Doctoral Dissertation

Arterial Road Travel Time Study using Probe Vehicle Data

by

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Abstract

Travel time-based measure, such as mean travel time, is easy to understand by both the professional transportation community and the traveling public. Travel time-based measure is also applicable across modes and is a common measure of effectiveness for all modes. These advantages make travel time-based measure extremely powerful, versatile, and desirable. By probe vehicle (PV) technique, point-to-point travel time (link or path) can be measured directly and thus there is a growing attention to PV technique with the progressive implementation of ATIS.

Path travel time is OD specific and there are numerous OD combinations in a city. Thus, ATIS service providers normally collect and disseminate real-time traffic information at link or section level rather than path level. A set of travel time reports from PVs on a link in a time interval is a sample from travel times of all vehicles (population) and usually the sample size is very small because the cost imposes restrictions on the number of PVs.

The main objectives of this thesis are to investigate the statistical properties of link travel time and the transform of the properties over the change of the traffic conditions and to propose an efficient link travel time estimation method by small number of travel time reports from PVs. In this thesis, signalized arterial link is considered as *link*.

The statistical properties of link travel time and the transform of the properties over the change of the traffic conditions are investigated by historical data from Nagoya Probe Demonstration, qualitative analysis, and simulation based analysis. These analyses show that link travel time is two-peak distribution (two groups: one without delay and the other with delay) and as traffic condition becomes worse, the proportion of the group with delay increases and the means of the two groups also increase. For estimating mean travel time that is considered as an indicator of traffic condition, it is needed to estimate both the proportion and the means of the two groups correctly. However, using small size probe reports, it is difficult to estimate the proportion of the group with delay. Fortunately, the means of the two groups can be estimated by small size sample due to the variance of each group is relatively small. Furthermore, the proportion and the means of the groups are not independent and the relationship is established in this thesis under a reasonable assumption and using the information of traffic signal at upstream and downstream intersections.

These analyses are used to develop a link travel time estimation method and the essence of the proposed method is to estimate the means of two groups using small size probe reports and then estimate mean travel time using the two means and the proportion that is calculated by the relationship of the proportion and the two means instead of to estimate population mean using sample mean directly.

This thesis also examined the two commonly accepted methods that are used to estimate the adequate number of the probe reports: *standard deviation formulation* and *confidence interval method*. Traditionally, it is considered that the reliability of probe-based estimation depends on the number of the probe reports. These formulations are based on Central Limit Theorem and the result is doubtful when the population is severely nonnormal and sample size is small. The examination shows that the *standard deviation formulation* is sensitive with sampling error and cannot provide consistent result, and the *confidence interval method* is needed to add additional criterion to provide correct judgment.

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List of Abbreviation

ATIS	Advanced Traveler Information System
ATMS	Advanced Transportation Management System
AVI	Automatic Vehicle Identification
DRM	Digital Road Map
GIS	Geographic Information System
GPS	Global Positioning System
ITS	Intelligent Transportation System
LCT	Link Cost Table
MAPE	Mean Absolute Percent Error
NPVD	Nagoya Probe Vehicle Demonstration
NSAT	Number of Satellites
OD	Origin – Destination
PDOP	Position Dilution of Precision
PV	Probe Vehicle
SA	Selective Availability

Chapter 1

Introduction

1.1 Background

Traffic congestion reduces utilization of the transportation infrastructure and increases travel time, air pollution and fuel consumption, and thus is becoming a common world-wide problem. Due to the constraint of the physical space and the environmental impact, Intelligent Transportation System (ITS) is considered as an alternative approach to reduce congestion rather than building new roads (Pan et al., 2007). Advanced Traveler Information Systems (ATIS) is one important components of ITS and the data collection method used in an ATIS is critical for the reliability of the ATIS.

Travel time-based measure, such as mean travel time, space-mean speed, and delay, is easy to understand by both the professional transportation community (transportation engineers, planners, and administrators) and the traveling public (commuters, business persons, and consumers). Travel time-based measure is also applicable across modes and is a common measure of effectiveness for all modes. These advantages make travel time-based measure extremely powerful, versatile, and desirable and an increasing number of transportation agencies are switching to travel time measure to monitor traffic condition (Quiroga, 2000).

Traditionally, travel time measure is collected “indirectly”. That is, traffic data such as volume, occupancy, and spot speed were obtained directly, and travel time is calculated using a function of these parameters. However, the general relation among these parameters has been explored widely and the specific coefficients in the function are most likely site specific. Further, this general relation might not stand during saturated/oversaturated flow condition (Chen and Chien, 2001). By probe vehicle (PV) technique, point-to-point travel time can be measured directly and thus there is a growing attention to PV technique with the progressive implementation of Advanced Traveler Information Systems (ATIS). PVs can be instrumented with different types of electronic equipment to locate vehicle, including Signpost-Based Automatic Vehicle Location, AVI tag (Automatic Vehicle Identification), Ground-Based Radio Navigation, Cellular Phone Tracking and Global Positioning System (GPS).

In Nagoya, Japan, an urban-wide GPS-based PV demonstration, namely Nagoya Probe Vehicle Demonstration (NPVD), was established by Internet ITS Joint-Research Group in 2001 (Internet ITS Joint-Research Group, 2002). NPVD is implemented using 1,570 taxis as PVs. In NPVD, the location (longitude, latitude), time and additional information (e.g., heading direction, speed and in-service tag) of PVs are collected by in-vehicle equipment and are transmitted to the operation center through telecommunication network when pre-defined events occurred. In this study, travel time reports from NPVD during October 2002 to March 2003 are used to investigate link travel time properties. NPVD provides an opportunity to verify PV technique and to find a way for developing effective PV-based ATIS.

1.2 Research objective

Traffic conditions evolve over time and the information provided to users by ATIS, to be useful and applicable for intelligent travel decision, should accurately reflect traffic conditions. Travel time-based indicators, such as mean travel time, space-mean speed, and delay, are powerful, versatile, and desirable. However, by traditional devices, such as loop detectors, microwave detectors, radar, etc., these indicators are obtained “indirectly” and the result is unreliable. Moreover, it is unrealistic to expect that the whole network is completely covered by such devices. Unlike traditional devices, probe vehicle provide direct travel time measurement and can cover the whole network. Therefore, there is a growing attention to PV technique with the progressive implementation of ATIS.

The population of link travel time is usually defined by link travel times of all vehicles traveling a link during a time interval. For a typical link, there are nine distinct subpopulations associated with each combination of access and departure movements (left turning, right turning and through) and these subpopulations have different travel time characteristics. Further, the population also can be divided by intersection delay (some vehicles will experience the intersection delay at downstream intersection of the link, while others will depart without intersection delay) and the two subpopulations also have significant different travel time. Therefore, the population of link travel time has large variance and it is difficult to reliably estimate the population mean from the sample mean when sample size is small.

Link travel time data from PVs on a link in a time interval is a sample and the sample size is small: the cost and capacity of the communication between PVs and the operation center impose restrictions on the number of PVs and the reliable estimation should be obtained by small number of PVs.

For probe-based estimation, in which the population has large variance and the sample size is small, a new estimation method is needed to provide reliable estimation of link performance. The primary objective of this research is to develop a reliable estimation method of link performance using small size probe data, especially for saturated/oversaturated conditions. The proposed estimation method will contribute to the establishment of efficient probe-based ATIS.

1.3 Organization of this dissertation

The remainder of this thesis consists of eight chapters.

Chapter 2 presents a comprehensive review on the studies of probe vehicle technique. First, probe vehicle technique is introduced and advantages over traditional traffic data collection technique are described. Second, the issues about the reliability of GPS-based probe vehicle technique are described. PVs can be instrumented with different types of electronic equipment to locate vehicle, and GPS is the most popular one. Third, the efforts to improve the reliability of GPS-based PV technique are presented. Finally, probe-based studies including travel time studies, delay measurement, and congestion measurement are reviewed.

Chapter 3 introduces the Nagoya Probe Vehicle Demonstration and describes data processing procedure used in this research. In the processing procedure, a new map matching algorithm is included.

Chapter 4 and Chapter 5 investigate the statistical properties of link travel time. In Chapter 4, the definition of link travel time is discussed, which includes the concerns about link definition and the effect of turning movement. Then historical travel time reports on an arterial road are presented. Finally, traffic situation on a link is separated into three phases and the statistical properties of link travel time are analyzed qualitatively. In Chapter 5, a simple network is modeled using VISSIM, a microscopic traffic simulation model, and the qualitative analysis in previous chapter is confirmed.

Chapter 6 examines two commonly accepted methods to estimate the adequate number of PVs: *standard deviation formulation* and *confidence interval method*. The two methods are based on Central Limit Theorem and thus the result is doubtful when the population is severely nonnormal and sample size is small.

Chapter 7 introduces a new performance indicator[1] and proposes a method to estimate the new performance indicator using small size probe reports on signalized link based on the knowledge from Chapter 4 and Chapter 5. The new performance indicator is essentially equivalent to conventional time-based performance indicators such as mean travel time or space-mean speed and has some desirable features.

Chapter 8 presents a simulation based method to measure the variability of vehicle-to-vehicle on a link and on corridor at three performance levels[2]. Though the simulation is very simple, performance level and vehicle movement at intersection are considered explicitly, which are two critical factors that influence travel time. The performance indicator proposed in Chapter 7 is employed to demonstrate the stability of the performance in each three levels.

Finally, the conclusions of this thesis are summarized and discussed in Chapter 9.

A work flowchart of this research is illustrated in Figure 1-1.

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[1] performance indicator: the indictor of traffic conditions such as flow, queue length, and mean travel time

[2] performance level: the level of traffic conditions

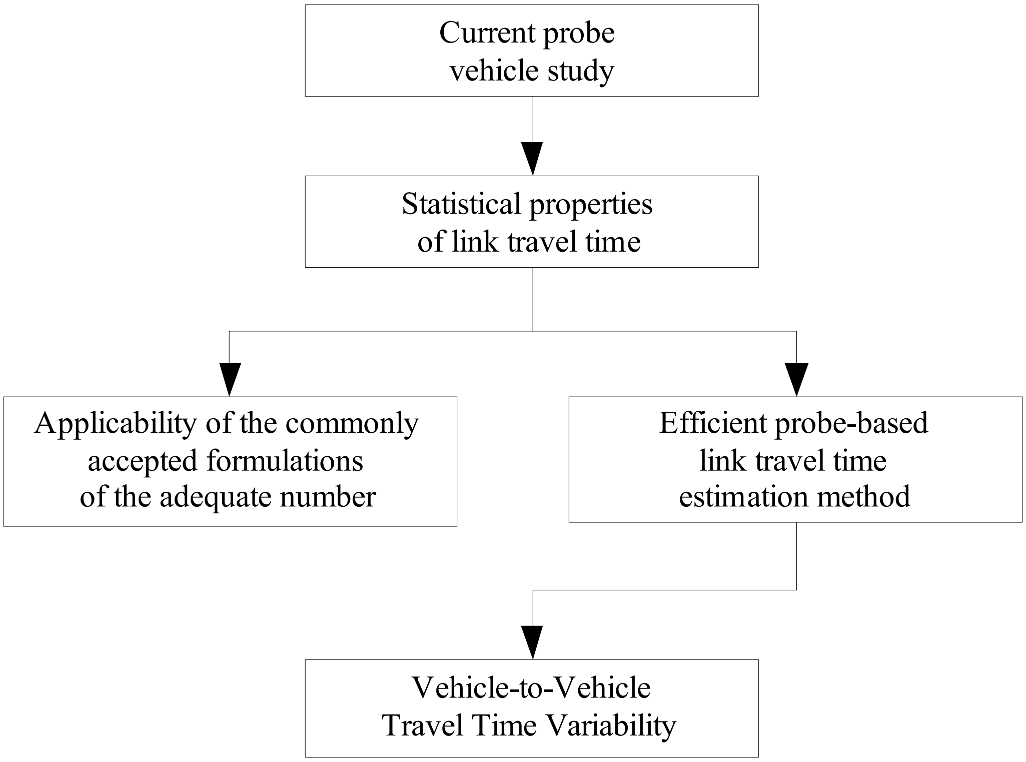

Figure 1-1. Work flowchart

Chapter 2

Literature Review

2.1 GPS-based probe vehicle (Turner and Holdener, 1995; Turner et al., 1998)

Real-time travel information is important in many intelligent transportation system (ITS) applications, such as congestion avoidance, route guidance, commercial vehicle routing, and pre-trip information.

The approaches used to collect real-time travel information can be grouped into two categories. One approach relies on the traditional detectors that can be used to collect information like vehicles volumes, time mean speeds, headways, and lane occupancy, such as inductance loop and infrared detector. The other approach relies on instrumented vehicles, also known as probe vehicles (PVs). PVs maintain frequent communications with operation center that "track" the vehicle location and time along the traveled route. The most important advantage of PV technique is direct measurement of point-to-point travel time.

PV technique is different from test vehicle technique. In test vehicle technique, the driver of the test vehicle is a member of the data collection team and the driving behavior is controlled to match desired driving styles, such as average car, floating car, and maximum car. Thus, the test vehicle technique is referred to as “active” vehicle. In contrast, in PV technique, the driver of PV is not a member of the data collection team. These PVs are already in the traffic stream and the drivers do not follow specific driving styles. Thus, PV technique is referred to as “passive” vehicle.

PVs can be instrumented with different types of electronic equipment to locate vehicle, including Signpost-Based Automatic Vehicle Location, AVI tag (Automatic Vehicle Identification), Ground-Based Radio Navigation, Cellular Phone Tracking and Global Positioning System (GPS). The GPS is a Global Navigation Satellite System and the signals of the GPS can be used to monitor location, direction, and speed of vehicle anywhere in the world. Currently, there are many applications of GPS for tracking vehicle in real-time, including emergency service vehicles, rental cars, commercial fleets, taxis, and transit vehicles.

In Nagoya Probe Vehicle Demonstration (NPVD), GPS-based PV technique is used and PVs are tracked by GPS alone or by revising original GPS with digital map in navigation system.

2.2 Reliability of GPS-based probe vehicle report

2.2.1 Reliability of location information from GPS

When PV location is tracked by GPS alone in a field test or ATIS, the availability of GPS for monitoring PV along its route in real time is a crucial factor.

Zito et al. (1995) conducted a field test at two places (Mallala, a small rural town north of Adelaide, South Australia and the CBD of Adelaide) and examined the performance of the GPS. At Mallala, a long flat stretch of road with an all-round clear view to the sky was chosen and it was considered as the “ideal” condition of the GPS. The CBD was chosen because the signal blockage of the GPS may be more apparent in the CBD, where high rise buildings form concrete canons that make it difficult for the GPS signals to reach down to the antenna on a PV. They concluded that although the accuracies obtained by GPS at Mallala can be quite satisfactory for traffic monitoring, the errors of GPS increase in the CBD. Importantly, they indicated that a GPS user can gain some idea on the quality of the GPS data, by observing the position dilution of precision (PDOP) as well as the number of satellites (NSAT), which are provided as part of the standard GPS information strings. For example, if the GPS data shows that there are only three satellites in view and that the PDOP is greater than three, then the GPS data is likely to be unreliable.

Ochieng and Sauer (2002) examined the performance of the GPS after selective availability (SA). The SA was the biggest source of error from the GPS and was removed by the U.S. Government on 1 May 2000. With SA operational, the instantaneous horizontal positional accuracy was 100 m 95 % of the time. The route in Central London was chosen because it has a good mix of important spatial urban characteristics such as open spaces, urban canyons, tunnels and bridges. In their study, four main parameters were employed to measure the performance of the GPS: *accuracy*, *integrity*, *continuity of service* and *availability*. Their analysis showed that though the accuracy required for most navigation requirements can be achieved by stand-alone GPS, the availability of the required accuracy is very low. They suggested that GPS augmentation using other aids, such as rate gyro, compass, odometer, map-matching and inertial navigation systems, is needed to achieve navigation performance in urban area.

Makimura et al. (2002) illustrated the disadvantage of the GPS inside tunnels, beneath elevated structures and route in CBD by comparing with the location information from car navigation system.

In summary, the accuracy and the availability of the stand-alone GPS can not meet the requirement of the vehicle tracking in urban area and GPS augmentation is needed.

2.2.2 Accuracy of point-to-point travel time measurement

Point-to-point travel time information of PV can be transmitted to the operation center via two means: memory card or the communication system (Sen and Thakuriah, 1995). When memory card is used, location and time of PV can be tracked at relatively short time interval (e.g., one second) and it does not increase the transmission cost significantly. By location and time information made at small time interval, point-to-point travel time can be measured accurately. However, this means can not provide real-time information and the second means should be chosen for real-time information.

In the second means, the information of PV is usually tracked and transmitted at relatively long time interval (e.g. 30 s or 1 min) due to the cost and capacity of the current communication system. There is no knowledge about the speed change between two successive PV records, thus the uniform motion assumption is employed for calculating the cross time of each interested point. Obviously, the assumption is not appropriate at urban network and a measurement error will accrue.

Liu et al. (2006) attempted to study the relationship between the magnitude of the link travel time measurement error and the transmission frequency. They found that besides the transmission frequency, link length also has a great effect on the magnitude of the measurement error. However, in their study, relatively short link (50 m ~ 150 m) was treated and Mean Absolute Percent Error (MAPE) was used to represent the measurement error. In my opinion, it is needed to study longer link (300 m ~ 1000 m) and the distribution of the measurement error instead of MAPE.

2.2.3 The adequate number of probes

The cost and capacity of the communication between PVs and the operation center impose restrictions on the number of PVs and it is impossible to make all vehicles as PVs. Thus, a set of travel times from PVs on a link in a time interval is a sample from travel times of all vehicles (population). Consequently, the adequate number of PVs that are required to estimate the population mean has been an imperative issue since probe vehicle technique was recognized as a method to collect traffic condition.

Various approaches have been developed by several studies to estimate the adequate number of PVs (Boyce et al., 1991; Chen and Chien, 2000; Cheu et al., 2002; Hellinga and Fu, 1999; Sen et al., 1997; Srinivasan and Jovanis, 1996; Turner and Holdener, 1995). These studies can be classified into two categories: network level studies and link level studies.

At network level, the studies focus on the relation between the number of PVs and the proportion of links in the network to be covered reliably. The general procedure in these studies is (1) sample N PV trips from the pool of all vehicle trips, (2) assign these N PV trips to the network, (3) use reliability criterion to judge whether each link in the network is covered by PVs reliably, and (4) above steps are repeated with increasing N until the pre-specified proportion of links in the network are covered reliably. However, various sampling strategies, assignment models and reliability criteria on link are suggested in the previous studies. Boyce et al. (1991) used random sampling, static user-optimal route choice model and traversing by PV at least once as reliability criterion. Srinivasan and Jovanis (1996) suggested using dynamic route assignment process instead of static route assignment and explicitly considers related factors, such as the reliability criterion on link, the time interval for travel time estimation (e.g., 5, 10, or 15 min) and the length of the peak period. Chen and Chien (2000) employed microscopic simulation model to assign the PV trips to the network and used standard deviation formulation as the reliability criterion for the links with normal distribution and confidence interval method for the links without normal distribution (two methods are described below). Cheu et al. (2002) also used simulation model and standard deviation formulation and used the OD-based sampling strategy instead of random sampling. Obviously, the reliability criterion on link plays a key role in network level studies and the criteria are studied in link level studies.

At link level, when the sample size n is large or the distribution is not severely nonnormal, *standard deviation formulation*, termed by Quiroga and Bullock (1998), is commonly accepted to determine the adequate number of PVs for a link:

$$n \geq \left(\frac{t_{\alpha/2,n-1} s}{\varepsilon} \right)^2 \tag{1}$$

where ε is a pre-specified permitted error, s is sample standard deviation and $t_{\alpha/2,n-1}$ is the *t*-distribution statistic for $1-\alpha$ confidence interval with $n-1$ degrees of freedom. When the population is severely nonnormal and the sample size is lower than 30, Eq.1 is not applicable because the statistical principle behind Eq.1 is the Central Limit Theorem, which is doubtful in such case (Montgomery, 1994). For nonnormal and small sample case, Chen and Chien (2000) proposed a criterion for determining the adequate number of PVs using confidence interval: if the $100(1-\alpha)$ percent confidence interval calculated from samples (PVs) contains population mean (all vehicles), it is concluded that those samples are adequate to provide reliable estimation of population mean. It should be noted that the commonly used formulation for confidence interval given by

$$\bar{x} - t_{\alpha/2,n-1} s/\sqrt{n} \le \mu \le \bar{x} + t_{\alpha/2,n-1} s/\sqrt{n} \tag{2}$$

is also based on Central Limit Theorem. That is the confidence interval from Eq.2 is also doubtful when the population is severely nonnormal and sample size is small. Additionally, when the range of confidence interval is lager than $2\times\varepsilon$, the adequate number calculated from the method may be meaningless even if the population mean falls into the confidence interval. The applicability of the two formulations (*standard deviation formulation* and *confidence interval method*) on signalized link will be discussed in Chapter 6.

Hellinga and Fu (1999) indicated that past research has provided contradictory conclusions regarding the adequate number of PVs. Van Aerde et al. (1993) assumed that a set of probe reports is an independent random sample from the population and indicated that as the number of probe reports increases, the sample mean approaches the population mean. Conversely, Sen et al. (1999) and Sen et al. (1997) found that probe reports are not independent and thus the sample mean can not approach the population mean regardless of the sample size. For a typical link, which is bounded by a four-leg intersection at the upstream and downstream intersections, there are nine distinct subpopulations, each of which associates with each combination of access and departure movement. Hellinga and Fu (1999) showed that these subpopulations have different travel time characteristics and concluded that the sampling bias arises when the proportion of PVs is different over subpopulations. The conclusion from Sen et al. (1999) and Sen et al. (1997) is based on field data in which the probe vehicles traversed a set of links by using the same link access and departure movements. The sample used in Sen et al. (1999) and Sen et al. (1997) has a level of bias due to the sample of a link is drawn from a subpopulation. On the contrary, the work of Van Aerde et al. (1993) is based on simulation and the sample is an unbiased sample of the population. Finally, Hellinga and Fu (1999) concluded that the contradictory conclusions are indeed correct, but each is only for specific traffic and sampling condition and neither is generalized.

