

## Preliminary Analysis on Link Travel Time for Probe-Based Estimation Method by Microscopic Simulation

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A set of travel time reports from probe vehicles is a sample. The adequate sample size required to estimate mean travel time of all vehicles (population) reliably has been studied in many literatures. However, in these literatures, the population is simply assumed as normal or approximate normal. In this paper, the properties of the population are discussed. The population is divided into three stages and the properties of the population in each stage are described in qualitative analysis and the description is verified by microscopic traffic simulation model. From this, some conclusions that are important to develop probe-based estimation method are made.

**Keywords:** *Link Travel Time, Probe Vehicle, Population, Simulation*

### 1. Introduction

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 [1].

Travel time or space-mean speed can be obtained by probe vehicles (PVs) directly and there is therefore a growing attention to probe vehicle technique with the progressive implementation of Advanced Traveler Information Systems (ATIS). However, 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 [2-7]. In these literatures, the

population is simply assumed as normal or approximate normal and the properties of the population have not received attention.

In this paper, the properties of the population that are important to PV-based estimation are discussed. In qualitative analysis, the population is divided into three stages and the properties of the population in each stage are described. Then, a microscopic traffic simulation model is employed to verify and extend the description in the qualitative analysis.

### 2. Qualitative Analysis

#### 2.1. Definition of link travel time

This section clarifies what is meant by the term 'link travel time' in this paper. Different definition will lead different properties of link travel time and thus it is necessary to define the concept explicitly.

Traditionally, the link travel time is defined as the travel times of all vehicles traveling a link during a time interval regardless of turning movement at the link's upstream and downstream intersections; that is, the effect of turning movement at intersection is neglected in the population definition (e.g., [4, 5, 7, 8]). The traditional traffic detectors, such as loop detector, cannot observe a vehicle's turning movement at a link's ends and it is one of the reasons why the effect of turning movement is neglected in the link travel time definition.

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 properties. Hellinga and Fu [5] 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. Though the effect of turning movement was recognized in their study, the population is still defined as above and the subsequent study [8]. Li *et al.* [9] also investigated the turning movement effect using travel times from PVs. Travel times from different turning movement patterns were shown in a box-and-whisker plot and it was concluded that these subpopulations have different travel time distributions. Additionally, it is possible that the traffic conditions are different over these subpopulations at same time interval. In summary, the subpopulations are not homogeneous and should be considered separately.

Therefore, in this study, the population is redefined as only the vehicles traveling a link with TT during a time interval. 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 intersections 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 and TT is used to denote through movement at both upstream and downstream intersections.

Figure 1 shows the reference points of the entrance and exit of *link i*. The reference points are located at immediately after upstream and downstream intersections. The exit point of *link i* is located at the subsequent link and it is also the entrance point of the subsequent link. At these reference points, the acceleration process of a vehicle is mostly finished and

running time and intersection delay are included between two reference points completely. In this paper, link travel time report from a vehicle is calculated by subtracting the enter time of entrance point from the enter time of exit point.

### 2.2. Properties of three stages

In this study, one signal cycle, which is the shortest time interval in aggregating real-time traffic data, is chosen as temporal aggregation unit. The situations of the vehicles that access a link in a signal cycle and have turning movement TT will change over signal cycle and the situations can be roughly divided into three stages by the traffic condition at the upstream intersection of the link. The properties of these vehicles in the stages are described below by *flow* (veh./cycle, only through movement) at the entrance of the link, *mean spot speed* at the entrance and *mean travel time*.

Stage I is during undersaturated conditions, which is the prevailing situation in off-peak time period. In this stage, there should be no increasing queue at downstream intersection. Then, these vehicles that access a link in a signal cycle at upstream can depart the link in the same signal cycle at downstream and the travel times of these vehicles will be small and similar. Consequently, mean travel time will be stable at a relatively low level over time. However, it is also possible that mean travel time will show temporary fluctuations due to some vehicles will experience delay at downstream intersection even during undersaturated conditions. For identifying undersaturated conditions by mean link travel time, the effect of the fluctuations should be considered to avoid overestimation. In Stage I, the flow will be smaller than 80 % ~ 90 % of the capacity of upstream intersection for through movement and the spot speed at the entrance will be fast.

