simply “averaging” the observed travel times from probe samples (Li et al. 2007b). Note that good probe coverage can also enhance the reliability of a system state estimate due to possible larger number of probe observation across time and space, while either data fusion of probes and fixed sensors nor data complementation based on part coverage probe data has unavoidable limitations (Liu et al. 2007a).

### 2.3 Cost-effectiveness Issues in Existing Research

The cost-effectiveness in a probe system is the key to promote the application progress. However, the general evaluations on traffic survey data mainly focus on such key quality measures like accuracy, completeness, validity, timeliness, coverage, and accessibility (Turner, 2004), while the operation costs are always neglected. Actually, cost-effectiveness is clearly one of the advantages of traffic data collection and a preponderant factor that should be considered by ITS projects planners.

There have been a number of studies that attempt to improve the cost-effectiveness from various aspects. For instance, the required minimum number of probe vehicles (Srinivasan and Jovanis, 1996; Chen and Chien, 2000; Cheu et al., 2002; Green et al., 2004) and the
coverage area (Fushiki et al., 2004) are the most popular issues. Ishizaka et al. (2005) 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 probe vehicles required and weighting the system operation cost associated with the amount of transmitted data.

Meanwhile, some other aspects have also been considered. Park et al. (2001) proposed a methodology for identifying the optimal aggregation interval size for estimating and forecasting traffic parameters. Zhu and Wu (2005) proposed a solution of maximizing the data performance by combining attribute costs and the relevance of each attribute to the target concept and paying more attention to those attributes that are cheap in price but informative for classification. Some other studies were initiated to address the effect of transmission frequency on system cost-effectiveness. Quiroga and Bullock (1998) examined the minimum sampling intervals for probe vehicles (i.e. the data transmission interval) on freeways and highways from the viewpoint of sampling theory. They suggest that the maximum time interval between consecutive GPS points is at most half the roadway segment travel time. Theoretical analysis results in a maximum of 6 seconds data transmission interval for freeway travel, which, however, neglect the cost and the effect of expected reliability. An elasticity analysis was conducted in our previous study to compare the cost-effectiveness of an individual probe vehicle at 12 types of time-interval polling frequencies ranging from 5s to 60s (Liu et al. 2006a). This study measures the trade-off between communication cost and the acquired information accuracy from two aspects: map matching and link travel time measurements.

The series researches of Wunderlich et al. (Wunderlich et al. 2001; Jung et al., 2002, 2003) measured the impacts of ATIS on on-time reliability from the aspect of ATIS investment guidance. They concluded that there exists a unique value for level of error, called the crossover points of error, below which ATIS provides positive travel reliability benefits on aggregate for a region. For ATIS services higher than these levels of error, only certain subgroups of trips with relatively longer length or higher variability may realize benefit. They also concluded that once ATIS reaches a level of error near or below 5%, benefit from further improvements may overweight the cost associated with these improvements (Jung et al., 2003). 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 user.

3. ENHANCING THE COST-EFFECTIVENESS OF PROBE TECHNOLOGY

Probe technology will certainly play increasing role in real-time traffic surveillance, since it provides more feasibility for system organizer and even private clubs/companies can operate such a probe system. Whether and when probe technology can substitute for fixed sensors depends on its comparative cost-effectiveness at system level: with higher reliability of traffic information and wider coverage area. Current attentions on the qualitative comparison offer limited insight into the optimization decision on all the key items of a probe system, such as polling frequency, probe size, aggregation time, and so on. With the desire of accomplishing ITS society characterized by higher safety and efficiency, more consideration on the cost-effectiveness should be the trends. This chapter explores the impending obstacles or trade-offs that were faced by the extension of probe implementation with respect of cost-effectiveness of a probe system, and then provides a perspective as to the evolution of
probe vehicles. Some other factors like GPS accuracy and Digital Road Map accuracy are also important but not summarized in this paper, because a slight improvement on GPS receivers and DRM accuracy would require much further investments, and thus be costly and uneconomical.