2.3 Improvement of reliability and effectiveness

2.3.1 Transmit interval

In NPVD, the trajectory of each probe vehicle is directly transmitted from in-vehicle equipment to operation center via telecommunication network, and in-vehicle equipment does not perform the data reduction; the data reduction is operated at server side and the useful information such as point-to-point travel time is drawn at server side. For this kind of probe vehicle system, transmit interval is a critical factor because the communication cost is dependent on the transmit interval.

Time interval is the simplest implementation. In this implementation, the trajectory of probe vehicle is tracked and transmitted at predefined time interval (e.g., every 30 s or 60 s). However, time interval has no connection with the running state of probe vehicle and some useful information, such as the locations of starting and stopping, cannot be collected (Horiguchi, 2002).

Horiguchi (2002) proposed a transmit interval based on SS/ST events and indicated that this interval is effective than time interval. The events SS and ST are happened when probe vehicle is starting or stopping and thus it can be used to identify the locations of starting and stopping of probe vehicle. The comparison with 30 s time interval transmission showed that the SS/ST-based transmission reduces the transmit times significantly and has more useful information. For example, the pattern of SS/ST can be used to identify congestion (Horiguchi and Wada, 2005).

2.3.2 Disposition of taxi probe

In NPVD, taxi is used as probe vehicle and Miwa (2005) examined the average travel distance per taxi probe per day. They showed that it is about 200 km/veh/day and is much more than private car. In TrafficScan system in Singapore, taxi is also chosen as probe vehicle and Cheu et al. (2002) indicated that the percentage of "active" probe is much higher than the percentage of taxi probe in the entire vehicle population. In brief, taxi is more active and is very attractive to be chosen as probe vehicle.

The links covered by a taxi are highly dependent on the activity base of the taxi, such as terminal, railway station, etc. That is, the cover rate of each link in a time period is dependent on both the number of the taxi probes and the disposition of these taxi probes. Thus, a strategical disposition of taxi probe can reduce the number of the taxi probes and improve the effectiveness of probe vehicle system. Horiguchi (2002) proposed a theoretical framework to study the relationship between the link cover rate and the disposition of taxi probe and verified the theoretical framework by probe data from IPCar Project in Yokohama-city, Japan.

2.3.3 Fragmentary probe data

When estimating the travel time for the section shown in Figure 2-1, it is desirable that there are sufficient numbers of travel time reports from the probes which traverse the whole section, such as the probe one. However, when the penetration of probe is low, it is hardly expected. Then, the availability of travel time reports on fragments from the probes which traverse the section partially is interested, such as the probe two and the probe three.

Uesugi et al. (2003) studied the availability of the fragmentary probe data by considering the three cases: case 1 is only using the PVs traverse the whole section, case 2 is using the PVs traverse the whole section and the PVs traverse the section partially (includes the fragmentary travel time △ and ○ for ③ in Figure 2-1), and case 3 is using the PVs traverse the whole section and the PVs traverse the section partially and with the same turning movement (only the fragmentary travel time ○ for ③ in Figure 2-1). Two indicators *hitting rate* and *no probe data rate* are used in their study to examine the availability of the fragmentary probe data. The *hitting rate* represents the probability of the accurate estimation and the *no probe data rate*

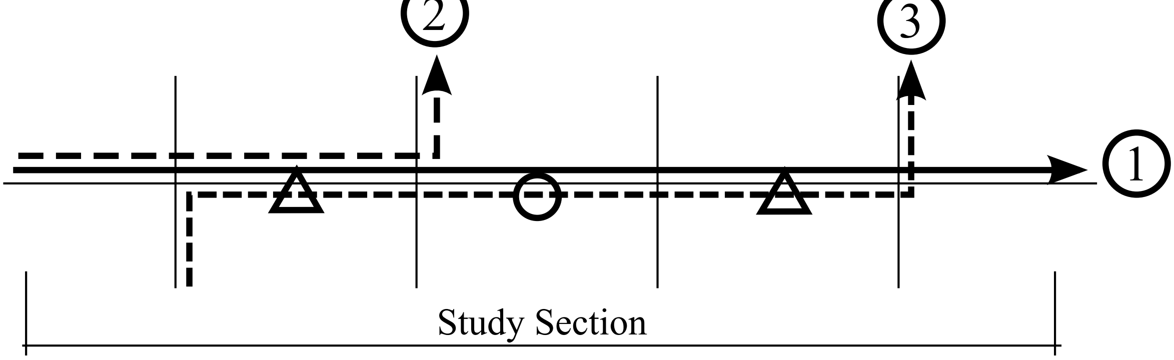

Figure 2-1. Fragmentary probe reports

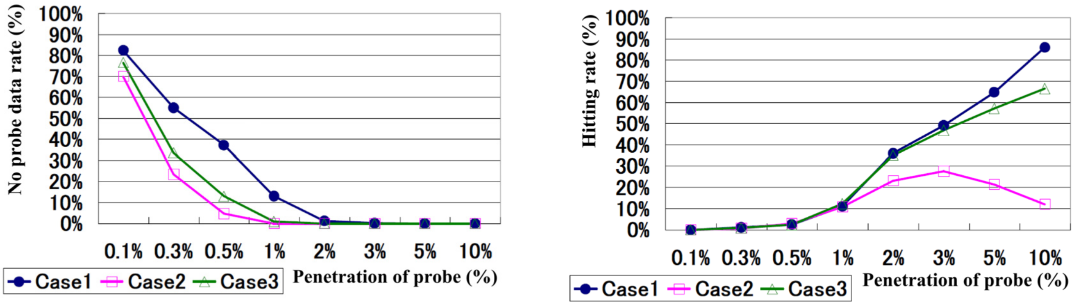

Figure 2-2. Comparison between Case 1, 2, and 3
(adapted from Uesugi et al. (2003))

presents the probability that probe reports meet the minimum requirement that there is at least one probe report. They concluded that (1) when the penetration of probe is lower than 3 %, the fragmentary probe data (case 2 or case 3) can improve the *no probe data rate* and however, the hitting rate is lower than 60 % in all cases; (2) when the penetration of probe is greater than 3 %, the *hitting rate* of case 1 is better than case 2 and case 3 and the fragmentary probe data (case 2 and case 3) does not improve the *no probe data rate*. For case 2, the hitting rate even decreases as the penetration of probe increases. It indicates that different turning movement causes systemic error (see Figure 2-2).

2.4 Probe-based studies

2.4.1 Travel time (or space-mean speed)

Quiroga and Bullock (1998b) provided a comprehensive methodology to integrate GPS and GIS to collect travel time data along highway. The three analyses were included in their study: segment lengths, sampling rates, and central tendency. The segment lengths analysis investigates the appropriate segment length that is need to detect traffic disturbances and concludes that relatively short segments (0.2 ~ 0.5 miles long) are needed. The sampling rate focuses the effect of collecting GPS data at different sampling periods (e.g., one second or one minute) and suggested that the GPS sampling period should be smaller than half the shortest travel time associated with the segment length. In the central tendency analysis, they show that median speeds are more robust estimators of central tendency than harmonic mean speeds.

For predicting path travel time, travel time information from PV can be aggregated in two different ways: Link-based or Path-based. In Link-based, travel time information from PV is aggregated at link level and path travel time is assumed as the addition of travel times on the consisting links. In Path-based, travel time information from PV is directly aggregated at path level. Chen and Chien (2001) investigated the short-term prediction accuracy of the two ways when the penetration of PV is relatively low (1%). In their study, the conclusion regarding link-based and path-based prediction is based on the recurrent traffic condition and it is concluded that under recurrent traffic condition, direct measuring of path based travel time rather than link based travel times could generate a more accurate prediction. However, path travel time is OD (origin – destination) specific and in an urban road network there are numerous OD combinations demanded by drivers. Thus, ATMS and ATIS service providers normally collect and disseminate traffic information at link or section level rather than path level (Cheu et al., 2002). Additionally, the path-based method would suffer from low probe observations because it uses only those probes traveling entire paths (Cetin et al., 2005).

Chien and Kuchipudi (2002) proposed a travel time prediction model integrating real-time and historical data. They indicated three limitations of real-time data: higher standard deviation of properties such as link travel time in consecutive time periods, reader information missing, and missing vehicle data in off-peak hours, especially when short time interval like 5 min is chosen. The result shows that in addition to the real-time information the aggregate data of previous time intervals or days as historical seed can improve the prediction accuracy.

Asano et al. (2003) and Oyama et al. (1976) described some statistical properties of link travel time using AVI and manual measurement, respectively. Asano et al. (2003) described that link travel time has two groups: one without intersection delay and the other with intersection delay. Oyama et al. (1976) indicated that there are three types of links: links with one-peak travel time distribution, links with two-peak travel time distribution, and links with multi-peak travel time distribution. Though the descriptions are not based on travel time from PV, it has important implication for PV-based travel time study.

2.4.2 Intersection delay

Intersection delay is a common measure of intersection performance for both design and evaluation. However, the precise definition of delay is not so simple and two definitions, stopped delay and overall delay, are commonly used. Stopped delay is the time during which vehicle is stationary at an intersection approach. Overall delay (sometimes called "total delay") is the difference between the actual time taken to traverse a road segment, which includes an intersection, and the time to traverse the same road segment at the desired cruising speed. The overall delay includes stopped delay as well as deceleration delay and acceleration delay. The stopped delay is easier to measure and the overall delay better reflects the disutility caused by a signalized intersection. Thus the relationship between the above two delay measures is of interest

(Olszewski, 1993).

Mousa (2002) presented a methodology for measuring and analyzing stopped delay as well as acceleration and deceleration delay at an isolated signalized intersection. Vehicles are randomly selected from the vehicles traversing a study filed and crossing times of these vehicles at 12 screen lines are collected and are utilized to estimate vehicle speed and delay components. They found that the average deceleration–acceleration delay is 18.6 s and the stopped delay at the studied site comprises about 50% of the total delay. They noticed that the relationship between delay components found in their study cannot be generalized because the stopped delay—unlike acceleration/deceleration delay—is a function of other parameters related to geometric properties, flow characteristics, and traffic signal settings at the concerned site. They also indicated that deceleration and acceleration lengths of "stopped" vehicles varied over a wide range, as did the deceleration and acceleration rates. They also confirmed the founding of Quiroga and Bullock (1999); that is, significant percentage of total delay takes place while accelerating downstream of the intersection stop line.

Quiroga and Bullock (1999) proposed a methodology to analyze the relationship between delay components using probe vehicle technique. In their study, the time, location, and speed of PVs are tracked every 1 s. To calculate delay components, critical delay points should be detected and they solved this issue using speed and forward and backward acceleration algorithms. They found that the stopped delay versus overall delay relationship is linear and the relationship does not pass through the origin. In other words, a deceleration-acceleration delay value had to be added to the stopped delay term to obtain overall delay and the deceleration-acceleration delay value is relatively constant.

2.4.3 Congestion measurement

Traffic congestion is a critical problem and usually causes time delays, increased fuel consumption, pollution, stress, health hazards, and added vehicle wear (Quiroga, 2000).

Bertini (2006) conducted a survey about metropolitan area congestion for framing congestion measurement. In the survey, transportation professionals and academics are asked four qualitative questions about congestion definition, congestion measurement, reliability of congestion measurement, and changes in congestion. Travel time, speed, volume, LOS and traffic signal cycle failure (meaning that one has to wait through more than one cycle to clear the queue) are mentioned by respondents as primary definitions of congestion; in other words, there is no widely accepted definition of congestion. For congestion measurement, most responses were related to time: delay, speed, travel time and LOS and other measures include volume/capacity, queue length, and density; that is, there are a variety of measures and models to identify congestion and again, there is no widely accepted measure of congestion.

Kuwahara (2003) briefed the phenomenon and the characteristics of traffic congestion and provided useful information to understand the mechanism of traffic congestion.

Quiroga (2000) proposed a congestion management system based on the integration of GIS (Geographic Information System) and GPS technology. Performance measures, data collection method, and data management (including geographic database design, data reduction procedure, and data reporting) are presented in their study. In the paper, travel time is suggested as a robust, easy to understand performance measure and segment speed is used to report the performance.

Taylor et al. (2000) also proposed a comprehensive system design for traffic congestion studies based on the integration of GIS and GPS. A number of parametric measures of congestion including Congestion Index, Proportion Stopped Time, Acceleration Noise, and Queue Length are discussed and the computation of these parameters from the integrated GPS-GIS system is described. The measures can be calculated from a run of PV simultaneously and the use of multiple measures may improve the robustness of the congestion identification.

Horiguchi and Wada (2005) proposed an algorithm to detect congestion using ST+SS sequence that is obtained from PV with SS/ST-based transmission described in 2.3.1. The relationship between ST+SS sequence and congestion was analyzed.

2.5 Research requirements

Traffic conditions evolve over time and thus the information provided to users by ATIS should accurately reflect real-time network traffic conditions and the anticipated traffic conditions at a future time (short-term and long-term).

In probe-based ATIS, real-time network traffic conditions should be estimated reliably by relatively small number of PVs and thus this estimation process is more fundamental issue than the future-state prediction in probe-based ATIS. My research only concentrates on the improvement of the estimation of real-time traffic conditions by small number of PVs and does not consider the prediction issue.

For estimating real-time traffic conditions accurately in probe-based ATIS, the following issues should be considered explicitly.

2.5.1 Indicators of traffic conditions

Vlahogianni et al. (2004) discussed the variables that are considered suitable to describe traffic conditions and listed the literatures that estimate and predict these variables. In these literatures, three fundamental macroscopic traffic parameters (flow, occupancy and speed) are the most commonly used variables in traffic forecasting and traffic flow storage rates (difference between incoming and outcoming flow from a freeway section), density, congestion index, queue length, delay, travel time are also considered as suitable variables. Vlahogianni et al. (2004) point out that predicting travel time is conceptually more useful in ATIS applications than other variables when direct travel time measurement is available.

Probe vehicle data provide direct point-to-point (link or path) travel time measurement and thus in probe-based ATIS, travel time can be chosen as the indicator of traffic conditions and it may be the most suitable indicator than other variables. However, as mentioned in section 2.4.1, probe travel time reports should be aggregated at link level instead of at path level to collect real-time information. Therefore, in probe-based ATIS, *mean link travel time* can be chosen as a representative indicator of traffic conditions rather than mean path travel time.

2.5.2 The definition of population of link travel time

Turning movements at upstream and downstream intersections are usually neglected in practice and the population of link travel time is defined by link travel times of all vehicles traveling a link during a time interval. For a typical link, there are nine distinct subpopulations associated with each combination of access and departure movements (see Figure 2-3) and Hellinga and Fu (1999) showed that these subpopulations have

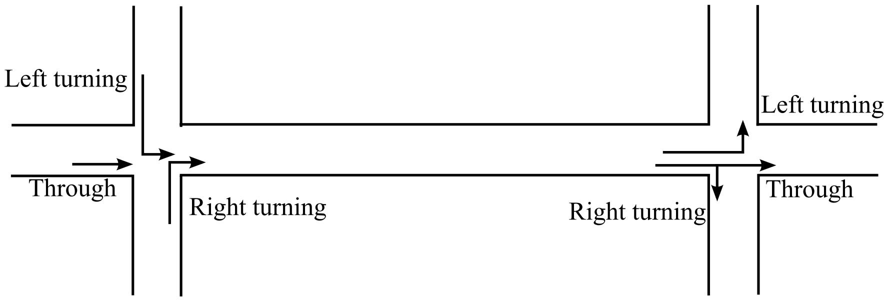

Figure 2-3. Access and departure movements

different travel time characteristics. The existence of the subpopulations causes the large variance of the population and it is difficult to reliably estimate the population mean from small size samples. Further, as shown in section 2.3.3, when estimating section travel time, using the vehicles with different turning movements causes systemic error and the hitting rate even decreases as the penetration of probe increases. In summary, the conventional population definition should be questioned.

An alternative definition of population is to consider the effect of turning movements and to define the population by only the link travel times of the vehicles with through movements at upstream and downstream.

Two criteria will be used to judge the more appropriate definition of population: (1) the availability to describe real-time traffic condition and its evolvement over time and (2) the possibility of the reliable estimation of population mean by small size probe data.

2.5.3 The statistical properties of population and its evolvement over time

For estimating population mean by small size probe travel time reports (sample) accurately, understanding the statistical properties of population and its evolvement over time are necessary. However, population distribution is usually approximated as normal or neglected (see the literatures shown in section 2.2.3).

Even if the population is redefined as the link travel times of the vehicles with through movements at upstream and downstream and time interval is short (e.g., 5 min), there are two groups with different link travel time: one without intersection delay and the other with intersection delay. Asano et al. (2003) and Oyama et al. (1976) also described that link travel time has two or more peaks. Consequently, the approximate normal may be inappropriate and the statistical properties of population and its evolvement should be investigated.

2.5.4 The probe-based estimation method of population mean

Figure 2-4 shows the time-space diagram of all vehicles (population) and probe vehicles (dot line) that enter a link in the same signal cycle at a saturated traffic condition. In this illustration, the population is defined by only the link travel times of the vehicles with through movements at upstream and downstream intersections. For identifying the traffic situation experienced by these vehicles, population mean must be

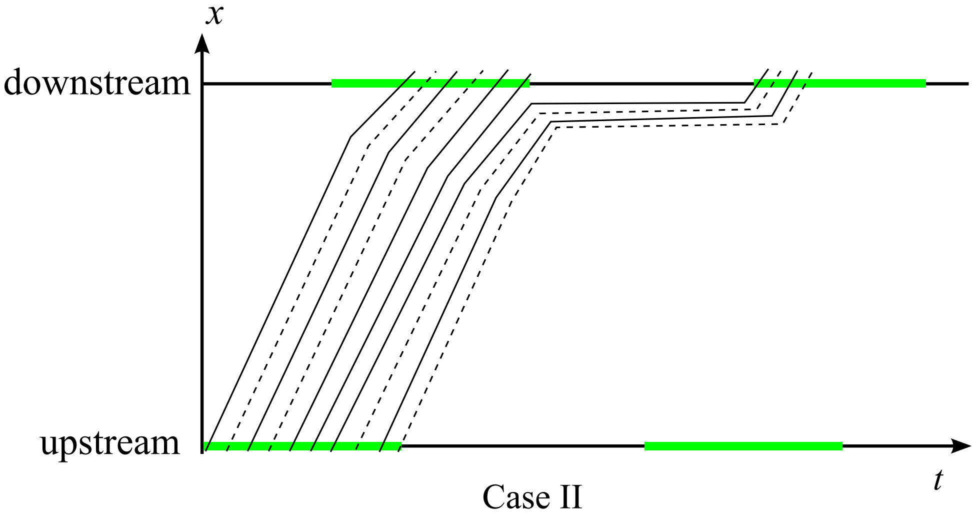

Figure 2-4. The time-space diagram of population and probe vehicles

estimated by probe travel time reports accurately. However, as shown in the figure, there are two groups in the population and the two groups have different link travel time. Further, the proportion of the group without delay in probe data is 50 % and is significantly different from the proportion of the group without delay in the population (60 %). When the proportion of the group without delay (or with delay) in probe data is different from the proportion of the group without delay (or with delay) in the population, sampling error arises and the estimation result is unreliable.

When the population has multi-categories and the sample size is small, it is difficult to avoid sampling error and the estimation of the population mean from the sample mean is unreliable. Traditional solution for this kind of sampling error is increasing the sample size. However, for probe-based estimation, the solution is unavailable in practice: the cost and capacity of the communication between PVs and the operation center impose restrictions on the number of PVs and it is expected that the reliable estimation can be obtained by small number of PVs. Consequently, a new estimation method that can minimize the effect of the sampling error is necessary.

If traffic condition becomes worse, there will be more vehicles that experience delay at downstream intersection in Figure 2-4 and population mean will increase. However, the number of vehicle accesses in a signal cycle (the number of population) is restricted by the capacity of the upstream intersection and will be almost constant. It indicates that the change of traffic condition at saturated situation cannot be identified by flow measured by traditional detector such as loop detector and probe vehicle technique provides a chance to identify the saturated traffic conditions.

Chapter 3

Nagoya Probe Vehicle Demonstration

In this chapter, Nagoya Probe Vehicle Demonstration (NPVD) is introduced and the processing procedure of probe data from the demonstration is described. In the processing procedure, a new map matching algorithm is included.

3.1 Nagoya Probe Vehicle Demonstration

Nagoya Probe Vehicle Demonstration, an urban-wide PV demonstration, was established by Internet ITS Joint-Research Group in Nagoya, Japan, in 2001 (Internet ITS Joint-Research Group, 2002). NPVD is implemented using 1,570 taxis as PVs, which is about one-fifth of all taxis in Nagoya City.

In NPVD, the location (longitude, latitude), time and additional information (e.g., heading direction, speed and in-service tag) of PVs are collected by in-vehicle equipment and are transmitted to the operation center through telecommunication network when pre-defined events occurred.

There are three types of in-vehicle equipment. Type 1 and Type 3 are simple equipment and the location of PV equipped with Type 1 and Type 3 is obtained by GPS only. Type 2 is more complex equipment and the location of PV equipped Type 2 is

Table 3-1. Patterns of Pre-defined Events

Pattern no.			1	2	3	4	5	6
Events	Distance interval	300 m	○	○	○	○		
		100 m					○	
		50 m						○
	Time interval	550 sec				○	○	○
		10 sec		○				
		5 sec			○			
	SS/ST			○	○	○	○	○

obtained from the integration of GPS and the digital map in car navigation system.

The telecommunication cost increases as transmit frequency increases. However, low transmit frequency will inevitably accompany with high map matching error and travel time measurement error. To investigate the relationship of transmit frequency and reliability of PV data, six kinds of PVs are designed, each of which has different pattern of pre-defined events (Table 3-1). There are three types of primary events: distance interval, time interval and SS/ST. The meanings of distance interval and time interval are straightforward. The SS (Short Stop) event is happened when PV speed above 7km/h is maintained for 3 seconds and the ST (Short Trip) event is happened when PV speed below 3km/h is maintained for 3 seconds. The SS/ST events can be used to identify the location and time of starting and stopping of vehicle. Thus the use of SS/ST events has the advantage of catching the changing of vehicle state by using less data transmission than distance interval only or time interval only (Horiguchi, 2002).

Some PV records are shown in Table 3-2. In the table, only the fields used in this paper are presented and each row is a record sent by PV when a pre-event happened.