Under saturated/oversaturated conditions, the vehicles accessing a link with through movement will be

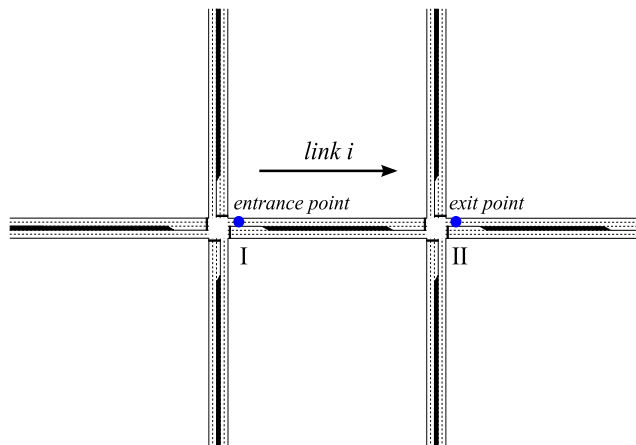


Figure 1. Entrance and exit points of *link i*

restricted by the upstream signal and thus the number of these vehicles will be stable at near the capacity of the upstream intersection (for through movement) and the arrival distribution of these vehicles may be close to uniform over green time, which is referred to Stage II and is the prevailing situation in peak time period for non-congestion links. Although the number of these vehicles is restricted at the capacity, it is possible that for through movement at downstream intersection, incoming flow (the vehicles with TT/LT/RT) exceeds outgoing flow, especially when the lengths of green times of upstream and downstream signals for through are similar (that is, the capacities are similar) and the turning rate of the through movement is high at downstream intersection. Consequently, the queue length at downstream intersection increases over time and mean travel time also increases over time. In this stage, the vehicles that access the link in a signal cycle and have turning movement TT cannot depart the link in the same signal cycle and the travel times of these vehicles will be divided to two groups: one without delay and the other with delay. That is, the distribution of travel time is two-peak. In Stage II, the flow will be stable at near the capacity and the spot speed at upstream will be still fast.

When the queue at downstream extends to near the upstream intersection, the vehicle accesses will be affected by the queued vehicles and the flow will reduce and the speed at entrance will slow down, which is referred to Stage III and is the prevailing situation in peak time period for congestion links. This stage reduces the utilization of the transportation infrastructure and should be avoided.

### 2.3. Indicators for identification

In previous section, it is indicated that the traffic conditions of a link can be roughly divided into three stages by the traffic condition at the upstream intersection of the link (for through movement): undersaturated condition (Stage I), saturated-oversaturated condition (Stage II) and the reduction of the flow due to queued vehicles (Stage III). Obviously, traffic condition becomes worse from Stage I to Stage III. For identifying these stages efficiently, the selection of

the indicator is important.

In Stage I, mean travel time will be stable at a relatively low level over time and also will show temporary fluctuations. If the fluctuation happened and is not treated properly, by mean travel time, it is possible that traffic condition is overestimated to Stage II. Consequently, instead of mean travel time, flow is a good indicator to distinguish Stage I and Stage II.

Stage III is undesirable situation and avoiding is more desirable than identifying. Identifying the increase of the queue length in Stage II and decreasing the arrivals before queue length reaches the critical value (starting to affect the arrivals) by taking some action such as reducing the green time of upstream intersection is a possible approach for avoiding Stage III. For this, dividing Stage II into several sub-stages and identifying these sub-stages is necessary.

Stage I and Stage II can be further divided into several sub-stages by flow or mean travel time.