3.1 Trade-off between the Polling Frequency and the Required Probe Size
Although lower polling frequency might reduce communication costs significantly, the required probe size might be much larger due to the reduced observation accuracy (Liu et al. 2006b). An optimized combination of polling frequency and required probe size determines the cost-effectiveness of a probe system in a large scale. Previous studies on probe size generally ignored the data polling frequency or just determined an acceptable polling interval intuitively. Actually, polling frequencies have a direct influence on the required probe size because they provide information with different reliability. In practice, dropping the frequency down to a reasonable extent is one of the effective methods. Given limited funds, transportation authorities are faced with the decision of whether to expand probe size or increase transmission frequencies of the existing probes for improving the traffic monitoring accuracy. When frequencies are high, the most cost-effective deployment decision may be to expand the probe size and accordingly the surveillance coverage. If probe size is already extensive, increasing frequency for the existing probe vehicles may be the most cost-effective option.

Events data in the probe experiments in Japan (Horiguchi, 2002a, 2004) offer much useful information through an effective way, say, only the short trip (deceleration) events and short stop (acceleration) events, together with the data at a long polling interval, are delivered to the management center. Those events data are very efficiency in judging traffic conditions. For instance, the pattern of alternating acceleration and deceleration indicates stop and go conditions. Event-based transmission is regarded as an effective data collection technique as it reduces the amount of data by about 18% compared with transmission at a fixed time interval of 30 seconds, without a significant loss in the quality of travel time and congestion information (Horiguchi, 2002a). However a corresponding in-vehicle device is required to judge vehicle status. Some commercial vehicles equipped with GPS might be the alternative selection to equipping such an expensive device, if only most of uncertainties with respect to the systems can be reduced to an acceptable level (Yamamoto et al. 2006).

Future studies should consider more constraints in the situation of real-time monitoring. Besides the probe size and communication charge system, more factors such like communication channel capacity, total items required to be monitored, coverage area, as well as probe distribution across time and space, should be taking into account before determining the pooling frequency. Although a wide variety of communication networks, such like DSRC, GRPS, cellular phone, and so on, provide wide channel for data reporting in real-time with relatively lower communication cost, a large scale probe system still need a favorable polling frequency, since more information are required to be monitored in real-time (Bishop, 2005). More advanced communication technologies will induce demand of more real-time information. It is mentioned that polling frequency of one probe system might be time-specified and space-specified other than a constant value.

3.2 Trade-off between Coverage Area and Sample Observations on Each Link
Probe size should satisfy both requirements of enough sample size for individual link travel time estimation and reasonable coverage area. The travel time/speed estimates by Quiroga and Bullock (1998, 1999) revealed the trade-offs between sampling ration and the reliability of the
section speed. Suited probe size and reasonable probe distribution can sample the network with high efficiency. Probe penetration rate is an alternative indicator reflecting the extent of probe deployment. The recommendation of the OPTIS report (Karlsson, 2005) called for a total 3%-5% of all vehicles to be employed as probe vehicles, where they did not give a clear coverage image.

Although Green et al. (2004) and Yakkala et al. (2006) noticed the problem of treating the network as a uniform entity in conventional studies and show the fluctuations in flow conditions over time and across different locations require varying sample sizes, their solutions still lack of enough consideration on the uncontrolled probe distribution. Even though probe taxis are generally concentrated in the city center (Liu et al. 2007a) and appear frequently around the subway/railway stations (Horiguchi, 2002b), the locations during any time period are far from controllable.

The great divergence between taxis distribution and all vehicle distribution is a well known phenomenon. As an open topic, the relationship between coverage area and distribution characteristics of probes, as well as that between sample observations and distribution characteristics, is still untapped really up to date. Intuitively, the newly employed probes will not only extend the coverage area but also increase the sample size for most links in current coverage area. One certain issue is that the new additional probe vehicles can neither result in the same percentage of extension in coverage area, nor lead to an identical increase of observed sample size. It is clear that parts of links with enough sample size also obtain new probe reports, while some new covered links might not get enough observations. The coverage efficiency that measures the increased valid coverage per unit of probe supplementation is a good index of this trade-off. The issue of dynamic probe coverage and minimum probe size must attract increasing attentions in near future.

3.3 Cost-Effective Scheme and Probe System Evolution

The optimization research of these trade-offs will do help to make a cost-effective plan, that is to say, improving the system accuracy and reliability while keeping the same investment, or, saving investment by keeping the same level of system reliability. Besides the transportation authorities and informatics solution providers, there are some other entities that might involve in probe evolution, such as communication providers, commercial vehicle companies, auto manufactures, digital road map operators, and so on. Some of these contributors also gain valuable information from probe data, and thus are potential cost sharers.