Table 3-2. Probe Vehicle Data

PV ID	DateTime	Latitude	Longitude	SS	ST	In-Service*
		……				
1005	20021015175315	35.190677	136.898802	0	1	0
1005	20021015175342	35.190681	136.898655	1	0	0
1005	20021015175342	35.190681	136.898655	1	0	1
1005	20021015175432	35.190566	136.895425	1	0	1
1005	20021015175510	35.190994	136.893655	0	1	1
		……				
1005	20021015180515	35.214091	136.886762	0	0	1
1005	20021015180520	35.214130	136.886701	0	1	1
1005	20021015180648	35.214132	136.886693	0	0	0
1005	20021015180709	35.214210	136.886554	1	0	0
		……				

* 1: In-service mode, 0: empty cruising mode

Additional information about the demonstration and the PV data can be found in Miwa and Morikawa (2003), Miwa et al. (2004), Miwa (2005), Internet ITS Joint-Research Group (2002) and Liu (2006).

3.2 Data processing procedure

The procedure includes drawing taxi trips through study link, map matching, and link travel time calculation. Though the map matching algorithm is used for processing historical probe data, it can be used as an on-line map matching algorithm.

3.2.1 Taxi trips through study link

Miwa and Morikawa (2003) compared the PV's speed between in-service mode and empty cruising mode using PV data from NPVD. They found that the speed of the latter mode is lower than that of the former mode. Therefore, only PV reports from in-service mode are used in this study for calculating link travel time. The field in-service (see Table 3-2) is used for judging a taxi trip (from a passenger pick-up to the passenger drop-off) from original PV data and each taxi trip is specified a unique trip ID by combining PV ID and the start time of the taxi trip (e.g., T1005.20021015175342 for the trip shown in Table 3-2).

The map matching procedure described below is extremely time-consuming, thus it is necessary to draw the trips that likely through a study link in a study period from all trips generated during six months. For judging a trip likely though the study link, a relatively loose criterion is used. If there are three or more PV records in a trip away from the study link less than 60m, the trip is accepted.

The PVs with Pattern 1 have no SS/ST event and only transmit the location and time every 300m distance interval (see Table 3-1). From these PV, the stop location and time at an intersection cannot be identified. Under uniform motion assumption (see 3.2.3 Link travel time calculation), the trip made by PV with Pattern 1 inevitably leads unexpected travel time measurement error and these trips are excluded.

3.2.2 Map matching algorithm

For calculating link travel time, an algorithm is needed to reconcile the location of PV obtained from GPS with the DRM. This algorithm is known as map matching and a formal definition of map matching can be found in White et al. (2000). Some algorithms which can be used for relatively short transmit intervals (about 1 second) are reviewed in Quddus et al. (2003) and the algorithms which can be used for relatively long transmit time intervals (about 2~5 minutes) are reviewed in Yang et al. (2005).

The map matching algorithm proposed in this study considers historical information (previous match) and topological information (connectivity information) explicitly, as has been suggested in many literatures.

For matching new PV data P_i, A* algorithm, a path-finding algorithm, is used to identify the route from the current matched node N_{i-1} to the new matched node N_i. A DRM node is called *matched node* of a PV data when the PV data "nears" the node or

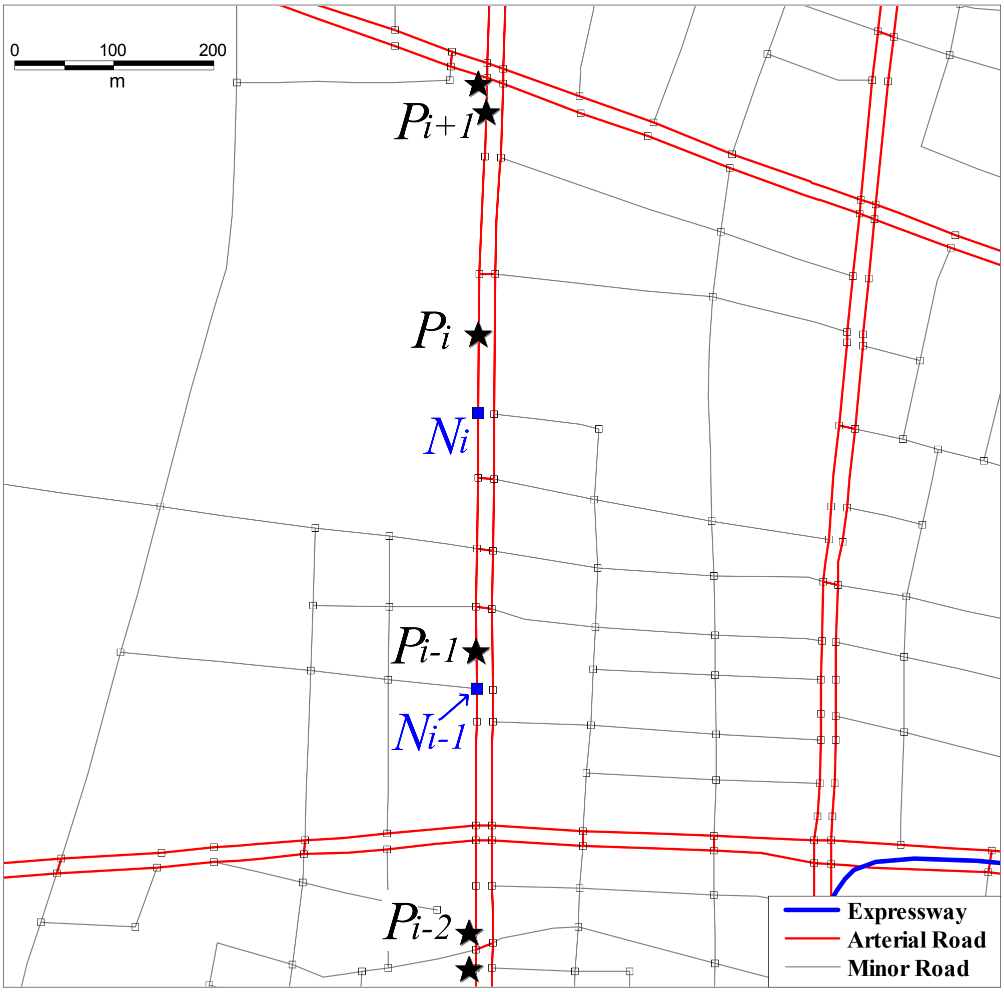

Figure 3-1. Map matching for new PV data *Pi*

“nears” any adjacent links of the node (“nears” is the distance is smaller than a pre-selected distance tolerance, which is 40m in this study). For example, N_i is the matched node of the P_i because the distance between P_i and an adjacent link of N_i is smaller than the pre-selected distance tolerance (Figure 3-1). Using the concept of *matched node*, the algorithm solved the map matching problem at intersection effectively. For A* algorithm please refer to Lester (2005).

Wrong map matching leads unexpected travel time measurement error. However, it is difficult to develop an algorithm that can match all trips perfectly. To guarantee that the trips used to calculate link travel time are matched accurately, a small program is developed within MapInfo environment to assist to check the result of map matching. The program provides the ability to display a trip’s location data, matching result and DRM simultaneously and navigate previous, next and specified trip conveniently. By this program, the wrong matched trips are eliminated.

3.2.3 Link travel time calculation

In this study, only the trips that completely pass through a study link are used for calculating the travel time on the study link. A trip’s travel time along the study link is calculated by subtracting the arrival time from the departure time. There is no knowledge about the speed change between two successive PV records, thus the uniform motion assumption is employed for calculating the arrival time or the departure time. The procedure of link travel time calculation can be found in Miwa et al. (2004).

Chapter 4

Link Travel Time: Qualitative Analysis

Travel time reports are normally aggregated at link level instead of route level to calculate travel time-based measure. Travel time-based measures, such as mean travel time, space-mean speed, and delay, are usually considered as performance indicator[3]. The analysis whether these indicators truly represent performance level[4] is necessary because if the performance indicators do not represent performance level, the effort for estimating these indicators is meaningless. If the performance indicators represent performance levels at some situation, understanding about these indicators at these performance levels is also necessary.

The historical data from NPVD is shown and is used to analysis the properties of link travel time. Traditionally, time interval (e.g., 5min) is the primary concern when aggregating travel time reports at link level and two factors, that are link definition and turning movement, are usually neglected in practice; that is, the links of digital road map (DRM-Links) are directly chosen as spatial aggregation unit *link* and the effect of turning movement is not considered. The major cities in Japan, such as Nagoya, have high-density road network and the digital road maps (DRM) of these cities have

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[3] performance indicator: indicator of traffic conditions

[4] performance level: the level of traffic conditions

accurate and detailed information of the road networks. Though accuracy and detail are desirable features of a DRM, there is an undesirable side effect: DRM-Links are very short and numerous. In this chapter, travel time reports from PVs on two DRM-Links are presented and the problems are indicated, and then Arterial-Link that connects two adjacent main intersections is suggested as *link*.

The traditional traffic detectors cannot observe a vehicle's turning movement at a link's ends. Consequently, turning movement is usually neglected; that is, the population is defined as all vehicles traveling a link during a time interval regardless of turning movement at the link's end (e.g., Cheu et al., 2002; Hellinga and Fu, 2002; Hellinga and Fu, 1999; Srinivasan and Jovanis, 1996). The effect of turning movement on link travel time is analyzed. It is suggested that the subpopulation with through movements at both two ends should be considered first. Unlike traditional detectors, PV records its own trajectory and turning movement at link's ends can be judged.

A qualitative analysis is performed to explain the properties of the link travel time from the historical probe data. In the qualitative analysis, real-time traffic situation is considered and the traffic situation is divided into three phases. By the analysis, whether mean travel time can be used to identify link's performance level is examined and the link travel time distribution is analyzed.

In summary, the effects of the neglected critical factors on aggregating travel time reports are indicated. The properties of link travel time at different performance levels are analyzed and the common senses of performance indicator and travel time distribution are questioned.

4.1 Link definition

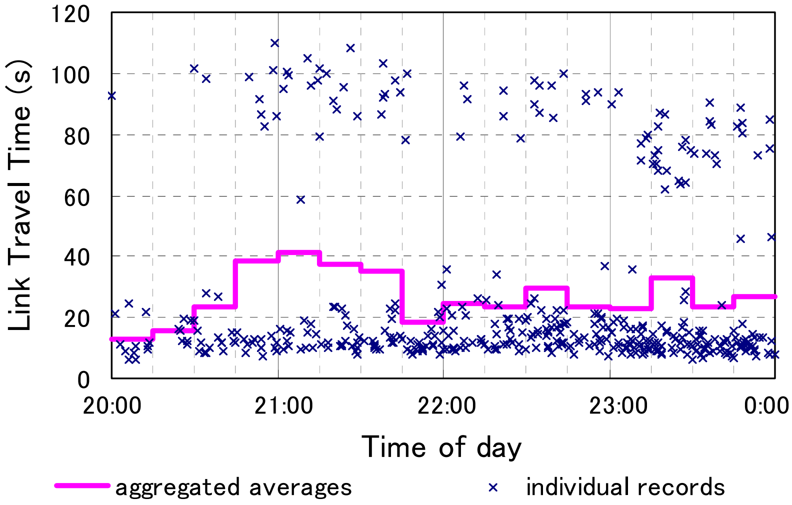
Link travel time is a commonly used term in transportation. However, in practice, it is necessary to define link travel time explicitly for estimating and predicting link performance level.

Miwa et al. (2004) proposed an approach to process travel time reports from NPVD and generate *Link Cost Table* (LCT). LCT is the common idea of travel time data reduction and each cell of LCT is the link cost of each link (mean travel time) in every 5 min interval. In their study, four types of LCT, weekday or holiday and fine weather or wet, are generated and are used in route travel time prediction. In the approach, DRM-Link is chosen as spatial aggregation unit *link*.

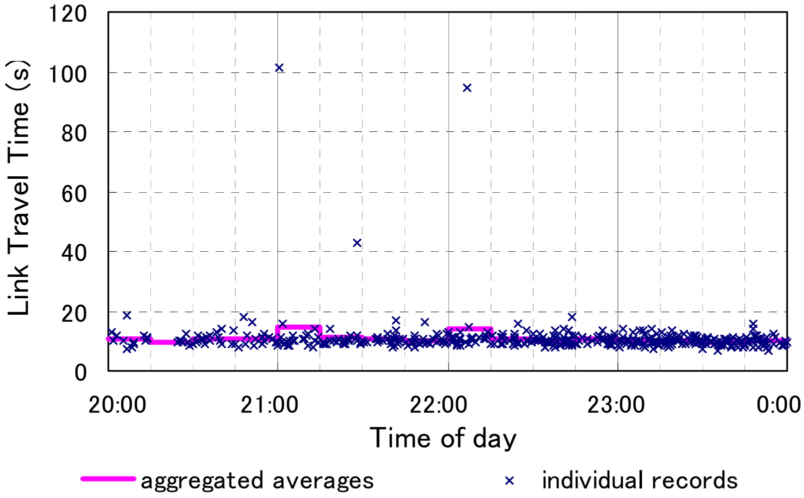
When DRM has detailed information of the road network, using DRM-Link as *link* is convenient and almost trips can be presented by combination of DRM-Links. However, this is not always appropriate, especially for the major cities in Japan. For example, Nagoya has high-density road network, and the DRM of the city, digitized by Japan Digital Road Map Association, has accurate and detailed information of the road network. Though accuracy and detail are desirable features of a DRM, there is an undesirable side effect; that is, the DRM-Links are very short and numerous.

Figure 4-1 shows travel time reports from PVs for upstream DRM-Link of a main intersection in Nagoya and for downstream DRM-Link of the main intersection, which is originally shown in Yamamoto et al. (2006). The data is historical data during four hours on weekdays from October 1st, 2002 to March 31st, 2003 and the averages are calculated using the data in each fifteen-minute. The lengths of the two links are very short, which are 115 m and 129 m, respectively. The travel time reports for upstream link are two-peak distribution and range from 7 s to 110 s, while the reports for downstream link are around 10 s. If mean travel time is used as performance indicator, we will draw a conclusion that the upstream link usually exhibits worse performance than the downstream link. The two links are adjacent and the above conclusion is inappropriate. In summary, it is hardly expected that link performance level can be estimated from the data aggregated at DRM-Link level.

Figure 4-2 shows a portion of the DRM of Nagoya. As shown in the figure, the



Upstream DRM-Link (a)



Downstream DRM-Link (b)

Figure 4-1. DRM-Link travel time reports from PVs

length of DRM-Link is very short and the number of DRM-Link is numerous. However, these DRM-Links belong to different road types (e.g., express way, arterial road and minor road) and the above approach based on DRM-Link ignores these road types completely. In these road types, arterial road is the most important one for drivers and should be focused first. Arterial-Link that connects two adjacent main intersections is fundamental element in arterial road and can be considered as *link*. Choosing Arterial-Link as *link* needs some additional efforts based on the DRM. Each Arterial-Link needs to assign unique id and build connection to adjacent main intersections and DRM Links from which the Arterial-Link is composed. A trip will include some minor links and the combination of only Arterial-Links cannot present the trip. Even though choosing Arterial-Link as link has some limitation, as will be shown, useful information can be obtained from the data aggregated at Arterial-Link.

4.2 Study link

The Basic Road Version of The Japan Digital Road Map Database digitized by Japan Digital Road Map Association (http://www.drm.jp/) is used as the underlying digital map in this study. The DRM contains all expressways, arterial roads and minor roads with more than 5.5m width.

The Arterial-Link from Sakurayama intersection to Gokiso intersection (north bound only) is chosen as study link (see Figure 4-2). The study link has three lanes and the length is about 950m. The study link consists of twelve DRM-Links and there are five signalized intersections on the study link except Sakurayama and Gokiso intersections. Arterial-Link is fundamental element of arterials and the features are important for predicting travel time on the arterials. The green, amber and red time of Sakurayama

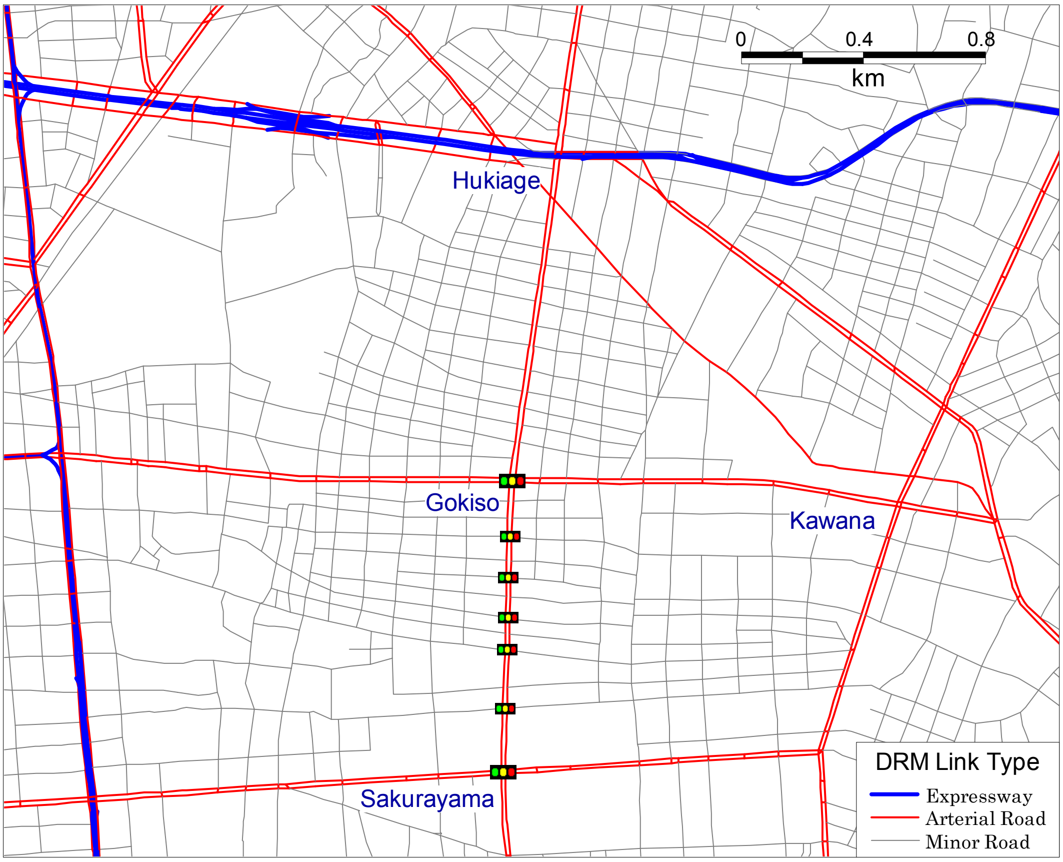


Figure 4-2. Study link and its vicinity

for through movement are 53 s, 3 s and 84 s, respectively, and the Gokiso are 61 s, 4 s and 75 s, respectively. The cycle length of the two intersections is 140 s and the offset time is 123 s. The signal time is an observation of one day.

4.3 Turning movement

The traditional traffic detectors cannot observe a vehicle's turning movement at a link's ends. Consequently, turning movement is usually neglected in practice when aggregating traffic data at link; that is, all vehicles traveling a link during a time interval regardless of turning movement at the link's ends are defined as population.

4.3.1 Aggregation without considering turning movement

In this section, travel time reports on the study link without considering turning movement are presented. The travel time reports are obtained from NPVD during October 2002 to March 2003. Due to lack of sufficient number of PVs, NPVD can not provide sufficient real-time data to study the properties of link travel time and only historical data can be used.

Only travel time reports on Tuesday are used to eliminate day-of-week effects. Figure 4-3 shows the individual reports and mean travel time aggregated by 15-min. As shown in the figure, the morning peak is located about 11:00 and evening peak is located about 16:00. It is different from the observation about traffic condition and thus the mean can not reflect the true traffic condition. Additionally, compared with mean travel time, individual travel time reports have large variation.

There are many causes about the large variability, such as time-of-day and day-to-day. In these causes, turning movement is a commonly accepted but ignored cause.

4.3.2 Effect of turning movement

For simplicity of later discussions, through movement, left turning movement and right turning movement are abbreviated as T, L and R, respectively. Then, vehicle's turning movement at upstream and downstream intersection is presented using two sequent above characters. For example, TL is used to denote through movement at upstream intersection and left turning movement at downstream intersection.