In the morning, flow will increase before a link reaches Stage II. However, mean travel time will be stable or will fluctuate temporary and cannot reflect the increase of the flow. Consequently, in Stage I, the flow is better indicator for dividing the Stage I than mean travel time.

In Stage II, mean travel time will increase with the increase of the queue length at downstream intersection. However, the flow will be stable at near the capacity of the upstream intersection and cannot reflect the increase of mean travel time. Therefore, in our opinion, mean travel time is better than the flow in this stage.

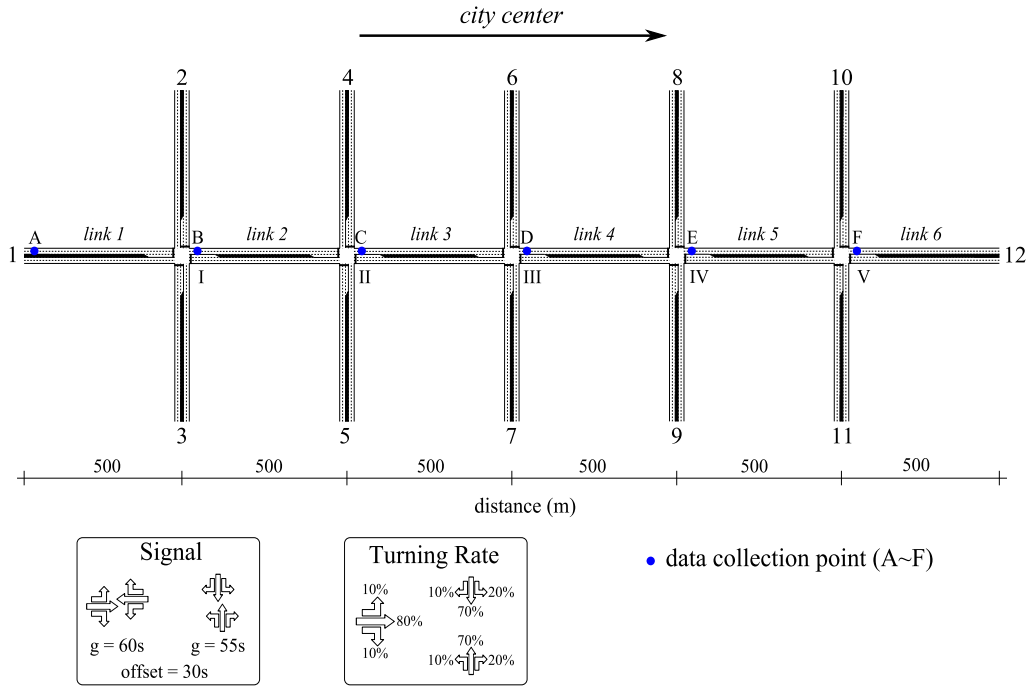
By mean travel time, it is difficult to identify the change of traffic condition in Stage I. On the contrary, by flow, it is difficult to identify the change of traffic condition in Stage II. It is the reason why we divided the traffic condition of a signalized link into three stages and analyzed the properties of the stages separately and suggested that the change of traffic condition of a signalized link should be identified by different indicators in different stages.

Table 1 summarizes the properties of three stages and the indicators for identification.

### 3. Simulation Analysis

**Table 1. Summary of three stages**

Stage	Prevailing Situation	Flow	Spot Speed	Mean Travel Time	Indicator
I	off-peak	< capacity	high	small temporary fluctuation	flow
II	peak for non-congestion link	near capacity uniform	high	two-peak	mean travel time
III	peak for congestion link	< capacity	low	large	avoiding by identifying Stage II



**Figure 2. Simulation network**

**3.1. 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/>).

Figure 2 shows the network, origin zones (1~12), signal scheme and turning rate. Vehicles are generated at each origin zone with Poisson distribution. The imaginary time period is morning (3 hours) and the base vehicle input of each zone and the temporal variation are set as Table 2. 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 imaginary network is a corridor towards city center and

thus the turning movements towards city center are emphasized in turning rate setting.