Figure 1 presents the proposed framework of cost-effective optimization, where all entities that involve in probe implementation (dot line boxes), the facets or functions related to each entity (solid line box), and the factors required to be optimized (dot-and-dash line box) are integrated. Four indicators of polling frequencies, probe coverage areas, required probe size and items need to be monitored are controllable and should be optimized by taking other uncontrollable influence factors, along with the interaction among these four indicators, into well consideration. The factors that are beyond the control of probe system operator but have influence on the cost-effectiveness level include: required system reliability determined by data collection purpose and current traffic condition, network characteristics that are reflected by digital road map, probe distribution characteristics under specific destinations and travel behaviors due to various types of probe vehicle, the existing traffic control systems, and communication factors consisting of communication coverage area, channel capacity, and charge systems (Liu et al. 2006b). All listed communication factors have direct impacts on the four cost-effective indicators, while other factors affect part of these optimization items.
Transportation authorities and transportation informatics solution providers should be the main actor of optimizing the investment usage and existing infrastructures and equipments from all other involved contributors. Moreover, better arrangement of cost share and data ownership among all contributors and road/informatics users would contribute to implementing of this framework.

Some new effective data sources are sure to be the impetus of probe evolutions, among which taxi dispatch system has great potential in providing traffic information as taxies traverse the urban network. Taxi dispatching systems are widely used for improving the management efficiency by reducing both passenger waiting times and vacant taxi times. It is proposed that the ability of such system to automatically determine traveling locations provides an opportunity to acquire large quantities of travel time data without the need to employ a costly communication network. (Yamamoto et al. 2006)

The potential to obtain real-time traffic information from a taxi dispatch system is recognized, while there are still some limitations that should be overcome before being put into routine service application. To date, such systems have been widely deployed by taxi companies in most metropolitan areas of the world. The methods of reducing observation uncertainties from such lower cost data with longer polling intervals are open research questions. Furthermore, some new developed communication technologies, such as 802.11a wireless communication technology and digital multi channel access (D-MCA) technology, have great potentials to allow more transmission capacity at the same time and therefore have a lower data missing rate, which allows high frequency transmitting or more information transmitting in real-time. It should be noted that whether polling frequencies need attention in future depends on the extending speed of communication capacity and the quantity of new required monitoring data, along with the extent of reducing cost.
Probe systems have been shown to be an advanced tool for facilitating human transportation activities, therefore both communication and car manufactures realized great markets and put its application forward. With the eventual objective of enhancing the efficiency of road infrastructures and improving travelers’ mobility other than only providing services for private road/vehicle users, the future evolution of probe systems should also cooperate with public transportation systems and deal with the possible induced private vehicle usage.

4. SUMMARY

Communication and location technologies exist to alter the action of probe systems in the ITS domain, making it feasible for traffic manager, as well as individuals, to participate in the activities in transportation management and control. Probe was designed to improve the cost-effectiveness of traffic data collection and extend traffic surveillance coverage to the entire network. The issue of probe coverage is worthy of attention not only because probe system is the first one that is capable of achieving full-scale traffic surveillance in practice, but the most important, the extent of coverage have great impacts on the cost-effectiveness of a probe system.

The technologies related to data collection and data processing have already achieved great advances over the past decade, however, the ubiquitous coverage within entire network is still far away from reality because such advantage relies on a large amount of active probe vehicles and thus great costs are required for real-time communication, which usually can not be afforded by most of cities. The lack of effective data collection scheme of a probe system is still the bottleneck of large scale deployment and industrialization, which might lead to a negative effect on the continuous data collection because few customers can be satisfied with the service based on a small sample size.

The potential power of practically servicing travelers’ daily life for probe systems depends urgently on an available cost-effective deployment scheme. The proposed optimization scheme lists all contributors and their functions in probe implementation, some uncontrollable factors affecting the cost-effectiveness level, as well as four controllable indicators for optimization. These indicators include probe polling frequencies, probe coverage area, required probe size, and all required monitoring items, of which only part have been considered before.

While ITS projects will certainly benefit from this cost-effectiveness scheme by allowing more efficient and reliable traffic observation, future evolution of probe systems should not ignore the cooperation with public sector of transportation system and should consider beforehand the possible induced travel demand arise with improved traffic conditions.

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