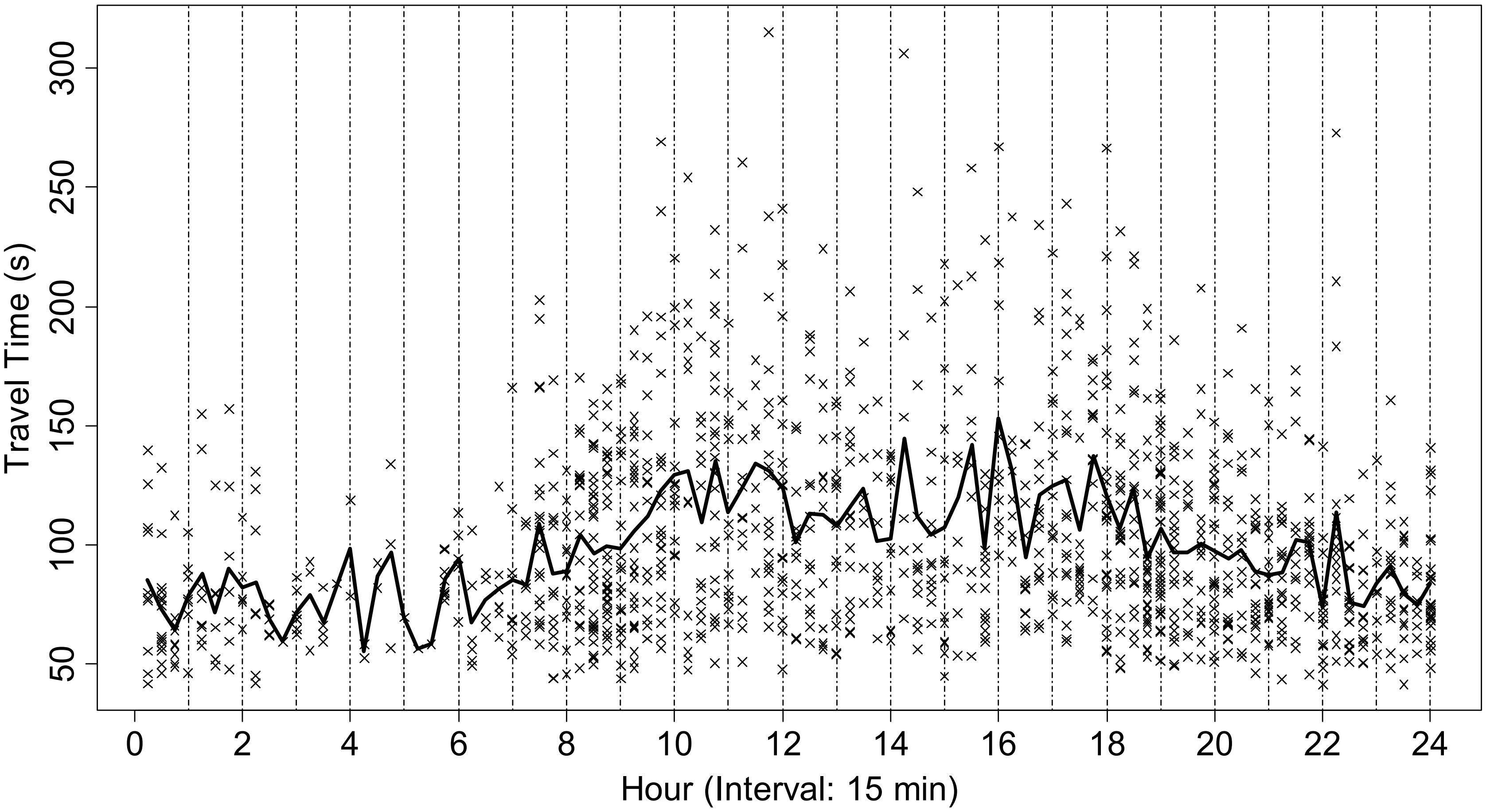


Figure 4-3. Travel time reports without considering turning movement

For a link bounded by a four-leg intersection at the upstream and downstream intersections, there are nine distinct subpopulations and these subpopulations have different travel time characteristics. Hellinga and Fu (1999) investigated the effect of turning movement on travel time using simulated data and showed that the mean 5-min travel times from a subpopulation is consistently different with the mean 5-min travel times from all vehicles. However, in their study, the population is still defined regardless of turning movement, and they indicate that travel time from PV will lead to sampling bias when the proportion of PV varies across these nine subpopulations.

Figure 4-4 presents travel times from five different turning movement patterns, TT, LT, RT, TL and TR. TL and TR have the same arrival movement as TT, and LT and RT have the same departure movement as TT. An Arterial-Link, from Sakurayama intersection to Gokiso intersection (north bound only) is chosen as *link* and travel time reports on the link from October 2002 to March 2003 are used (see Figure 4-2). In Figure 4-4, the box enclosing the middle 50% of the distribution and the bold line across the middle identifies the median sample value. The numbers that are surrounded by brackets on the x-axis show the sample sizes. As shown in the figure, LT has the largest median value, which is larger than TT by 32 s in peak hour and 34 s in off-peak hour, respectively. It is noted that intersection delay at upstream intersection subject to left turning is not included in the study link travel time reported by PV with LT. RT, TL and TR also have larger median value than TT, which are range from 3 s to 21 s in peak hour and from 9s to 12 s in off-peak hour. In summary, the subpopulations with different movement patterns have different travel time distributions. In other words, except time of day and day of week, turning movement is also a critical source of variability in link travel time.

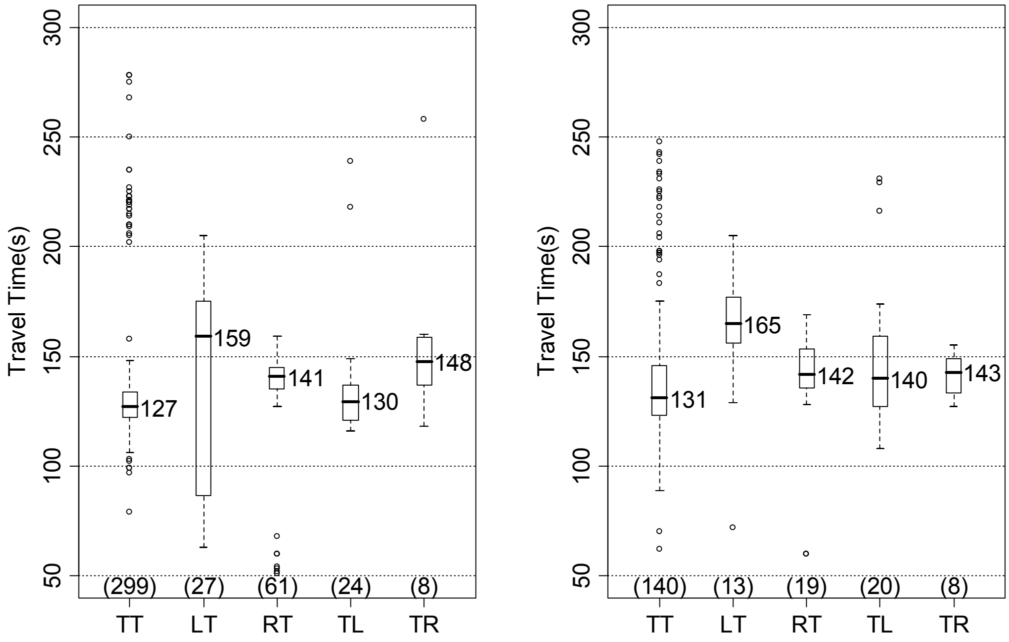


Figure 4-4. The effect of turning movement on travel time 8:00~9:00 am (left) and 10:00~11:00 am (right)

Unlike traditional detectors, PV records its own trajectory and thus gives researchers opportunity to judge the turning movement at the ends of a link. Therefore, in my opinion, the subpopulation with TT should be considered first. The reasons are (1) an ATIS should provide information for individual drivers who travel a link by one of these subpopulations, (2) the subpopulation with TT is dominant in these subpopulations for most links, and (3) left or right turning movements are usually limited in a trip.

4.4 Aggregation on study link with TT

In this section, travel time reports on the study link with TT are presented. The travel time reports are obtained during October 2002 to March 2003. Historical data is used instead of real-time data. However, some useful conclusions are made from historical data. Though several studies have demonstrated the use of PV in travel time study, due to the constraint that the data is generated by short-term field experiment or simulation, no previous studies have presented the properties of travel time reports from long-term PV demonstration on signalized urban link.

The one hour periods 8:00~9:00 am and 10:00~11:00 am on weekdays are chosen for comparing the difference of the statistical properties between peak and off-peak hours; That is, the trips generated on weekends are excluded and the weekdays is not separated further.

After the procedures described in Chapter 3, the dataset includes 440 trips which completely pass through the study link and arrive at the study link in 8:00~9:00 am and 10:00~11:00 am on weekdays. In these trips, there is only one trip that exhibits extremely long travel time, which is 585 sec. In contrast to this, all other trips' travel times are less than 300 sec. Therefore, the trip is considered as abnormal data and is eliminated.

The travel time reports from TT in peak (8:00 ~ 9:00 am) and off-peak (10:00 ~ 11:00 am) are shown using histogram and the travel time reports from other turning patterns are shown using small vertical lines on the x-axis in Figure 4-5 and the summary are shown in Table 4-1. As shown in the figure, the travel time from TT is two-peak distribution. The data from other turning patterns tend to bury the gap between two peaks in the histogram and shift to smaller value. Consequently, if travel times are aggregated regardless of turning movement, normal or lognormal distribution will be concluded. The subpopulations with different turning patterns are not homogeneous, as mentioned earlier, and these one-peak distributions, which are commonly accepted, are not appropriate in my opinion.

Table 4-1. Summary of travel times on study link with TT

Group	Item	8:00~9:00	10:00~11:00
All	sample size	299	140
	mean	135 s	143 s
First peak	sample size	271 (91%)	115 (82%)
	mean	126 s	128 s
Second peak	sample size	24 (8%)	25 (18%)
	mean	220 s	214 s

As shown in Table 4-1, mean travel time is larger in off-peak time period than in peak time period. If mean travel time is chosen as performance indicator, we will draw a conclusion that the study link usually exhibits worse performance in off-peak than peak. However, in off-peak, there will be fewer vehicles that access the study link and the conclusion is improper.

4.5 Qualitative analysis

4.5.1 Three phases

One signal cycle, which is the shortest time interval in aggregating real-time traffic data, is chosen as temporal aggregation unit in this section. Then, a queue of vehicles that access a link in a signal cycle and have turning movement TT is considered as a whole and the travel times of these vehicles are considered as a population.

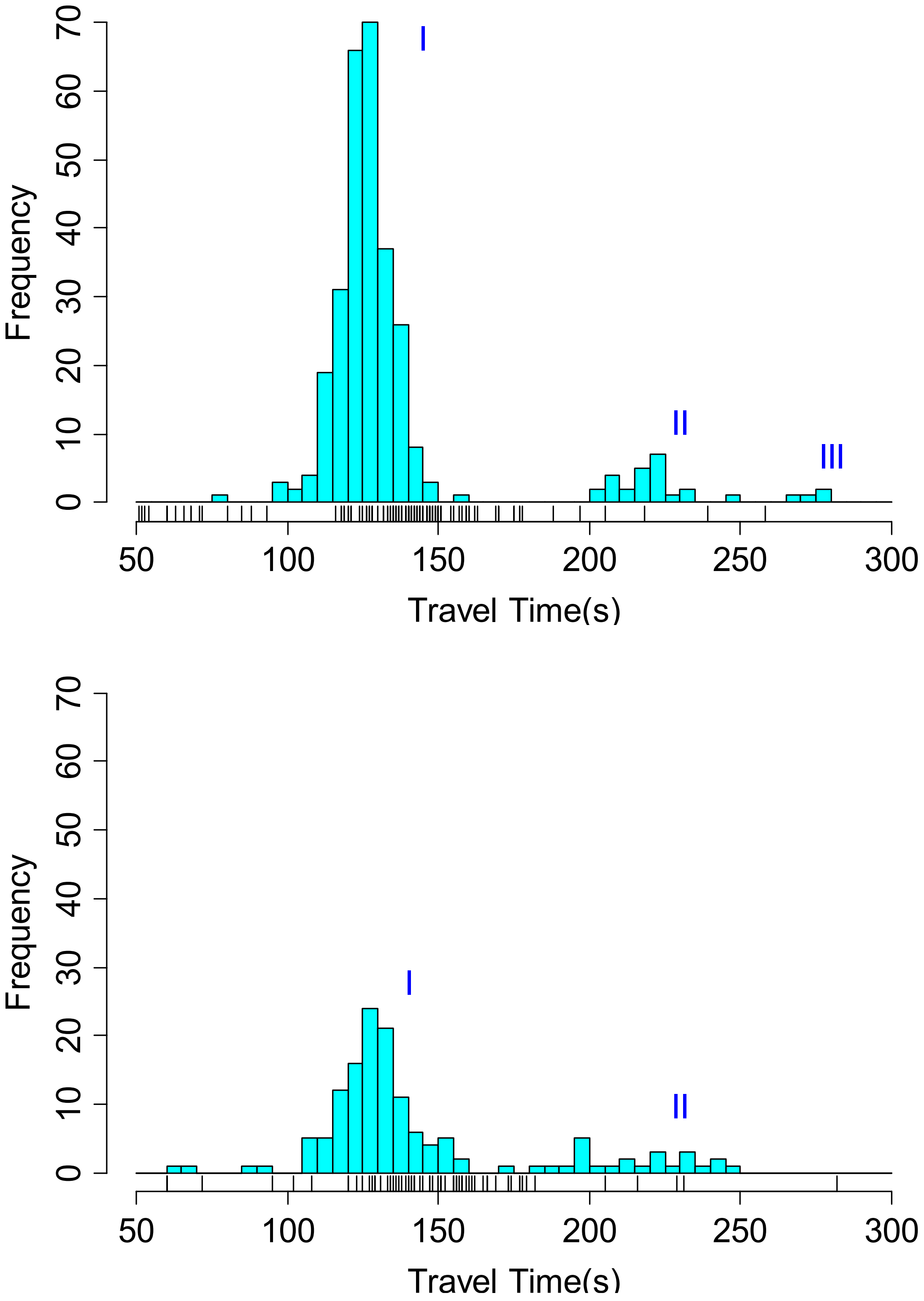
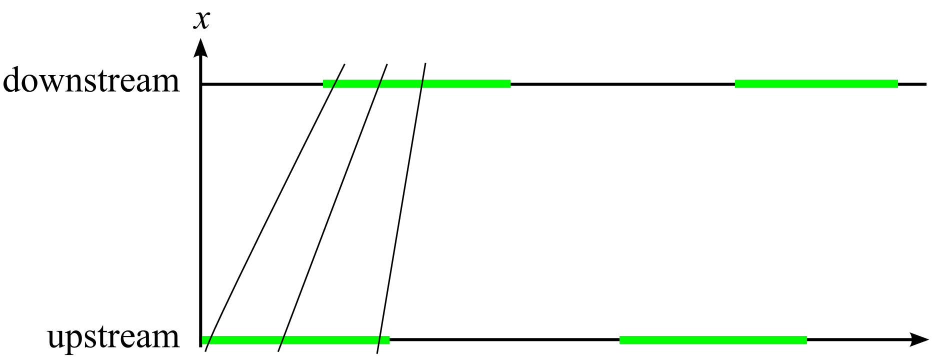
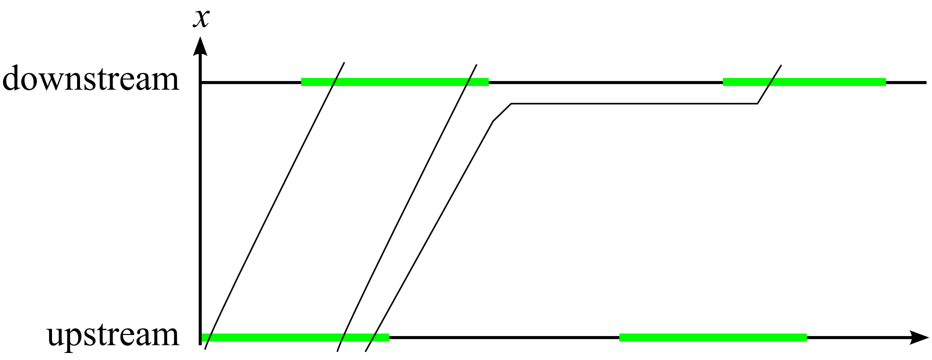


Figure 4-5. Histograms of Travel Times on Study Link with TT for 8:00~9:00 am (Top) and 10:00~11:00 am (Bottom)



Case I



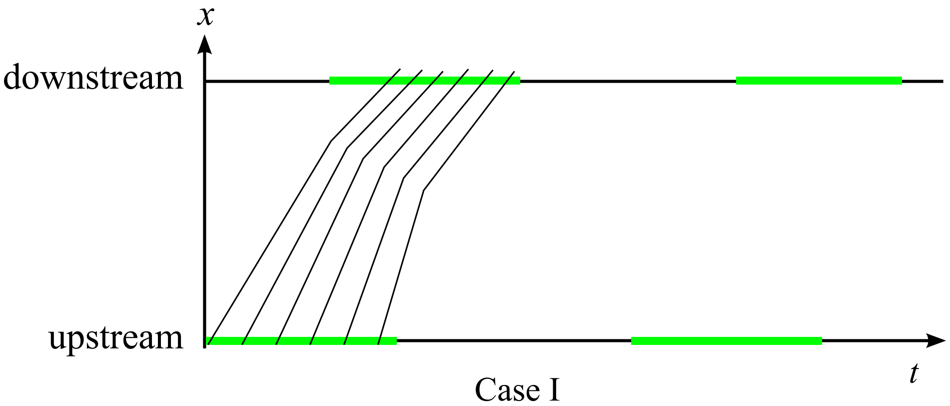
Case II

Figure 4-6. The queue in Phase I

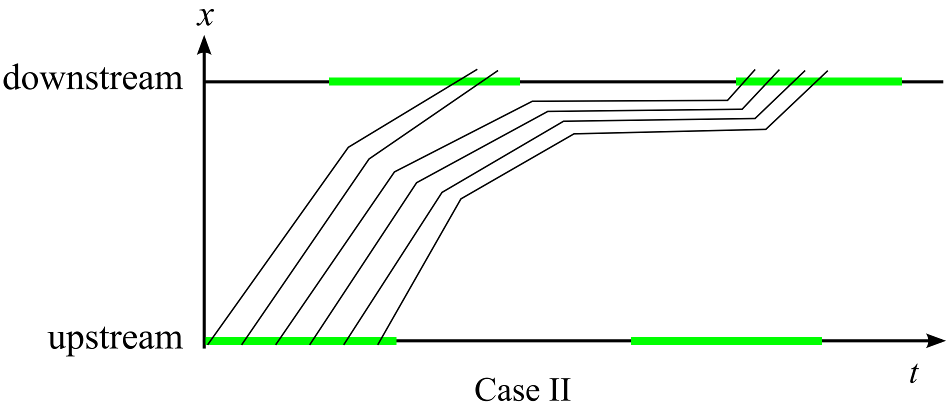
When the performance level of the link changes over time, the situation of the vehicles will also change and will reflect the performance level experienced by these vehicles. The situations of the vehicles are divided into three phases roughly and the characteristics of these phases are described in the sense of the number of accesses, spot speed at upstream and mean travel time below.

Phase I is when demand is lower than 90 % of the capacity at upstream intersection, which is the prevailing situation in off-peak time period and is usually called "undersaturated condition". Figure 4-6 shows two cases of the queue of vehicles in the phase. The figure is a time-space diagram of all vehicles that access a link in same signal cycle and color bars at upstream and downstream intersection present the green period of traffic signal. In Phase I, the vehicles will spread in green period irregularly and the population will be one-peak (Case I) or two-peak (Case II). The second peak in Case II is happened due to some vehicles will experience intersection delay at downstream. The Case II will happen randomly over signal cycles and the proportion of the second peak may also vary largely over signal cycles when Case II happened. Consequently, mean travel time will have large variance over signal cycles. In Phase I, the number of accesses will be smaller than the capacity and the spot speed at upstream will be fast.

When demand exceeds 90 % of the capacity at upstream intersection, it is reasonable to assume that the vehicles with through movement will access a link with uniform over green period and the number of the vehicles that is restricted by the length of



Case I



Case II

Figure 4-7. The queue in Phase II

green will be stable, which is referred to Phase II and is the prevailing situation in peak time period. If we further assume that the vehicles with TT also access the link with uniform and the number of vehicles with TT is stable, the vehicles can be illustrated as Figure 4-7. The vehicles with TT will depart the link with Case I or Case II. However, the Case I can be considered as a special case of Case II; the proportion of the first peak (*p*) is 100 %. When a queue of vehicles with TT access the link, there are vehicles with TL/TR among the queue and the vehicles with TL/TR will queue on left/right turning lane when the queue arrives downstream. That is, the vehicles with TT will make a new queue at downstream in which there are only the vehicles with TT, and thus the length of the queue with TT at downstream will become shorter than the length at upstream. The reduction of the distance between two vehicles in the figure is presented the phenomenon. Further, Case I in the figure shows the worst case of p = 100 %; that is the queue in downstream can shift left side when there are no vehicles that accessed the link in previous signal cycle and the situation become better. In Phase II, mean travel time, and p are essentially equivalent if signal is constant. As p decreases, the mean travel time will increase. Additionally, mean travel time (or p) will have some trend such as increase, decrease or keep over signal cycles in some time period (e.g., morning). In Phase II, the number of accesses will be stable at the capacity and the spot speed at upstream will be still fast.

When mean travel time (or p) reaches a critical value in Phase II, the accesses of the vehicles will be affected by the vehicles queued on the link and the number of accesses will reduce and the speed at upstream will slow down, which is referred to Phase III and is the prevailing situation in peak time period for congestion links. When Phase III happened on a link, the upstream link will also be affected and the congestion will extend towards the upstream.

By the way, Phase II and Phase III are usually called “saturated” or “oversaturated condition”. It depends on whether the number of vehicles with TT, LT and RT is equal to or exceeds the capacity for through movement at downstream intersection.

4.5.2 Indicators for Identification

In Phase I, mean travel time has large variance over signal cycles and thus it is possible that mean travel time in Phase I exceeds mean travel time in Phase II. The proportion of the second peak is larger in Case II of Phase I (Figure 4-6) than in Case I and Case II of Phase II (Figure 4-7) and thus mean travel time in the former is larger than in the latter. Indeed, the uniform assumption doesn’t hold in Phase I and mean travel time has no comparability between Phase I and Phase II. Instead of mean travel time, the number of accesses may be a good indicator to distinguish Phase I and Phase II. In a word, mean travel time cannot be used to identify whether a queue of vehicles belong to Phase I or Phase II consistently.

Phase III is undesirable situation and avoiding is more desirable than identifying. Identifying the increase of mean travel time in Phase II and decreasing the number of accesses before mean travel time reaches the critical value by taking some action such as reducing the green length of upstream intersection is a possible approach for avoiding Phase III. For this, dividing Phase II into several sub-phases and identifying these sub-phases is necessary. However, the critical value of mean travel time (or p) is link-specific, which will be affected by the geometric properties of the link, such as link length and lane number, and traffic signal. Fortunately, the values are not affected by dynamic fluctuation of flow or demand.

Phase I and Phase II can be further divided into several sub-phases for that each sub-phase reflects one performance level. Due to the large variance of the mean travel time in Phase I, the number of accesses is better indicator for dividing the Phase I than the mean travel time.

In Phase II, the increase of mean travel time means that the performance level goes down. Therefore, the mean travel time can be an indicator for dividing Phase II. However, as shown in Case II in Figure 4, travel time distribution at a performance level in Phase II is two-peak distribution. Two-peak distribution makes probe-based mean travel time estimation very difficult. A set of travel time reports from PVs is a sample from the population and sample size is relatively small. Obviously, it is difficult to estimate population mean using relatively small size sample in two-peak distribution. The relation between sample size and estimation accuracy will be discussed detail in Chapter 6.