In the network, only the links from *link 2* to *link 5* are interested. Figure 2 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, flow, mean spot speed, and mean travel time (only TT) of the interested links are aggregated in every signal cycle using the log file.

**3.2. Simulation result**

Figure 3 shows the aggregated result. Flow, mean spot speed, and mean travel time (only TT) in each

**Table 2. 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

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).

Each intersection in the simulation network has same geometric properties and thus the capacity of each intersection should be identical. From Figure 3d, it can be concluded that the capacity is about 55 vehicle/cycle (average during 3600 s ~ 5400 s).

As shown in Figure 3, when flow is lower than the capacity of upstream intersection (undersaturated condition), mean travel time on link 3 fluctuates while mean travel times on other links are relatively stable. That is consistent with the description in the qualitative analysis. 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 speed of a vehicle is lower than 16.7 m/s and access during the end of the green period or the amber period, the vehicle will stop at the downstream intersection and mean travel time will exhibit fluctuation. More importantly, mean travel time at all links can not trace the change of flow in Stage I. As mentioned in the qualitative analysis, in Stage I, mean travel time is not a good indicator of traffic condition and flow should be used for tracing the change of traffic conditions.

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

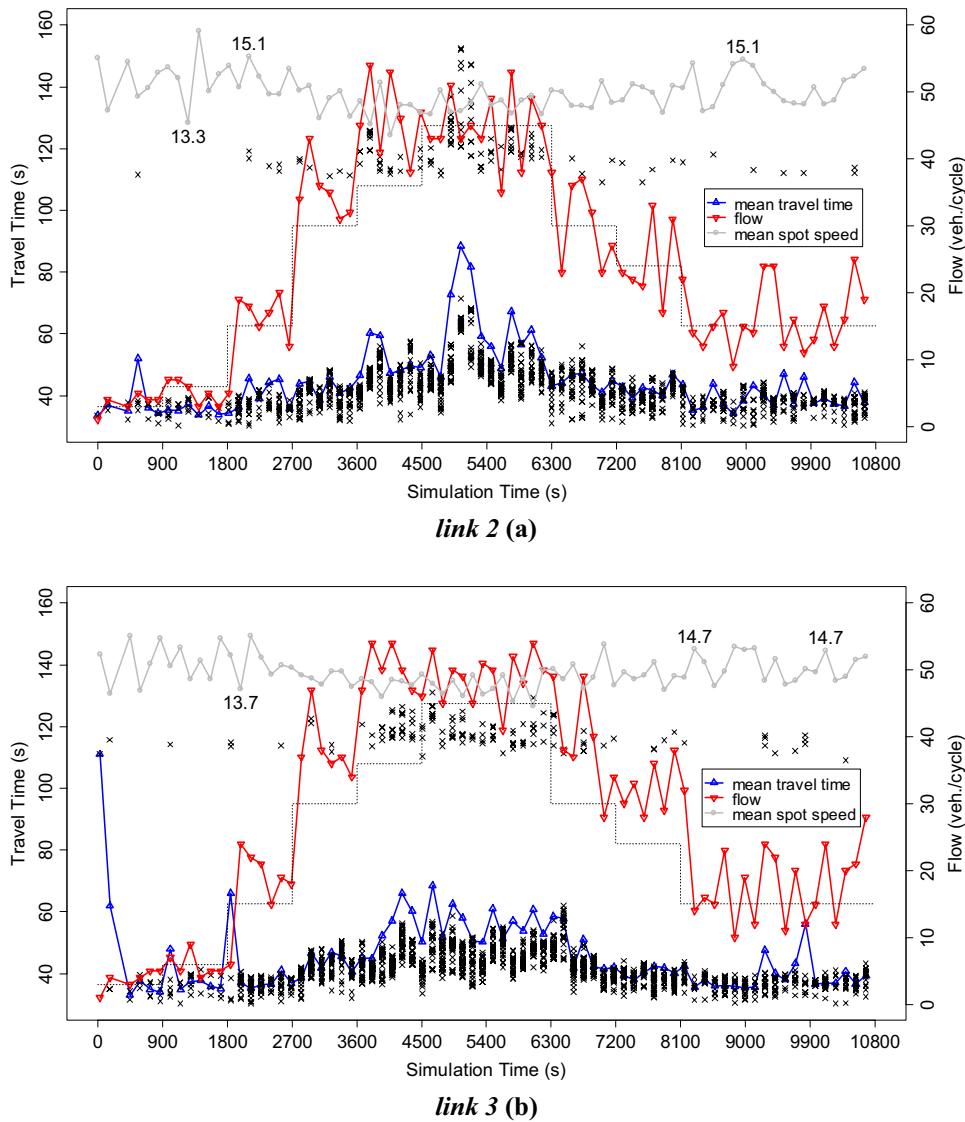


Figure 3. Illustration of simulation result (continue)