Table 4-2 summarizes the characteristics of three phases and the indicators for identification.

Table 4-2. Summary of three phases

Phase	Prevailing Situation	No. of Accesses	Spot Speed	Mean Travel Time	Indicator
I	off-peak	< capacity	high	large variance	no. of accesses spot speed
II	peak for non-congestion link	= capacity uniform	high	trend two-peak	mean travel time
III	peak for congestion link	< capacity	low	--	avoiding by identifying Phase II

4.6 Summary of this chapter

In practice, when aggregating travel time reports at link level, DRM-Link is usually chosen as *link* and turning movement is always neglected. Negative effects of the common approach are presented and the reasons why these two factors should not be neglected are provided.

The statistical properties of link travel time by historical data from long-term probe vehicle demonstration are shown. An Arterial-Link is chosen as *link* and only travel time reports from the probe vehicles with TT is considered. It shows that travel time is multi-peak distribution and mean travel time is larger in off-peak time period than in peak time period.

In qualitative analysis, a queue of vehicles that access an Arterial-Link in a signal cycle and have turning movement TT is considered as a population. The situations of the population over signal cycles are divided into three phases and the characteristics of the three phases are analyzed. The analysis shows that travel time distribution is two-peak rather than asymptotically normal. Despite this is not preferable result, it is consistent with the above observation and the widely accepted belief that link travel times belong to at least two different groups: one without delay at downstream intersection and the others with the delay. The analysis also shows that mean travel time is not a good indicator to identify the three phases consistently. It also confirms the above observation.

Chapter 5

Link Travel Time: Simulation Analysis

5.1 Simulation description

To verify the qualitative analysis proposed in the previous section, a simple network is modeled using VISSIM - a microscopic traffic simulation model by PTV AG (http://www.english.ptv.de/). The imaginary time period is morning and the imaginary network is a corridor towards city center.

The network is illustrated in Figure 5-1. Each intersection is controlled by a two-phase fixed-time signal with a cycle length of 140 s. The offset time of two consequent intersections is 30 s. The signal scheme is shown in Figure 5-1. Turning rate at each intersection is also shown in the figure.

The network is simulated for 3 h with time varying demands. Vehicles are generated at origin zones (1~12, see Figure 5-1) with Poisson distribution. Table 5-1 shows the base vehicle inputs of each zone and the temporal variation.

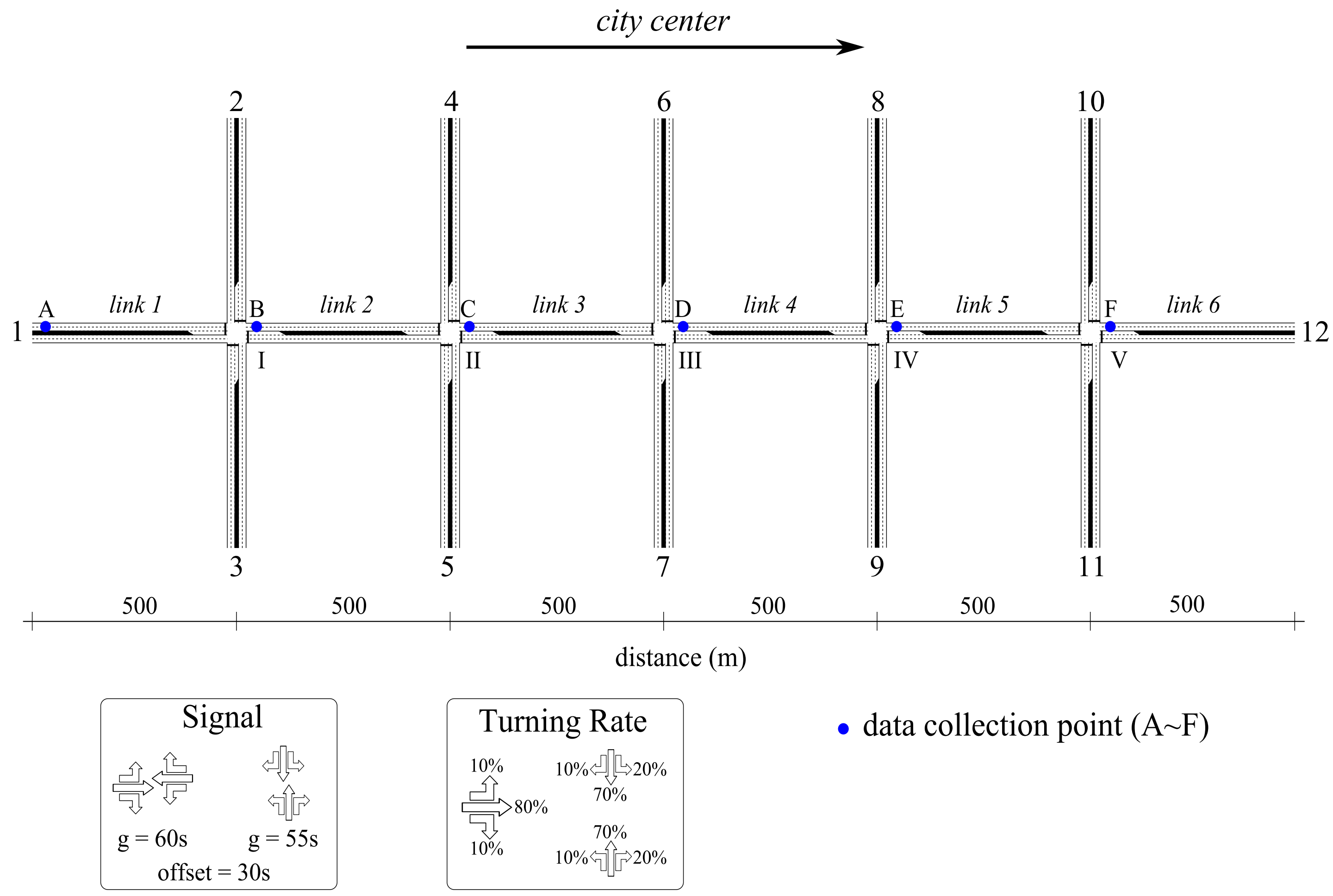


Figure 5-1. Simulation network

Table 5-1. Vehicle inputs

Base Vehicle Inputs (Veh/h)		Temporal Variation	
Origin Zone	Vehicle Inputs	Time (s)	Proportion of Base Vehicle Inputs
1	1000	0 ~ 900	0.1
2~11	800	900 ~ 1800	0.2
12	500	1800 ~ 2700	0.5
		2700 ~ 3600	1
		3600 ~ 4500	1.2
		4500 ~ 6300	1.5
		6300 ~ 7200	1
		7200 ~ 8100	0.8
		8100 ~ 10800	0.5

In the network, only the links from link 2 to link 5 are interested. Figure 5-1 shows the data collection points (A ~ F), which are located at the reference points of the entrance and exit of link. When a vehicle pass through any data collection points, the vehicle ID, pass time, and spot speed of the vehicle are collected and recorded into a log file. Then, the number of accesses (only through movement), mean spot speed at upstream (only through movement), and mean travel time (only TT) of the interested links are aggregated in every signal cycle using the log file.

5.2 Simulation result

Figure 5-2 shows the aggregated result. The number of accesses (only through movement), mean spot speed at upstream (only through movement, unit: m/s), and mean travel time (only TT) in each signal cycle are illustrated by three solid lines. The figure also shows the individual travel time reports (×) and the temporal variation of vehicle inputs (dot line).

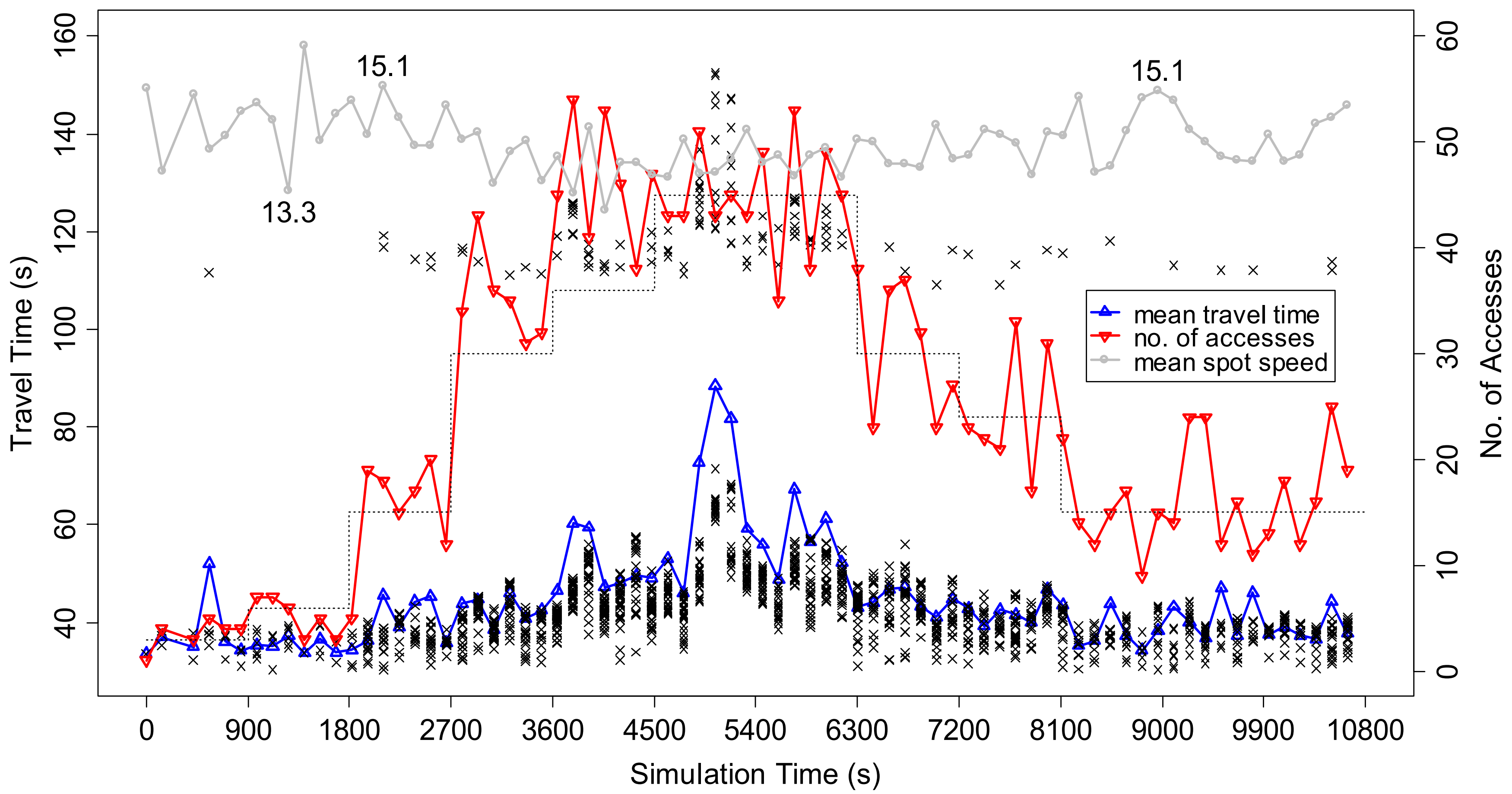


Figure 5-2(a). Illustration of simulation result (link 2)

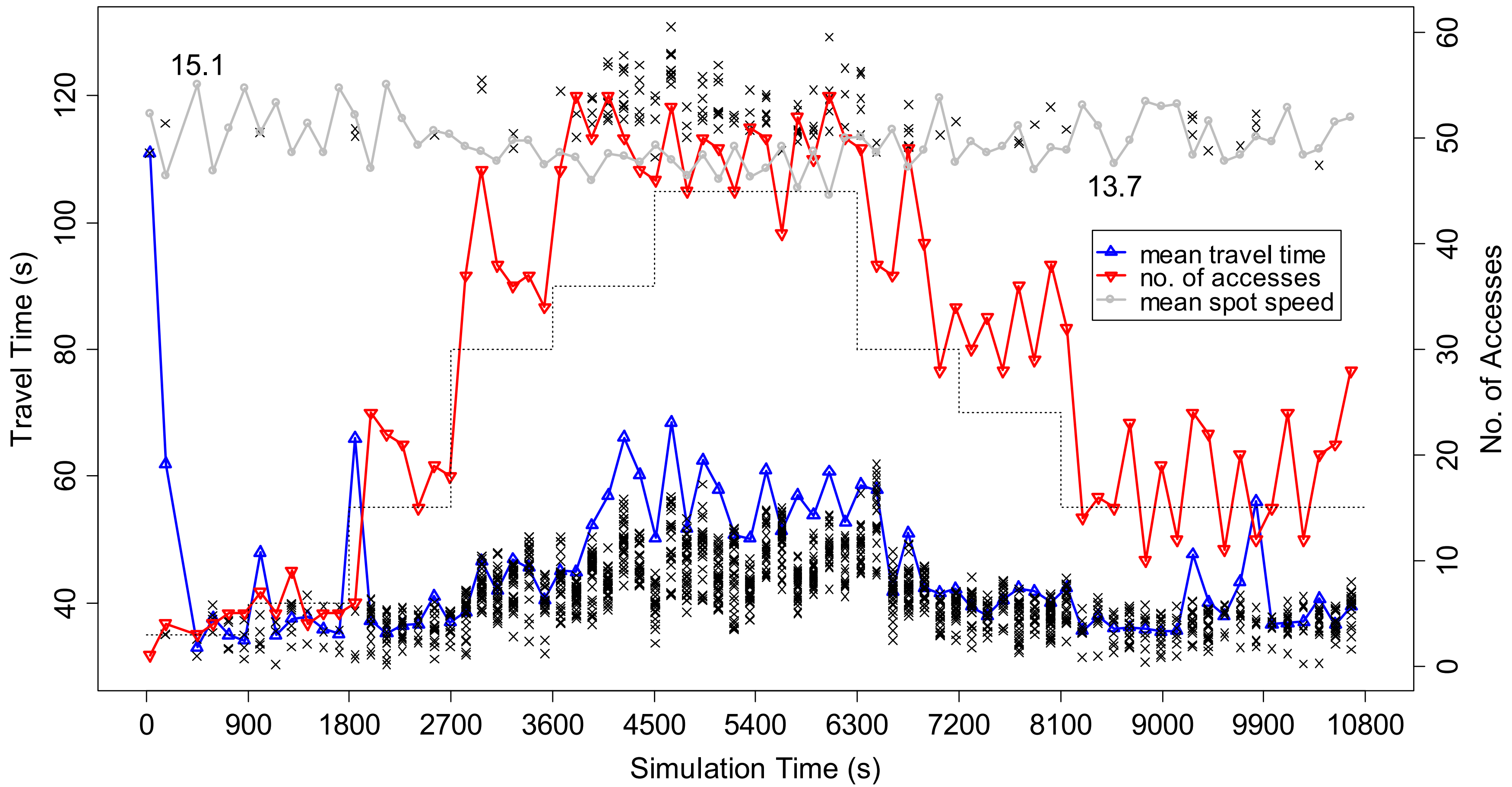


Figure 5-2(b). Illustration of simulation result (link 3)

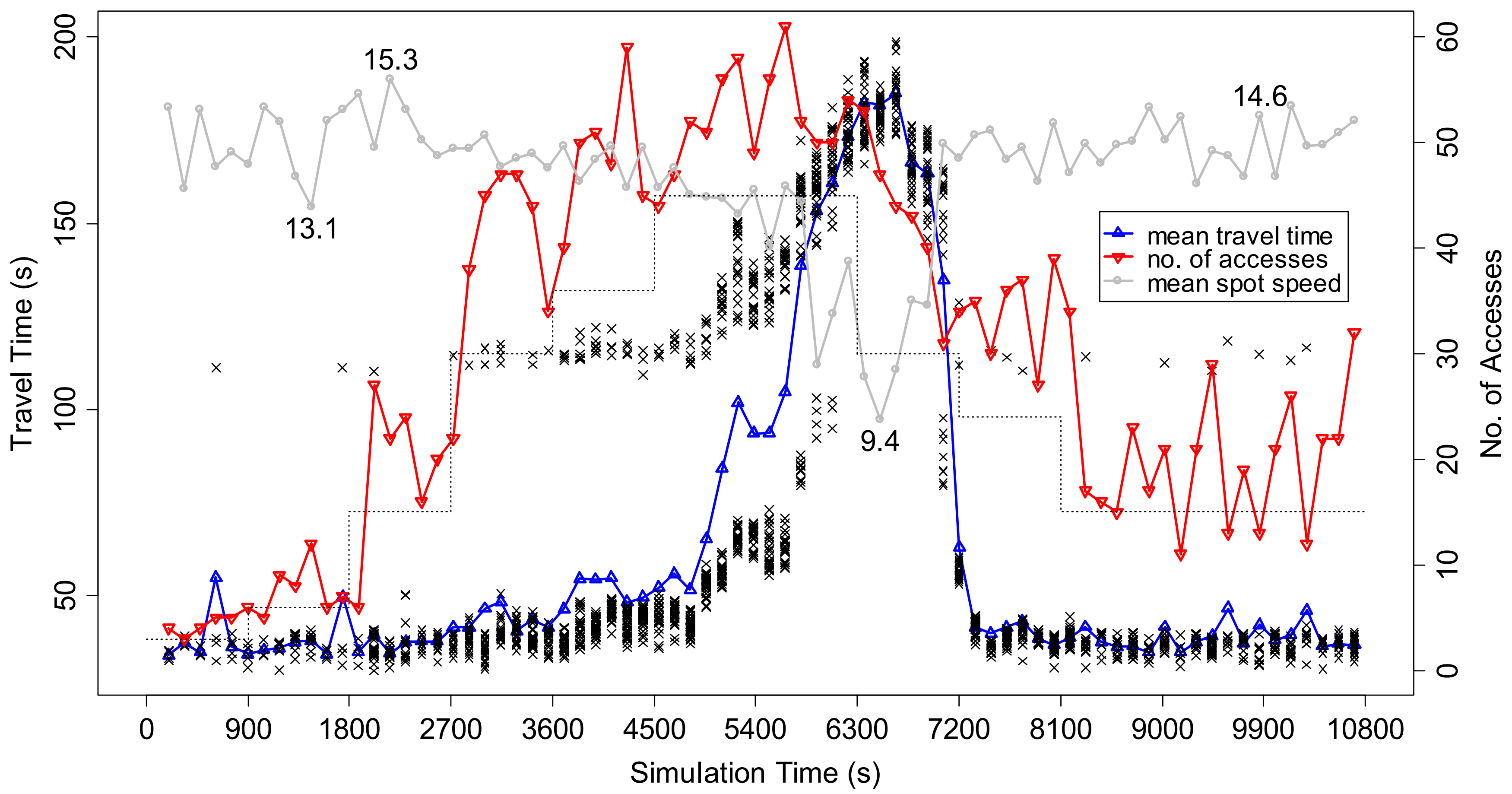


Figure 5-2 (c). Illustration of simulation result (link 4)

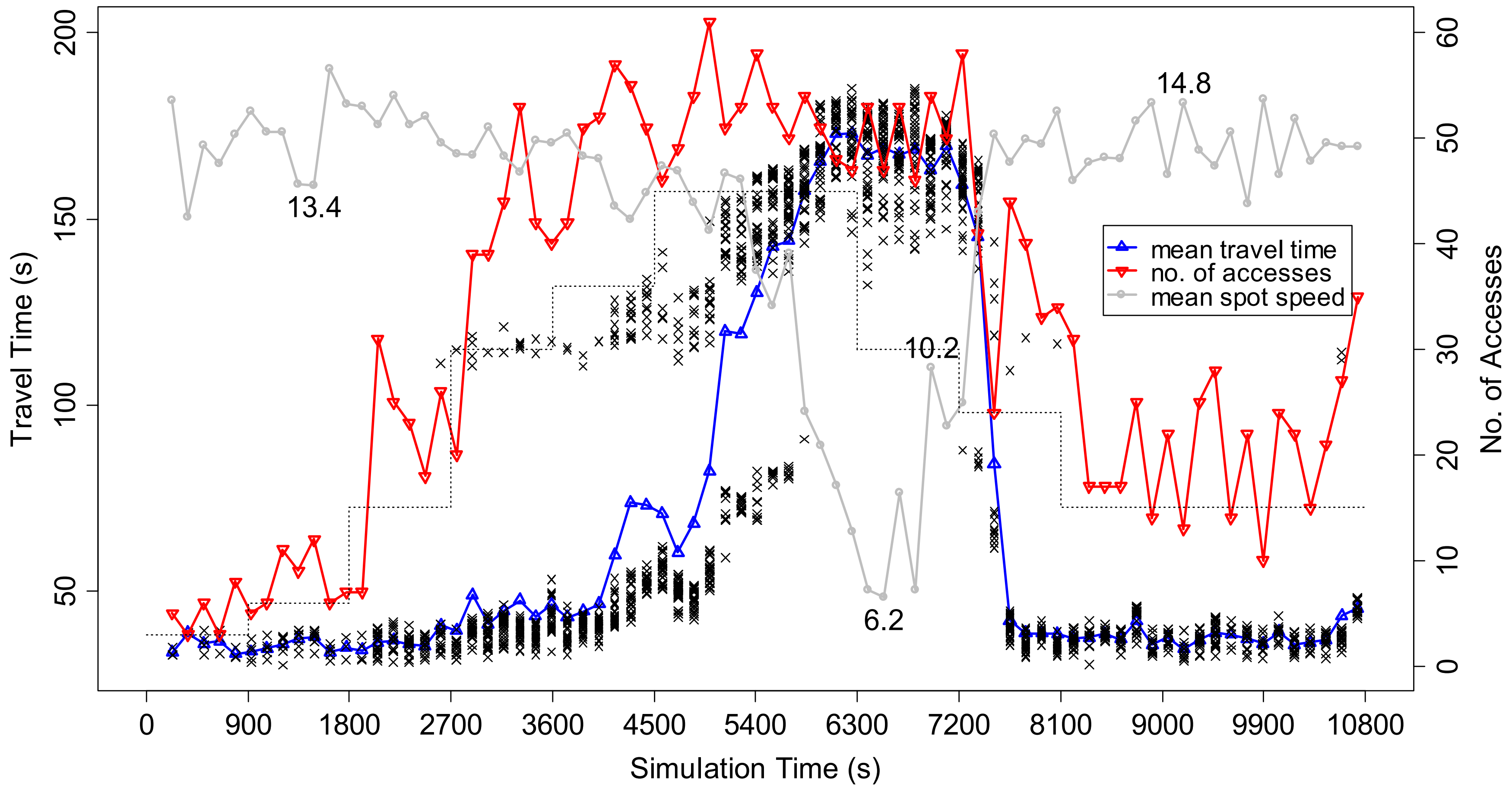


Figure 5-2 (d). Illustration of simulation result (link 5)

Each intersection in the simulation network has same geometric properties and thus the capacity of each intersection should be identical. From Figure 5-2d, it can be concluded that the capacity is about 55 vehicle/cycle.

As shown in Figure 5-2, when the number of accesses is lower than the capacity of upstream intersection, mean travel time on link 3 exhibits large variation while mean travel times on other links are relatively stable. That is, though the probability of Case II in Phase I is small, it still happened. In this simulation, the offset time of two consequent intersections is set as 30 s and the length of the links is 500 m. Thus, when a vehicle's speed exceeds 16.7 m/s (60 km/h), it is possible that the vehicle will pass through a link within 30 s and does not stop at the downstream intersection of the link even if it through the upstream intersection of the link in the end of the green period or in the amber period. However, when the offset time is set smaller than 30s, for example 20 s, the vehicle will stop at the downstream intersection, and the probability of Case II in Phase I will increase and mean travel time will exhibit more variation. More importantly, mean travel time at all links cannot trace the change of the number of accesses in Phase I. That is, in Phase I, mean travel time is not a good indicator of link performance and the number of accesses should be used for tracing the change of link performance.

At about 5400 s on link 4 and link 5, the spot speed start to decrease. The decrease of the spot speed at upstream of a link will increase air pollution and it can be considered as undesirable situation. At same time, as shown in Figure 5-2d, the number of the accesses is not reduced obviously. Choosing the spot speed or the number of accesses as the criterion of the undesirable situation should be determined based on the researchers' judgment. At this phase, mean travel time is obviously larger than other phase and the distribution of travel time tends to one peak. Therefore, it is easy to identify the phase using small size PV reports. However, as mentioned earlier, the phase is undesirable situation and should be avoided.

To avoid the above phase, it is important to identify the previous phase (Phase II) of the above phase. As shown in Figure 5-2c and Figure 5-2d, in Phase II, mean travel time increases gradually. In this phase, there are two sets in travel time reports: one without intersection delay and with intersection delay. The proportion of the set with delay increases and the means of the two sets also increase over time. It causes the increase of mean travel time. Using small size PV reports, it is hardly expected that the proportion of the set with delay (or without delay) can be estimated. However, the variance of each set is relatively small and the means of the two sets can be estimated by small size sample. This is the key idea of the estimation method proposed in Chapter 7.

5.3 Summary of this chapter

In this chapter, the microscopic traffic simulation model VISSIM is used to confirm the qualitative analysis proposed in the previous section.

The number of accesses, mean spot speed at upstream (only through movement, unit: m/s), and mean travel time (only TT) in each signal cycle are aggregated rather than mean travel time only. The aggregation shows that (1) in Phase I, mean travel time is not a good indicator of link performance and the number of accesses should be used for tracing the change of link performance, and (2) in Phase II, though mean travel time can trace the link performance, individual travel time reports show that the link travel time distribution is two-peak, which makes the estimation of mean travel time by small size travel time reports from PVs difficult.

Chapter 6

Applicability of the Formulations of the Adequate Number

The success of probe-based ATIS highly depends on the reliability of probe reports, and the cost and capacity of the communication between PVs and the operation center impose restrictions on the number of PVs. Therefore, it is impossible to make all vehicles as PVs. In other words, a set of travel time reports from PVs on a link in a time interval is a sample. The adequate sample size required to estimate mean travel time of all vehicles (population) reliably has been an imperative issue since probe vehicle was recognized as a method to collect traffic information and there are many literatures, for example Boyce et al. (1991), Chen and Chien (2000), Cheu et al. (2002), Hellinga and Fu (1999), Quiroga and Bullock (1998) and Srinivasan and Jovanis (1996).

Two methods *standard deviation formulation* and *confidence interval method* are commonly accepted, and were used as the reliability criterion. It should be noted that these formulations are based on Central Limit Theorem; that is, the result is doubtful when the population is severely nonnormal and sample size is small. This chapter will examine the applicability of the two methods on a signalized link.

6.1 Sample size formulations

A number of researchers have investigated the adequate number of PVs at network level and at link level. At link level, two methods *standard deviation formulation* (Eq. 1) and *confidence interval method* (Eq.2) were proposed and are commonly accepted, and were also used as the reliability criterion for each links in network level studies. In the two methods, the former is used for links with normal distribution and the latter is used for links without normal distribution.

$$n \geq \left(\frac{t_{\alpha/2,n-1} s}{\varepsilon} \right)^2 \tag{1}$$

$$\bar{x} - t_{\alpha/2,n-1} s / \sqrt{n} \leq \mu \leq \bar{x} + t_{\alpha/2,n-1} s / \sqrt{n} \tag{2}$$

6.2 Assumption of travel time distribution

Obviously, the percentage of Set I in the queue, abbreviated as *p*, is a critical factor that affects the average travel time of the vehicles in the queue (Figure 4-7). Thus *p* is considered as a performance indicator in this chapter, and travel time distribution at a certain performance level (*p* = 75% is chosen just as an example) is inferred based on Figure 4-7 and historical data described in section 4.4. In the figure, it is assumed that the vehicles spread during green period with uniform. In reality, the situation is more complex than the illustration in the figure. There are some vehicles with other turning movements and some vehicles partly through the link in the queue. However, the effects of these vehicles are ignored.

For p = 75%, the distribution can be approximated as a composite of two normal distribution and the mean and standard deviation of Set I and II can be determined from the historical data.

The means of Group I and II in historical data are considered as the means of Set I and Set II in real-time data at p = 90 %. Under uniform assumption, when p decreases Δp, the mean of Set I and Set II will increase $\Delta p \times G$ (G is length of green time). Consequently, the mean of Set I and Set II at p = 75 % can be calculated by adding 15% × G to the mean of Set I and Set II at p = 90 %, respectively. In this section, G is set as 60 s.

Unlike historical data, the day-to-day variation is not included in real-time data and it is reasonable to consider that the variation of each set in real-time is smaller than the variation in historical data. Additionally, the adequate sample size is a function of the standard deviation of link travel time, and the standard deviation is mainly contributed by the fact that there are two sets simultaneously but rarely contributed by the variation in each set. Thus, the standard deviations of all sets at p = 75 % are specified as one-half of the standard deviation of Group I.

Table 6-1 summarizes the mean and the standard deviation of all and each set at p = 75 %. Based on the assumption of normal distribution in each set, the distribution of travel time on the study link at p = 75 % is obtained.

Table 6-1. Travel time distribution at p = 75 %

	mean (s)	sd
Set I (75%)	135	4.62
Set II (25%)	229	4.62
All	158	41.12

6.3 Applicability

A simulation method is provided as a reference method against which the applicability of *standard deviation formulation* and *confidence interval method* is examined. In the three methods, 15 s is selected as the pre-specified permitted error (ε), which is about 10 % of mean at p = 75%.

A sample with size 1000 is drawn from the distribution at p = 75 % obtained from previous section and is considered as the population and further sampling with sample size n are performed from the population.

The simulated method is straightforward. For each sample size n, 1000 samples are taken and the percentage of accepted samples is calculated. Accepted sample means that the sample mean fall into $(\mu - \varepsilon, \mu + \varepsilon)$ (μ is population mean). The percentage for sample size from 10 to 40 is shown in Reference column in Table 6-2. The percentage increases as sample size increase and achieves 95 % when n = 27.

For *standard deviation formulation* (Eq. 1), 3 samples with sample size n are taken and the formulation is examined ($\alpha = 0.05$). The accepted/rejected, the percentage of Set I, sample mean and sample standard deviation of each sample are shown in Table 6-2. In the table, the accepted samples are highlighted by gray background. When n < 27, there are some accepted samples. The cause is the critical underestimation of standard deviation. The underestimation leads the right side of Eq. 1 to become small and the inequality to be satisfied. The cause of the underestimation is the sampling error. As shown in the table, p of accepted samples is much larger than the percentage of Set I of population (75 %). In contrast, when n >= 27, there are lots of rejected samples. The cause of most reject is the overestimation of standard deviation, and the cause of the overestimation is also sampling error. In summary, the *standard deviation* *formulation* is sensitive with sampling error and cannot provide consistent result.

For *confidence interval method*, one sample is taken for each n and the accepted/rejected, the percentage of Set I, range of confidence interval, lower-confidence bound and upper-confidence bound are calculated (Table 6-2). As shown in the table, the criterion that is the $100(1-\alpha)$ percent confidence interval calculated from samples contains the population mean is satisfied in most n ($\alpha = 0.05$). However, when n is small, the range of confidence interval is extremely large. It indicates that the above criterion is not enough to provide correct judgment and the range of confidence interval should be checked. When n >= 27, the most confidence interval ranges are smaller than $2 \times \varepsilon$ and the confidence interval method with checking the confidence interval range can be considered as a good estimation method.

It is enough to present the shortcomings of these two methods using three times sampling in *standard deviation formulation* and one time sampling in *confidence interval method*. Thus further sampling is not performed in this study.

In the observation describe in the next chapter, the accesses with through movement at Sakurayama in each signal cycle is about 50 vehicles and if we consider three signal cycles as aggregation time interval the accesses is about 150. Because we only consider the vehicles with TT, if 80 % of accesses with through movement at Gokiso, the size of population is about 120. Consequently, n = 27 means that about 22.5 % vehicles are needed as PVs to estimate the population mean of the study link with ε = 15 s.

Table 6-2. Applicability of prevalent formulations

n	Reference (%)	Standard deviation formulation												Confidence interval method				
		Sample 1				Sample 2				Sample 3								
		A/R	*p*	mean	sd	A/R	*p*	mean	sd	A/R	*p*	mean	sd	A/R	*p*	range	low	high
10	78	1	100	133	3.5	0	70	166	45.9	0	70	163	44.6	0	100	5	130	135
11	77	0	82	152	39.0	0	73	158	45.5	0	82	152	36.6	1	73	57	133	190
12	76	0	50	182	47.7	0	83	150	38.3	0	58	173	47.6	1	75	51	133	184
13	82	0	46	186	47.9	0	69	163	44.7	0	69	165	44.9	1	69	54	137	190
14	79	0	86	149	35.1	0	79	157	39.9	0	79	154	39.9	1	79	47	132	179
15	84	0	80	155	40.1	0	73	161	44.5	0	87	149	32.4	0	40	54	166	220
16	86	0	63	171	47.8	0	69	163	45.7	0	69	163	46.7	1	69	49	139	189
17	88	0	82	152	35.8	0	88	144	30.4	0	82	151	38.9	1	82	40	131	171
18	91	0	78	156	41.2	0	83	150	36.2	0	83	150	37.4	1	61	48	148	195
19	90	0	79	155	38.0	0	68	165	46.7	0	58	175	47.4	1	79	38	136	174
20	91	0	70	162	42.1	1	95	139	21.7	0	85	148	35.2	1	75	40	138	178
21	91	0	71	160	45.1	0	71	161	43.9	1	95	141	22.1	1	52	43	157	201
22	92	0	77	156	41.0	1	91	143	28.0	0	77	157	40.9	1	82	34	137	171
23	93	0	61	172	46.2	0	70	164	43.6	0	74	159	43.1	1	74	37	141	178
24	93	0	79	155	38.9	0	71	161	43.7	0	83	152	35.9	1	88	27	133	160
25	93	1	84	149	35.0	0	68	165	44.6	0	76	158	42.5	1	72	36	143	179
26	94	1	85	148	33.8	0	81	152	38.2	0	65	167	45.5	1	85	28	137	165
27	95	0	74	159	42.5	0	70	164	44.9	1	89	145	28.4	1	81	30	135	166
28	96	1	86	149	31.4	0	75	158	41.3	0	79	155	39.9	1	75	32	143	175
29	96	0	66	167	45.9	0	66	168	46.5	0	66	167	46.6	1	79	29	139	168
30	96	0	67	166	45.5	0	57	175	45.6	0	77	158	40.8	1	67	34	149	183
31	95	0	71	161	43.4	1	84	151	35.5	1	77	157	40.0	1	65	35	151	186
32	97	0	72	160	43.3	1	75	158	40.3	1	81	152	37.2	1	81	27	139	167
33	97	1	76	159	40.6	1	76	158	40.2	0	70	164	44.7	1	82	26	138	165
34	97	0	56	176	48.1	0	71	163	44.2	1	71	162	42.5	1	82	25	138	164
35	98	0	66	167	45.0	0	71	162	44.3	1	74	159	42.5	1	71	29	147	176
36	98	1	72	160	43.7	1	72	161	43.9	1	81	155	40.2	1	83	25	139	163
37	98	1	73	159	42.8	0	62	171	46.5	1	76	158	41.7	1	81	26	140	166
38	98	1	79	155	39.7	1	76	158	41.4	0	63	169	46.2	1	66	30	153	183
39	98	1	72	162	42.7	1	74	159	42.0	1	79	154	38.8	1	67	30	152	181
40	99	1	83	151	35.2	1	80	153	38.9	1	73	160	43.4	1	80	25	142	167

6.4 Summary of this chapter

Though *standard deviation formulation* and *confidence interval method* are considered as good estimation methods for the adequate number of PVs at link level and are used in several network level studies, this chapter shows that these methods are not available for a signalized link due to travel time has multi-peak distribution. *The standard deviation formulation* is sensitive with sampling error and cannot provide consistent result, and the *confidence interval method* is needed to add additional criterion to provide correct judgment.

Chapter 7

Performance Estimation

Even if the time period is very short (e.g., 5 min), the travel times of all vehicles on a signalized link always can be divided into several groups by turning movements at upstream and downstream intersection and the delay at downstream intersection, and each group has different travel time characteristics. Probe reports on a link within a time interval are considered as a sample. When the proportion of PVs is different over these subgroups, sampling error arises and becomes serious in small size sample.

This chapter introduces a new performance indicator and proposes a method to estimate the new performance indicator using small size probe reports on signalized link. The new performance indicator is essentially equivalent to conventional time-based performance indicators such as mean travel time or space-mean speed and has some desirable features.

7.1 Performance indicator

By probe vehicle technique, route or link travel time can be obtained directly. Therefore, time-based performance indicators such as mean travel time or space-mean speed are commonly suggested for probe-based Advanced Traveler Information Systems (ATIS). Quiroga (2000) also indicated that time-based indicators are extremely powerful, versatile and desirable. He compared three commonly used categories of performance indicators (highway capacity manual (HCM) based, queuing-related and time-based) and provided the reasons why time-based performance indicators are preferred.

Though time-based performance indicators have numerous advantages, it is difficult to estimate the conventional time-based indicators reliably by limited number of PVs as shown in the previous chapter.

Therefore, this chapter introduces a new performance indicator and proposes a method to estimate the new performance indicator using small size probe reports on signalized link. Further, it will be shown that the new performance indicator is essentially equivalent to conventional time-based performance indicators such as mean travel time or space-mean speed and has some desirable features.

When demand exceeds capacity at a link's upstream intersection (e.g., morning peak), it is reasonable to assume that the vehicles with through movement will access the link with uniform distribution over each green period. If we further assume that the vehicles with TT also access the link with uniform distribution, the ratio between the number of Set I and the number of vehicles with same access green period, p, can be considered as a performance indicator (Eq. 3).

$$p = \frac{N_{Set\ I}}{N_{Set\ I} + N_{Set\ II}} \tag{3}$$

where $N_{Set\ I}$ and $N_{Set\ II}$ represent numbers of vehicles in Set I and Set II, respectively.

The performance indicator has some desirable features.

Firstly, as a performance indicator, p is essentially equivalent to conventional time-based performance indicators such as mean travel time or space-mean speed. As p decreases, mean travel time increases and space-mean speed decreases monotonously.

Secondly, using p and information about traffic signal (such as cycle length, green time and offset time between downstream and upstream intersections), corresponding travel time distribution can be calculated approximately. For a given p, the distribution can be approximated as a composite of two normal distributions. Eq. 4 ~ 8 provide a possible form of formulations to calculate the means of two normal distribution and total mean using p and traffic signal. These formulations are acquired from Figure 7-1, which is illustrated based on uniform assumption. The vehicles with through access movement and left/right departure movement will queue in left/right turning lanes at downstream intersection and thus the length of queue of vehicles with TT at

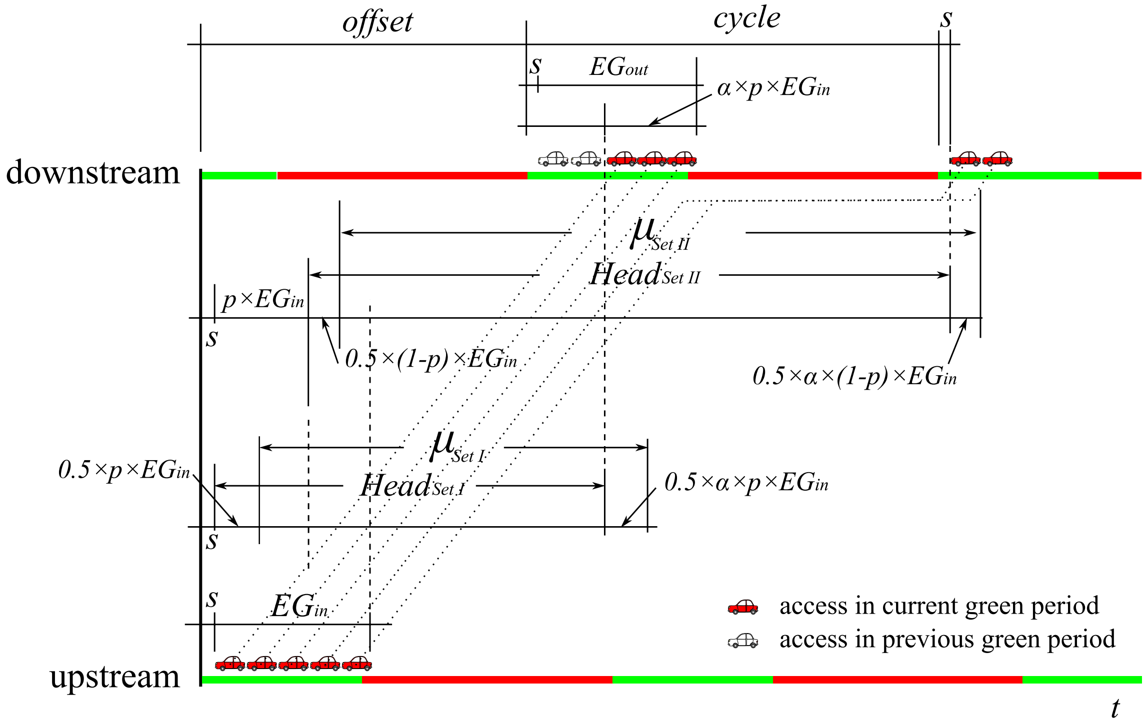


Figure 7-1. A queue of vehicles that access a link in same green period

downstream will become shorter than the length at upstream. The α in Eq. 4 ~ 5 reflects the reduction of the length and is dependent on the ratio of the vehicles with through access movement and left/right departure movement to the vehicles with TT. In this study, α is simply specified as 0.7 and the variation with space and time are not discussed precisely due to lack of real data for several links in road network. For δ, an estimated value is given based on an observation in next section. The variances of two normal distributions are in-queue variance and can be treated as constant. In contrast, mean travel time or space-mean speed has no ability to calculate the distribution.

$$\begin{aligned} \mu_{Set\ I} &= \underline{Head_{Set\ I}} - 0.5\times(1-\alpha)\times p\times EG_{in} \\ &= \underline{offset + EG_{out} - \alpha\times p\times EG_{in}} - 0.5\times(1-\alpha)\times p\times EG_{in} \end{aligned} \tag{4}$$

$$\begin{aligned} \mu_{Set\ II} &= \underline{Head_{Set\ II}} - 0.5\times(1-\alpha)\times(1-p)\times EG_{in} \\ &= \underline{offset + cycle - p\times EG_{in}} - 0.5\times(1-\alpha)\times(1-p)\times EG_{in} \end{aligned} \tag{5}$$

$$\mu_{all} = p\times\mu_{Set\ I} + (1-p)\times\mu_{Set\ II} \tag{6}$$

$$EG_{in} = G_{in} + \delta \tag{7}$$

$$EG_{out} = G_{out} + \delta \tag{8}$$

where

p = performance indicator

$Head_{Set\ I}, Head_{Set\ II}$ = travel times of head in Set I and Set II

$\mu_{Set\ I}, \mu_{Set\ II}, \mu_{all}$ = mean of Set I, Set II, all

$cycle, offset$ = signal length and signal offset between upstream and downstream instersection

G_{in}, G_{out} = green time of upstream and downstream intersection for through movement

α = reduction rate of length of vehicles with TT between downstream and upstream

δ = constant

Thirdly, using the knowledge about distribution, it is possible to develop a method that can minimize the effect of the sampling error arisen from intersection delay and efficiently estimate *p* from small sample. A simple estimation method is presented in the subsequent section.

When demand is lower than capacity (e.g., off-peak), the uniform assumption doesn't hold and it is possible that mean travel time in peak hour is smaller than that in off-peak. Consequently, the proposed performance indicator is not applicable in off-peak and in distinguishing peak and off-peak situation.