shown in Figure 3d, the flow is not reduced obviously. That is, the decreases of the spot speed and flow may not be simultaneous. Thus, choosing the spot speed or flow as the criterion of the undesirable situation should be determined based on the researchers' judgment. At this stage, mean travel time is obviously larger than other stage and the distribution of travel time tends to one peak. Therefore, it is easy to identify the stage using small size PV reports. However, as mentioned earlier, the stage is undesirable situation and should be avoided.

To avoid the above stage, it is important to identify the previous stage (Stage II) of the above stage. As shown in Figure 3c and Figure 3d, in Stage II (saturated-oversaturated condition, during 3600 s ~ 5400 s), mean travel time increases gradually and traffic conditions can be traced by mean travel time. However, in this stage, there are two groups in individual travel times from the simulation (one without intersection delay and the other

with intersection delay) and the two groups have significantly different travel times. That is, the population of link travel time has large variance and it is difficult to reliably estimate the population mean simply by the mean of PV reports (sample) when sample size is small. Fortunately, as shown in Figure 3c and Figure 3d, as mean travel time increases, the proportion of the group without delay ( $p$ ) decreases and the means of the two groups ( $\mu_1$  and  $\mu_2$ ) increase. That is,  $p$ ,  $\mu_1$  and  $\mu_2$  have some relationship. Further, the two groups have relatively small variances and  $\mu_1$  and  $\mu_2$  can be estimated by small size sample reliably. Obviously, estimating  $\mu_1$  (or  $\mu_2$ ) and then obtaining  $\mu_2$  (or  $\mu_1$ ) and  $p$  by the relationship and finally calculating mean travel time by  $\mu_1$ ,  $\mu_2$  and  $p$  is a possible method to estimate mean travel time. In the paper [10], the relationship is found by uniform assumption that is reasonable when the upstream intersection is saturated/oversaturated and a