7.2 Observation of vehicle accesses at upstream intersection

The observation was made on November 8th, 2005 (Tuesday). The link from Sakurayama intersection to Gokiso intersection (north bound only) is chosen and the two intersections are investigated (Figure 7-2). The link is a primary arterial link in Nagoya, Japan. The link has three lanes and is about 950m. Nagoya has a high density road network and there are five signalized intersections on the link except Sakurayama and Gokiso intersections. Such link is fundamental element of arterial road and the

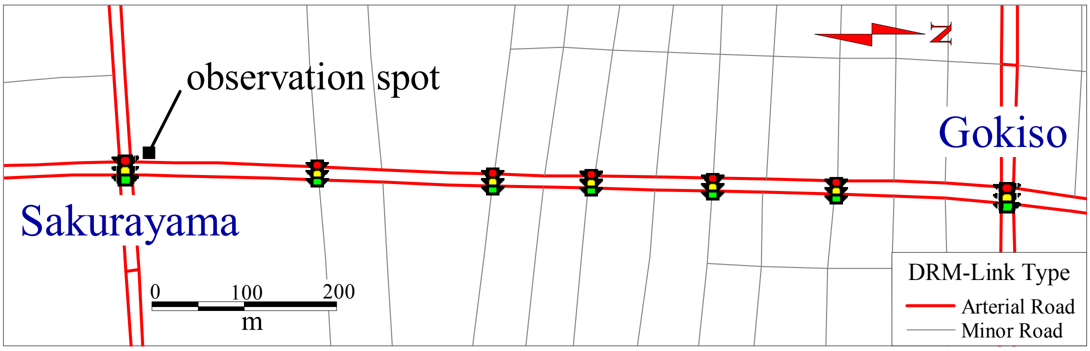


Figure 7-2. Study link and observation spot

properties are important.

The green, amber and red time of Sakurayama for through movement is 53 s, 3 s and 84 s, respectively and the Gokiso is 61 s, 4 s and 75 s, respectively. The cycle length of the two intersections is 140 s and the offset time is 123 s. The signal time is an observation of one day and day-to-day variation is unknown. In peak hour, the traffic signals should operate in optimized scheme and the variation may be very small.

The access times of all vehicles during 8:00 ~ 9:00 am (26 signal cycles) were observed at the observation spot shown in Figure 7-2. Then the access times are organized by signal cycle (green starting for through movement as cycle starting). The number of accesses, through accesses and left/right turnings (the sum of left and right turning) are summarized in each signal cycle and the access times are converted to the offset times from the corresponding signal cycle beginning. Figure 7-3 shows the number of accesses, through accesses and left/right turnings in each signal cycles. Because these flows decrease during the last half, only the fist 12 cycles are used in the

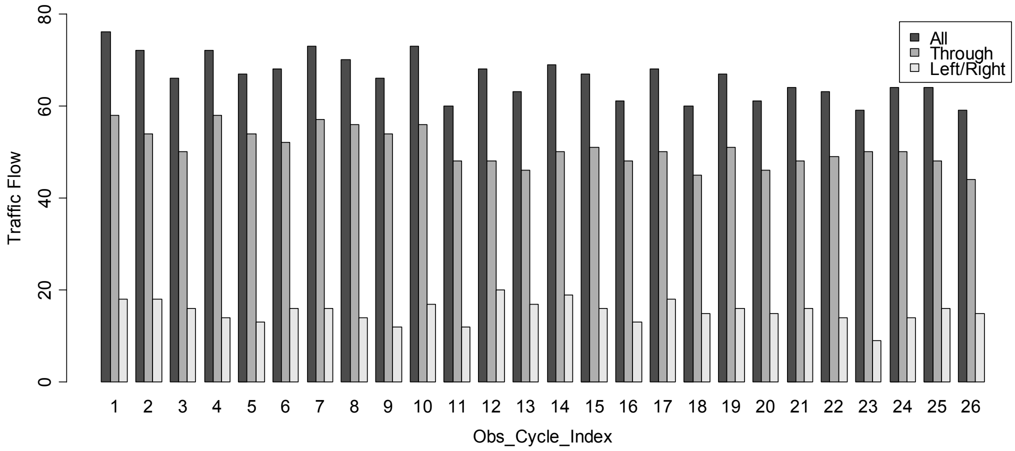


Figure 7-3. Traffic flow of each signal cycles

Table 7-1. Summary of accesses of signal cycles

Obs_Cycle_Index	All	T	L/R	Offset time from cycle beginning (s)	
1	76	58	18	T:[10,11,12,...,59,61]	L/R:[103,107,...,143]
2	72	54	18	T:[11,12,13,...,61,62]	L/R:[90,92,...,143]
3	66	50	16	T:[9,10,11,...,61,61]	L/R:[103,106,...,144]
4	72	58	14	T:[9,11,12,...,61,62]	L/R:[94,99,...,144]
5	67	54	13	T:[8,11,12,...,59,59]	L/R:[97,97,...,139]
6	68	52	16	T:[8,9,10,...,58,59]	L/R:[95,96,...,140]
7	73	57	16	T:[6,8,10,...,61,61]	L/R:[100,102,...,142]
8	70	56	14	T:[9,10,12,...,61,62]	L/R:[96,99,...,141]
9	66	54	12	T:[8,10,11,...,58,58]	L/R:[98,102,...,141]
10	73	56	17	T:[9,9,11,...,60,61]	L/R:[98,100,...,143]
11	60	48	12	T:[9,11,13,...,61,66]	L/R:[110,114,...,139]
12	68	48	20	T:[9,12,13,...,58,59]	L/R:[89,96,...,144]
Average	70	54	16	Beginning of T: 9 s	Range of T: 52 s

simulation, which needs stable flow input to keep a certain performance level. Table 7-1 shows the flows and offset times of the first 12 cycles and the average. The offset time in the table are separated into two groups by turning movement: through movement (T) and left/right turning (L/R). In Figure 7-3 and Table 7-1, the cycle index of observation is termed Obs_Cycle_Index and is distinguished from the cycle index of simulation used in the next section, which is termed Sim_Cycle_Index.

7.3 Simulation at performance levels

To obtain travel times of vehicles with TT across a link at different performance levels, a simple network that consists of a link (link 2 in Figure 7-4), upstream and downstream intersections, and adjacent links are modeled in a simulation developed based on an observation.

Figure 7-4 shows the position of reference points of entrance and exit of link 2. At these reference points, the access and departure of a vehicle can be judged easily and

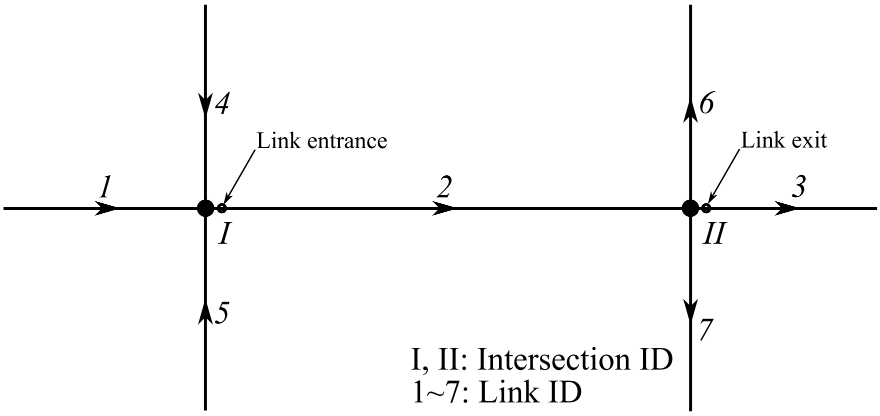


Figure 7-4. Simulation network

thus the time of access and departure can be measured accurately. Furthermore, acceleration process of vehicle is mostly finished at the reference points and running time and intersection delay are included between two reference points completely.

The behaviors of vehicles at the entrances of link 2 and link 3 are considered similar, and an observation at entrance of a real link is used to model the behaviors at the entrances of link 2 and 3. The entrance of link 3 is also the exit of link 2 (Figure 7-4).

The observations of each signal cycle, that consists of the number of accesses, through accesses and left/right turnings and the offset times from the corresponding signal cycle, are used on the two intersections (I and II) in the simulation. It is equivalent to that the signals of the two intersections are set as same as the signal of Sakurayama (cycle = 140 s, green = 53 s, amber = 3 s, and red = 84 s). The offset time of the two intersections is set as same as the offset time between Sakurayama and Gokiso (offset = 123 s).

Three levels of performance (p is 100%, 75% and 50%, respectively) are simulated. That is the range of p is from 100 % to 50 % and the resolution of performance level is 25 %. In each performance level, the simulation is run for 250 signal cycles and the vehicles that have TT and access link 2 during first 240 signal cycles are analyzed.

In the simulation program, each link is considered as FIFO (First In, First Out) queue — a type of data structure. Before running simulation for each performance level, the adjacent links at upstream intersection (id: 1, 4, and 5) are initialized by sufficient number of vehicles to provide the vehicles that access link 2 within 250 signal cycles. Link 2 is also initialized by different number of vehicles to realize three performance levels. All initialized vehicles are specified a unique numeric identifier.

The signal of upstream intersection (id: I) for through movement is switched to green at $0+(k-1)\times 140$ sec (k is Sim_Cycle_Index of intersection I and 1 ~ 250). The observations of 12 signal cycles are repeated 20 times to determine the number of through accesses (N_T, from link 1 to link 2), left/right turnings (N_{RL}, from link 4, 5 to link 2) and offset times for each k. For example, the 2nd observation in 12 signal cycles are used for k = 2 and 3rd observation is used for k = 15. At green starting of each cycles ($0+(k-1)\times 140$ sec), two operations are performed in the simulation: (1) N_T vehicles are transferred from link 1 to link 2 and the access times of the vehicles (through movement) are calculated using the green starting and the offset times from the relevant observation, and (2) N_{RL} vehicles are transferred from link 4, 5 to link 2 and the access times of the vehicles with left/right turning are set as 0; the travel times from vehicles without TT is not considered in this study.

The signal of downstream intersection (id: II) for through movement is switched to green at $123+(j-1)\times 140$ sec (j is Sim_Cycle_Index of intersection II and 1 ~ 250). The observations of 12 signal cycles are repeated as described above. The number of departures (N_{all}, link 2 to link 3, 6, 7) and the number of through departures (N_T, link 2 to link 3) in the simulation are determined using the number of accesses and through accesses in the observation, respectively. At green starting of each cycles, N_{all} vehicles are moved out from link2, then N_T vehicles are chosen randomly and moved into link 3 (through movement) and remainder are moved into link 6, 7 (left/right turning). The departure times of vehicles with through movement are calculated using the green starting and the offset times and the departure times of vehicles with left/right turning are set as 0.

When the simulation of each performance level is terminated, vehicle id, access cycle index, and travel time of each vehicles with TT (from link 1 to link 3) are recorded into a file.

7.4 The simulation output

Figure 7-5 illustrates the mean of Set I, the mean of Set II, and performance indicator *p* of each signal cycle for first 48 cycles from simulation for *p* = 75%. The minimum value and maximum value of Set I and Set II are also illustrated by dot line. N_{all}, N_T, N_{RL} change over signal cycles in the simulation, so *p* is not invariant and varies around the mean of *p* as shown in the figure.

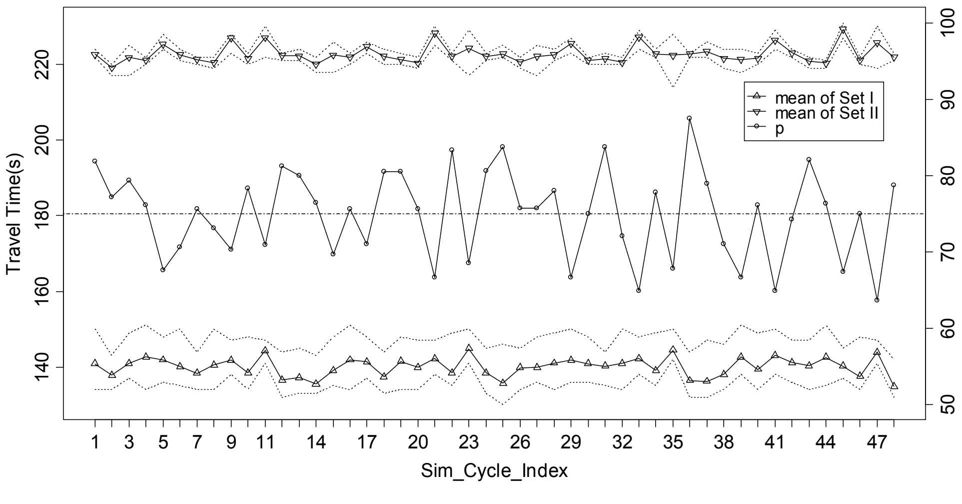


Figure 7-5. Travel times and *p* (Simulation for *p* = 75%)

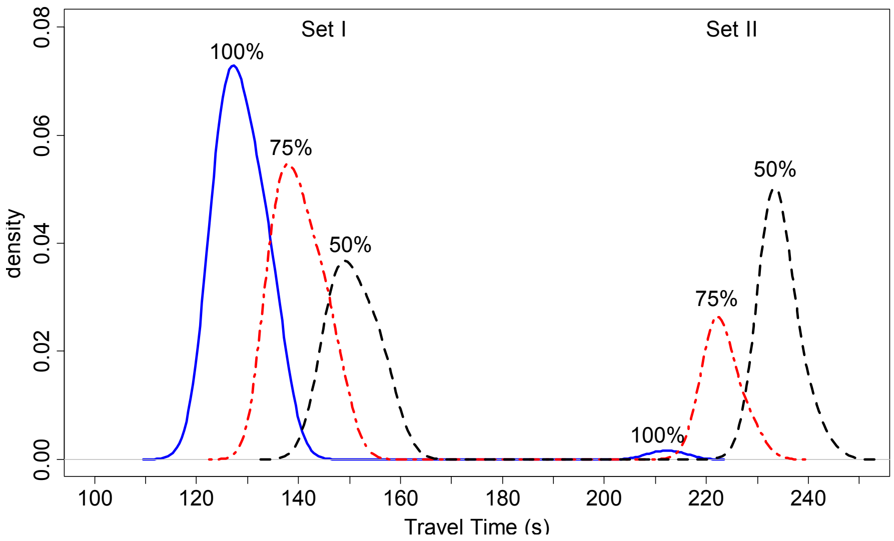


Figure 7-6. Link travel time distribution (p = 100%, 75%, and 50%)

Figure 7-6 illustrates the travel time distributions for p = 100 %, 75 %, and 50 % using travel time reports during 240 cycles. As shown in the figure, link travel time distribution at a certain performance level can be approximated as a composite of two normal distributions. The figure also shows that as p decreases, the proportion of the set with delay increases and the means of the two sets increase. Consequently, mean link travel time increases as p decreases.

Table 7-2 summarizes the output of the 240 signal cycles. The table presents the mean of all (μ_{all}), the mean of Set I ($\mu_{Set\ I}$) and the mean of Set II ($\mu_{Set\ II}$). The difference of μ_{all} between two consecutive performance levels is about 30 s. The space-mean speed is also presented. In the table, the items with hat are the result from Eq. 4~8 and

Table 7-2. Summary of simulation output

p	Speed(km/h)	μ_{all}	$\mu_{Set\ I}$	$\mu_{Set\ II}$	$\hat{\mu}_{all}$	$\hat{\mu}_{Set\ I}$	$\hat{\mu}_{Set\ II}$
100%	27	129	129	—	131 (-2)	131 (-2)	—
75%	21	161	140	223	162 (-1)	142 (-2)	222 (1)
50%	18	193	151	234	193 (0)	153 (-2)	233 (1)

the red values are the difference from the simulated values. *EGin* in Figure 7-1 is the range of offset times for through movement in each signal cycle and the average is 52 s from Table 7-1; that is δ = 1 s. In Eq. 4~8, $\alpha = 0.7$ are used and the formulations provide good estimates.

7.5 Proposed estimation method

Several studies estimated the smallest number of PVs that are required to estimate link travel time reliably: link level studies (Quiroga and Bullock, 1998; Hellinga and Fu, 1999) and network level studies (Srinivasan and Jovanis, 1996; Chen and Chien, 2000; Cheu et al., 2002). In these studies, sample mean (probe link travel time reports) is directly compared to population mean (travel times of all vehicles). For instance, if estimation error (the difference between sample mean and population mean) is small than allowable error (e.g., 10 % of population mean), it is considered that the estimation result is reliable.

Figure 7-6 and Table 7-2 show that as performance become worse (as *p* decreases), mean link travel time increases and the means of the two sets (without delay and with delay) also increase. It indicates that performance level can be estimated by the means of the two sets of a sample (probe travel time reports) except sample mean of link travel time. The essential of the proposed method is estimating performance level using the means of the two sets of a sample instead of sample mean.

The travel time reports in each signal cycle obtained from the simulation at performance level 75% is treated as a population. Samples are taken from these populations for each sample size *n* (240 times for each sample size *n*). For each sample, Eq.9 (proposed method) and Eq.10 (conventional method) are used to judge the

Table 7-3. Comparison between proposed and prevalent method

Sample size	Proposed method	Prevalent method
3	22 (9.2 %)	135 (56.3 %)
5	9 (3.8 %)	89 (37.1 %)
10	6 (2.5 %)	41 (17.1 %)
15	7 (2.9 %)	29 (12.1%)
20	4 (1.7 %)	17 (7.1 %)

estimated performance level: these equations are examined for p = 75 % and the two adjacent performance levels (p = 100 % and p = 50 %) ($\mu_{p,\text{Set I}}$, $\mu_{p,\text{Set II}}$, $\mu_{p,\text{all}}$ are obtained from Table 7-2) and the p^* that minimizes these equations is considered as the estimated performance level. If the performance level p = 75% is concluded by a sample, it is considered as success and if others (p = 50 % or 100 %) it is considered as failed. Table 7-3 shows the failed times and the error rate at five levels of sample size.

In Eq.9, each set of sample and population are compared respectively. By this, the influence of the sampling error arisen from intersection delay is eliminated. Due to the obvious difference between Set I and Set II, it is easy to judge which set a sample case belongs to.

$$e_p = (\mu_{p,Set\ I} - \bar{x}_{Set\ I})^2 + (\mu_{p,Set\ II} - \bar{x}_{Set\ II})^2 \tag{9}$$

where

e_p = the sum of the square of deviation of the means of the two sets of a sample from the means of the two sets of a performance level p

$\mu_{p,Set\ I}$, $\mu_{p,Set\ II}$ = mean of Set I and Set II of a performance level

$\bar{x}_{Set\ I}$, $\bar{x}_{Set\ II}$ = mean of samples in Set I and Set II

Population mean at p = 75 % is different from the means of two adjacent performance levels (p = 100 % and p = 50 %) about 30 s (see Table 7-2). Thus, for conventional method, if the difference between sample mean and population mean is larger than 15 s (about 10 % of mean at p = 75 %), it will be concluded that the estimated performance level is p = 100 % or p = 50 % (failed).

$$e_p = (\mu_{p,all} - \bar{x})^2 \tag{10}$$

where

e_p = the square of deviation of sample mean from true mean of a performance level p
$\mu_{p,all}$ = mean of a performance level
$\bar{x}$ = mean of samples

As shown in Table 7-3, at sample size 3, the error rate of proposed method is lower than 10 % while the error rate of conventional method is higher than 50 %. Even if the sample size increases to 15, the conventional method can not provide the same quality as proposed method at sample size 3. In the simulation, average number of vehicles with TT in each cycle is 36 (range: 25 ~ 45). If 10 % is regarded as acceptable error rate, the adequate PV rate is about 8 %. The conventional method needs about 42 % to obtain the same quality. If traffic condition is considered invariable in consecutive three signal cycles, the adequate PV rate in proposed method becomes about 3% and in conventional method becomes about 16 %. Obviously, the adequate PV rate is affected by the resolution of performance level (e.g., 25 % in this study). Higher resolution (e.g., 10 %) needs more PVs.

7.6 Summary of this chapter

It is expected that link travel time can be estimated reliably by relatively small number of PVs in Probe-based ATIS. However, when sample size is small, sampling error makes difficult to estimate population mean using sample mean directly.

Sampling error arises from two sources: turning movement and intersection delay. This study suggests that the effect of sampling bias from the former should be eliminated by redefining the population to only travel times from vehicles with TT. However, the latter is inevitable and this chapter proposes a new estimation method that minimizes sampling error from the latter.

As mentioned in Chapter 4 and Chapter 5, as link performance decreases, the proportion of the group with delay increases and the means of the two groups also increase. For estimating link performance, it is needed to estimate the proportion or the means of the two groups or both. In the proposed estimation method, the means of the two groups is estimated directly using probe reports instead of the proportion or mean travel time. The failure rate of the proposed method is lower than 10 % at sample size 3 and the conventional method can not provide the same quality even if sample size increases to 15.

When the link performance was identified, mean link travel time can be estimated by the means of the two groups and the relationship of the proportion and the means of the two groups. For estimating mean travel time, it is needed to estimate both the proportion and the means of the two groups. Fortunately, when traffic signal is known and under uniform assumption, the relationship between the proportion and the means of the two groups can be identified (see Eq. 4 ~ 8). The proportion can be obtained indirectly by the relationship and then the mean travel time can be estimated.

A new performance indicator is introduced and a set of formulations is proposed to obtain link travel time distribution at a certain performance level using information about traffic signal and the new performance indicator. In the formulations, there is a parameter (α) and the parameter might be link specific. Further research is needed to verify the availability of the formulations in different links.

Chapter 8

Vehicle-to-Vehicle Travel Time Variability

Travel time variability plays an important role in travel decision and there is a growing attention to travel time variability measurement (Graves et al., 2000; Li et al., 2006; Oh and Chung, 2006). Travel time variability has two components: one from the variability of performance level, and another from the variability of vehicle-to-vehicle at certain performance level. The performance levels of each link in a road network may vary over day-to-day and time-to-time. It can be measured by traffic detectors such as loop detector, video camera and probe vehicle. At a certain performance level, vehicle-to-vehicle variability still arises from driver behaviour such as aggressiveness and lane choice (Li et al., 2006) and from intersection delay. In peak time period, the behaviour of individual driver will be limited and the intersection delay becomes the major source of vehicle-to-vehicle variability.

The vehicle-to-vehicle variability of corridor travel time is important to probe-based estimation; if the variability is relatively small, travel time reports from PVs can be aggregated at corridor level directly and corridor travel time can be estimated by small number of PVs.