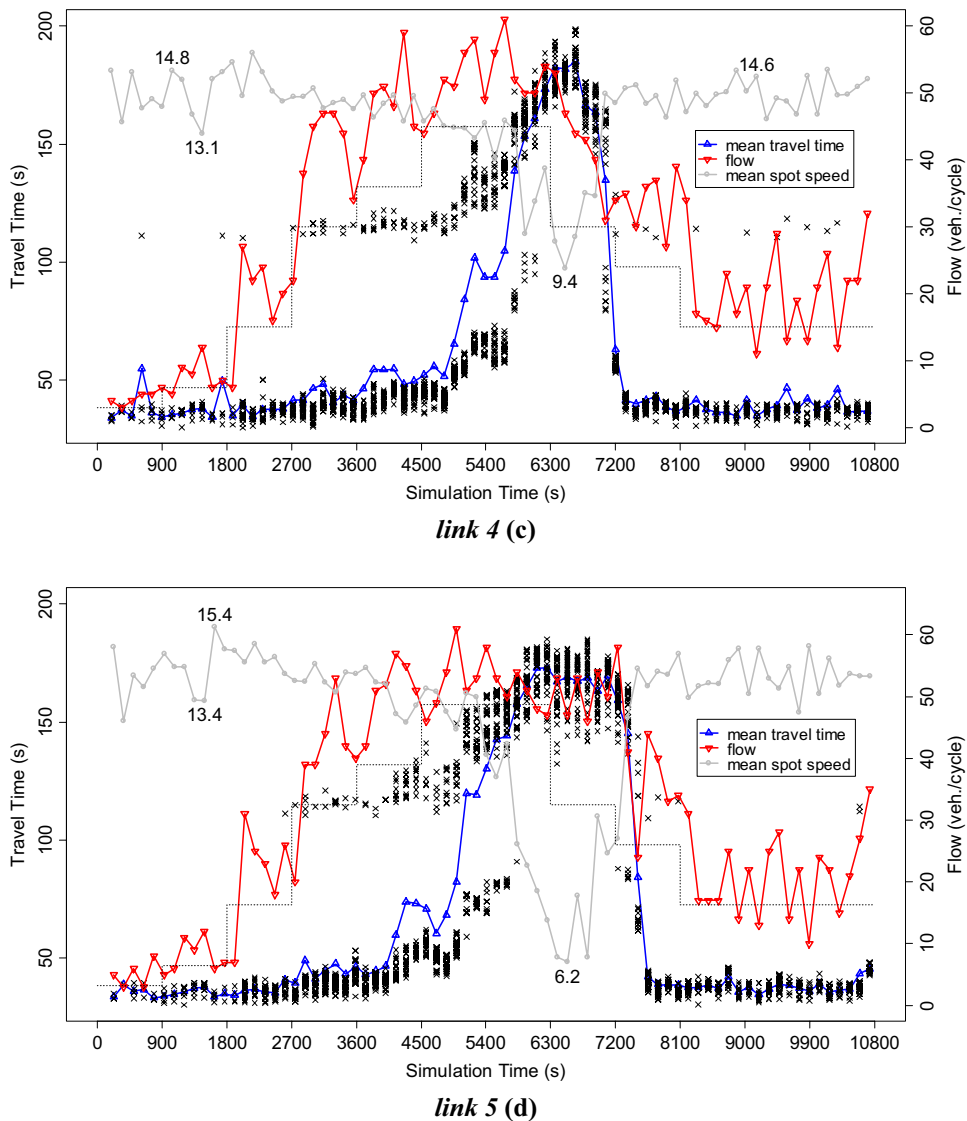


Figure 3. Illustration of simulation result (Continued)

estimation method is proposed for probe-based estimation.

#### 4. Conclusion

A set of travel time reports from PVs is a sample and it is necessary to understand the properties of the population for developing efficient PV-based estimation method.

In this paper, a queue of vehicles that access a link in a signal cycle and have turning movement TT is considered as a population. The situations of the population are divided into three stages and the properties of the three stages are analyzed and are verified by simulation. It shows that mean travel time is not a good indicator to identify the three stages consistently. It is also indicated that the second stage is very important for avoiding congestion. The travel time distribution in the second stage is two-peak. Obviously, it is difficult to estimate the proportion of the two peaks using small size sample. However, the means of the two peaks is different in different traffic conditions and the two peaks have relatively small variance. Consequently, it can be estimated by small size sample. Li *et al.* [10] used this phenomenon and provided an efficient probe-based estimation method.

A field test is needed in the future to verify the conclusions from the simulation performed in this paper. A data collection technique that can identify the license plate of the most vehicles at the referent points of a link is needed to realize the field test. At present, high-quality video camera may be an option of the collection technique.

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