This chapter presents vehicle-to-vehicle variability on a signalized corridor at three performance levels in peak time period. A simulation is developed to model the

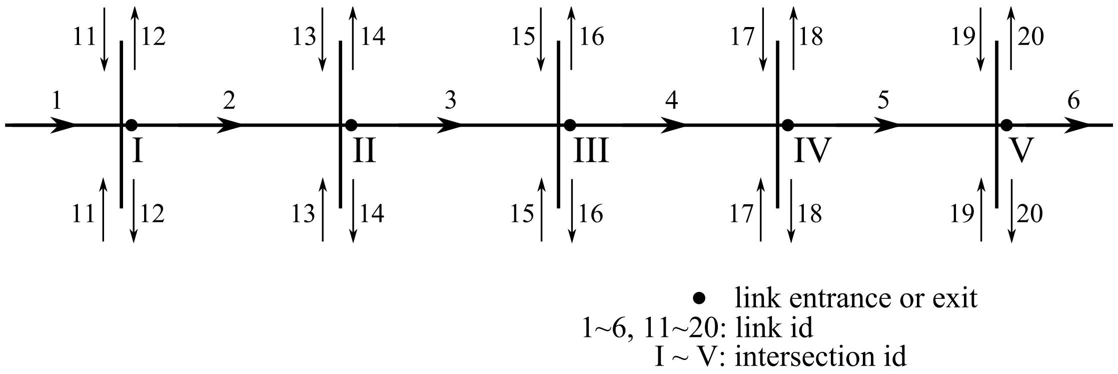


Figure 8-1. Simulation network

vehicles on the corridor and the adjacent links. Though the simulation is very simple, performance level and vehicle movement at intersection are considered explicitly, which are two critical factors that influence travel time. A performance indicator proposed in Chapter 7 is employed to demonstrate the stability of the performance in each three levels.

8.1 Simulation network

To obtain travel times of all vehicles that traverse a corridor completely at different performance levels, a simple network is modeled in a simulation that is a simple extension of the simulation shown in section 7.3 (Figure 8-1). In this figure, the intersections are numbered with Roman numerals and the links are numbered with Arabic numerals. The cross links are numbered using from 11 to 20 and the access link in the cross links are numbered using odd number and the departure link in the cross links are numbered using even number. The left and right turning movements at an intersection are not distinguished in this study and thus two access cross links are assigned by the same id and two departure cross links are also assigned by the same id.

When a vehicle accesses link 2 from link 1 and departs link 5 to link 6, the vehicle is considered as traversing the corridor completely and the travel time from link 2 to link 5 is considered as corridor travel time. The signals of the intersections and the offset times between consecutive two intersections are specified equally based on the observation shown in 7.2.

The figure also shows the positions of reference points of entrance and exit of each links. The entrance of a link is also the exit of previous link. For example, the entrance of link 3 is the exit of link 2.

8.2 Simulation procedure

Three levels of performance (*p* of link 2 ~ 5 are 100 %, 75 %, and 50%, respectively) are simulated. In each performance level, the simulation is run for 250 signal cycles and the link travel times of vehicles with TT and the corridor travel times are calculated.

In the simulation program, each link is simply considered as FIFO (First In, First Out) queue – a type of data structure. The access links (link 1, link 11, link 13, link 15, link 17, and link 19) are initialized by sufficient number of vehicles to provide the vehicles that access the network during 250 signal cycles. The links that compose the corridor (link 2 ~ 5) are also initialized by different number of vehicles to realize the three performance levels. All initialized vehicles are specified a unique numeric identifier.

The information of 12 signal cycles in the observation are repeated several times to determine the number of through accesses (N_T), the number of left/right turning accesses (N_{LR}), and offset times for a cycle index of an intersection in the simulation. For example, the information of 2nd signal cycle in the observation is used for cycle index = 2 and 3rd signal cycle is used for cycle index = 15 in the simulation. The number of left/right turning departures is specified as same as the number of left/right turning accesses N_{LR}.

At $123\times(i-1)+140\times(ci-1)$ sec, the signal of cycle index ci of intersection i for through movement is switched to green in the simulation (ci is 1 ~ 250). At the moment, two operations are performed in the simulation: (1) $N_T + N_{LR}$ vehicles are moved out from $\text{link}[i]$, then N_T vehicles are chosen randomly among these vehicles and moved into $\text{link}[i+1]$ and the rest of vehicles are moved into $\text{link}[10+2\times i]$. For the vehicles with through movement (N_T), the departure times of upstream link and the access times of downstream link are calculated using the green starting time and the offset times from the relevant signal cycle in the observation. For the vehicles with left/right turning, the departure times of upstream link and the access times of downstream link are set as 0; the link travel times of vehicles without TT is not discussed in this paper. (2) N_{LR} vehicles are transferred from $\text{link}[10+2\times i-1]$ into $\text{link}[i+1]$. The departure times of upstream link and the access times of downstream link of these vehicles are set as 0.

When the simulation of each performance level is terminated, the result is summarized by each vehicle. For a vehicle, the links that the vehicle traverse with TT are identified and link id, cycle index of access and link travel time of each link are recorded into a file.

In this simulation, performance level and vehicle behavior at intersection are considered explicitly, which are critical factors on travel time.

8.3 Travel time variability

8.3.1 Link travel time variability

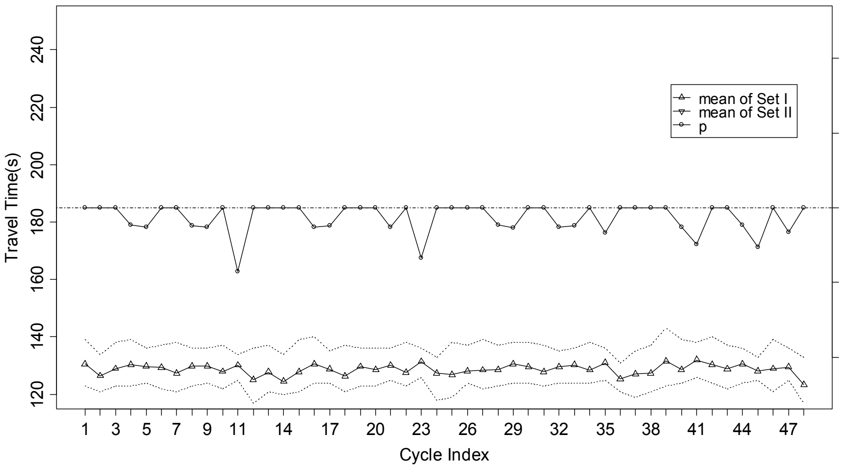
In this section, travel times on link 2 generated by the simulation are presented.

Figure 8-2 illustrates mean travel time of Set I, mean travel time of Set II, and performance indicator p for the first 48 signal cycles at three performance levels. The minimum value and maximum value of Set I and Set II of each signal cycle are also illustrated by dot lines. As shown in the figure, p fluctuates over signal cycles around expected value of each performance level. The causes are the variation of N_T and N_{LR} over signal cycles in the simulation, and pseudo-random number generated by the simulation. The former is consistent with the real situation. In this study, sufficient number of signal cycles (250 signal cycles) is simulated to counteract the influence of the latter on travel time distribution.

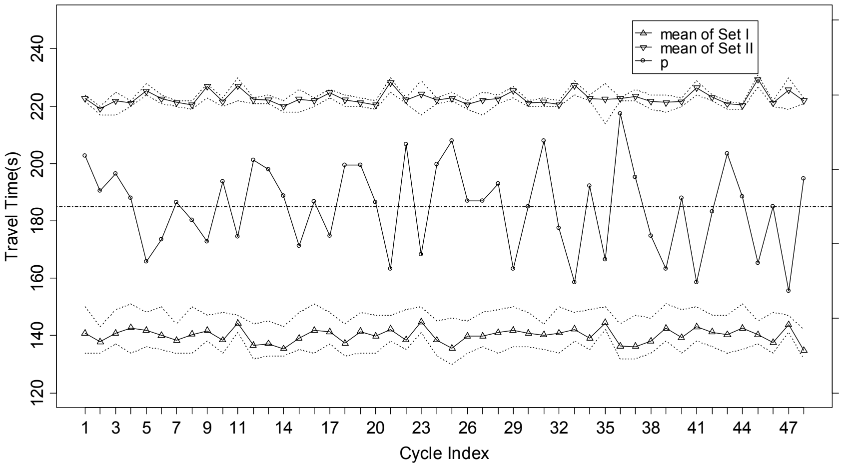
Figure 8-3 shows link travel time distributions at three performance levels, which are obtained using link travel times during 250 signal cycles. As shown in the figure, link travel time distribution has two peaks at each performance levels. As p decreases, the peak shifts towards right side and the ratio of Set II increases. Consequently, mean travel time on the link increases monotonously.

8.4 Corridor travel time variability

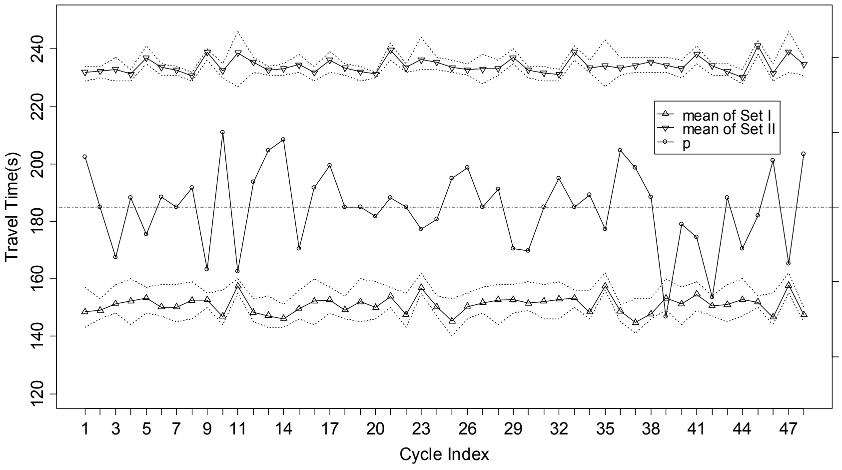
Figure 8-4 shows corridor travel time distribution at three performance levels. Link travel time will belong to Set I or Set II. Table 8-1 shows the percentage of vehicles in each combination of the number of Set I and Set II on the four links.



p = 100 % (a)



p = 75 % (b)



p = 50 % (c)

Figure 8-2. Link travel time and performance indicator

The distributions at each performance level are multi-peak distribution and the difference between two peaks is fairly large (about 20 % of travel time mean). That is travel time variability is still produced even if the performance level is invariable and the aggregated distance is relatively long. As the number of links traversed by vehicle as Set II increases, there are more intersection delay and the corridor travel time increases.

When performance level decreases, there are more Set II and the travel time increases rapidly.

Table 8-1. Percentage of combination of the of Set I and Set II on four links (%)

	4 : 0	3 : 1	2 : 2	1 : 3	0 : 4
$p = 100\%$	90.9	9.1	0	0	0
$p = 75\%$	0	81.3	18.7	0	0
$p = 50\%$	0	0.8	98.8	0.4	0

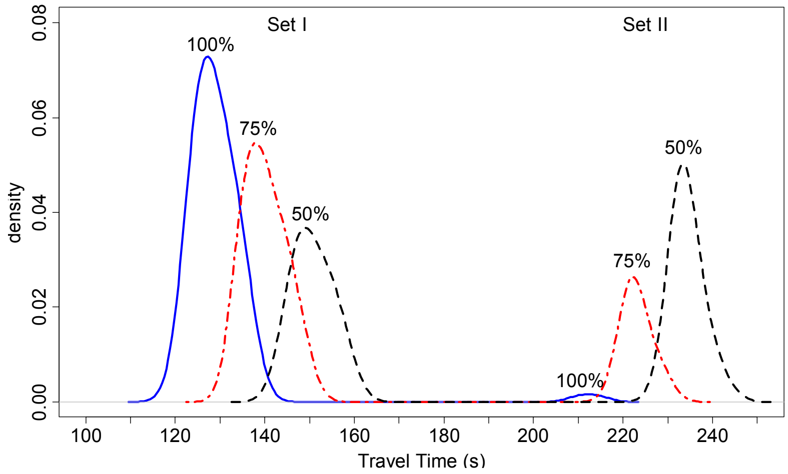
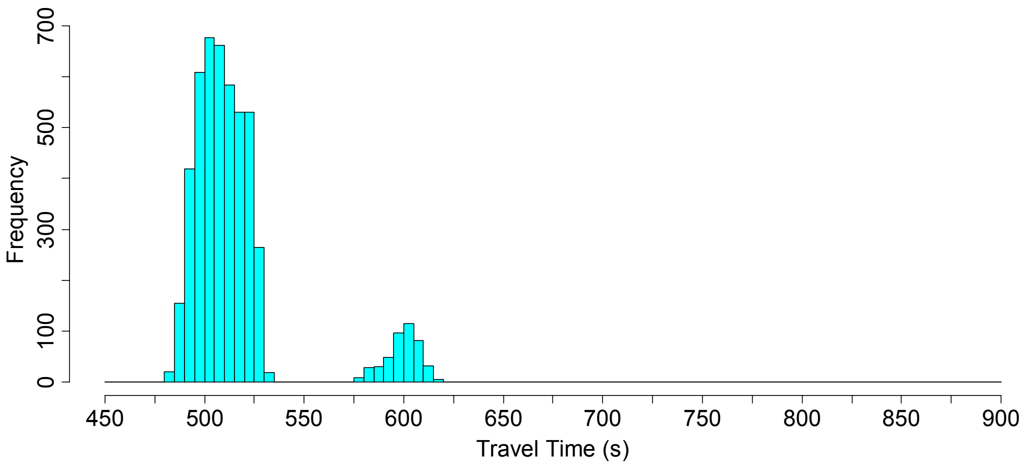
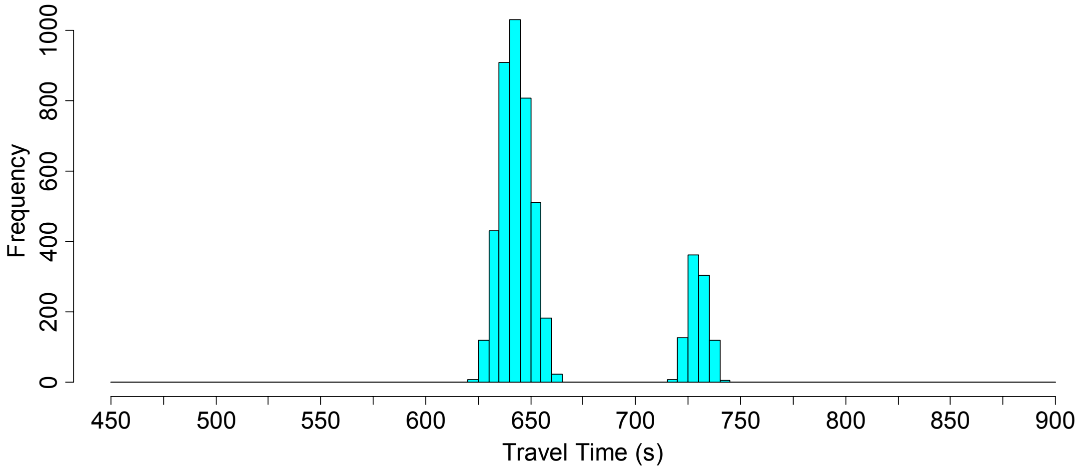


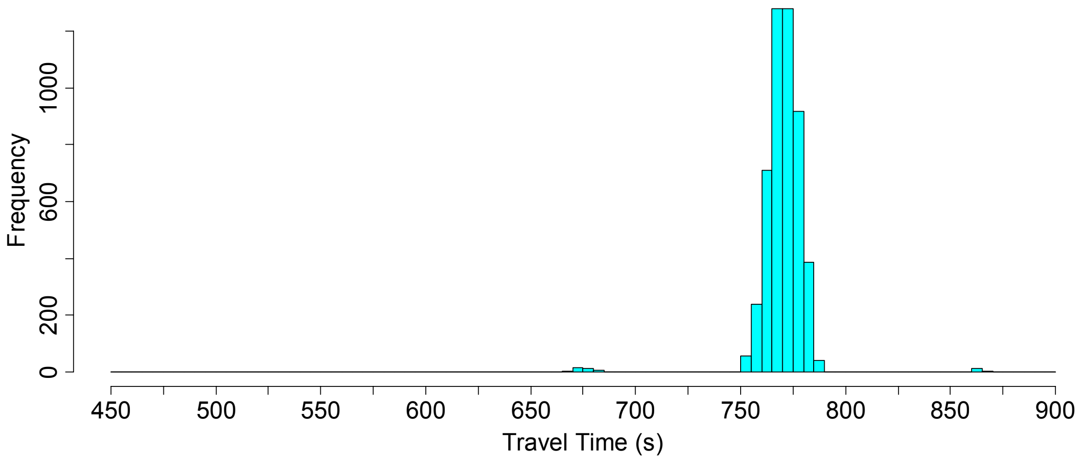
Figure 8-3. Link travel time distribution



p = 100 % (a)



p = 75 % (b)



p = 50 % (c)

Figure 8-4. Corridor travel time

8.5 Summary of this chapter

In this chapter, vehicle-to-vehicle variability of signalized corridor travel time at three performance levels is presented using travel times from a simulation that considers performance level and vehicle behavior at intersection.

Though an artificial corridor is modeled in the simulation, the simulation can be used to obtain travel time distribution (consequently, vehicle-to-vehicle variability) for a real signalized corridor. For estimating travel time of a real corridor by the proposed simulation, the vehicle accesses of each link and the relationship between the initial number of vehicles and the performance levels are needed. When demand exceeds intersection capacity, the accesses of a link will be controlled by the signal of upstream intersection and this is independent with performance level. That is the observation of the accesses at each intersections in peak hour can be used to identify the accesses for several performance levels. When the performance levels of each link are specified, the links can be initialized by different number of vehicles based on the performance levels and the corridor travel time can be obtained by the simulation. The relation should be affected by the geographic properties of each links and be link-specific. The relation between the initial number of vehicles and the performance level should be studied in the future.

Chapter 9

Conclusions and Future Studies

9.1 Conclusions

9.1.1 Statistical properties of link travel time

Travel time reports from PVs should be aggregated at link level instead of at path level because there are numerous paths in a city and the path-based method would suffer from low probe observations. Though the statistical properties of link travel time are important to implement probe-based real-time data collection system, little is known about the statistical properties.

Turning movement is usually neglected in practice when aggregating traffic data at link; that is, all vehicles traveling a link during a time interval regardless of turning movements at the link's ends are defined as population. By the traditional definition of link travel time, link travel time distribution will be concluded as normal or approximate normal. However, it will inevitably accompany with large variance and it is difficult to estimate mean link travel time using small size probe reports. Thus, the research proposes a new definition of link travel time: only consider the vehicles with through movement at upstream and downstream intersections.

By new definition, historical probe reports on an arterial link show that link travel time is two-peak distribution and mean travel time is larger in off-peak time period than in peak time period. To identify the intrinsic reasons of the phenomenon, a qualitative analysis and a simulation based analysis are performed and the following conclusions are made:

1) When the demand is lower than the capacity of upstream intersection, for example in off-peak time period, mean link travel time exhibits large variation over time and more importantly cannot trace the change of the number of vehicle accesses. That is, in this phase, mean travel time is not a good indicator of link performance and the number of accesses should be used for tracing the change of link performance.
2) When demand exceeds capacity at upstream intersection, it is reasonable to assume that the vehicle accesses are uniform over green period. In this phase, though mean travel time can trace the link performance, travel time distribution is two-peak rather than asymptotically normal. Despite this is not preferable result, it is consistent with the observation from historical data and the widely accepted belief that link travel times belong to at least two different groups: one without delay at downstream intersection and the others with the delay. As link performance decreases, the proportion of the group with delay increases and the means of the two groups also increase (see Figure 8-3). Using small size probe reports, though it is difficult to estimate the proportion of the group with delay, it is possible to estimate the means of the two groups due to their variances are relatively small. This fact is used to develop performance estimation method using small size probe reports.
3) For avoiding congestion, identifying the performance decrease in the second

phase is important.

9.1.2 The formulations of the adequate number

Traditionally, it is considered that the reliability of probe-based estimation depends on the number of the probe reports and the adequate sample size required to meet the reliability has been an imperative issue.

Two methods *standard deviation formulation* and *confidence interval method* are commonly accepted. However, these formulations are based on Central Limit Theorem and the result is doubtful when the population is severely nonnormal and sample size is small.

The examination described in Chapter 6 shows that these methods are not capable for a signalized link due to travel time has multi-peak distribution. The *standard deviation formulation* is sensitive with sampling error and cannot provide consistent result, and the *confidence interval method* is needed to add additional criterion to provide correct judgment.

9.1.3 Performance estimation

It is expected that link travel time can be estimated reliably by relatively small number of PVs in Probe-based ATIS. However, when sample size is small, sampling error makes difficult to estimate population mean using sample mean directly.

Sampling error arises from two sources: turning movement and intersection delay. This study suggests that the effect of sampling bias from the former should be eliminated by redefining the population to only travel times from vehicles with TT. However, the latter is inevitable and Chapter 7 proposes a new estimation method that minimizes sampling error from the latter. The failure rate of the proposed method is lower than 10 % at sample size 3 and the conventional method can not provide the same quality even if sample size increases to 15.

As mentioned earlier, as link performance decreases, the proportion of the group with delay increases and the means of the two groups also increase. For estimating link performance, it is needed to estimate the proportion or the means of the two groups or both. In the proposed estimation method, the means of the two groups are estimated directly using probe reports instead of the proportion or mean travel time.

When the link performance was identified, mean link travel time can be estimated by the means of the two groups and the relationship of the proportion and the means of the two groups. For estimating mean travel time, it is needed to estimate both the proportion and the means of the two groups. Fortunately, when traffic signal is known and under uniform assumption, the relationship between the proportion and the means of the two groups can be identified (see Eq. 4 ~ 8 in Chapter 7). The proportion can be obtained indirectly by the relationship and then the mean travel time can be estimated.

9.2 Future Studies

In this thesis, the statistical properties of link travel time and the transform of the properties over the change of the traffic condition were investigated by historical data, qualitative analysis, and simulation based analysis. However, the result of the analyses should be verified by a field test. A corridor that consists of several arterial links can be chosen as the target of the field study, such as the corridor used in simulation based analysis (see Figure 5-1). For the field test, a technique that can identify the most vehicles (e.g., 90 %) at the entrance of each link (see Figure 7-4) is needed. At present, high-quality video camera is one of the techniques.

For estimating path travel time, the effect of left/right turning movement should be studied. Furthermore, the travel time on local roads also should be studied.

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