Probe Date Usage in the Estimation of Volume, Travel Time and Delay in an Intersection: Methodology and Application

Sandy Mae GASPAY[1], Takashi OGUCHI[2] and Miho IRYO[3]

[1] Member of JSCE, Student, Institute of Industrial Science, University of Tokyo
(4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan)
E-mail: smgaspay@iis.u-tokyo.ac.jp
[2] Fellow of JSCE, Professor, Institute of Industrial Science, University of Tokyo
E-mail: takog@iis.u-tokyo.ac.jp
(4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan)
[3] Member of JSCE, Lecturer, Institute of Industrial Science, University of Tokyo
(4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan)
E-mail: m-iryo@iis.u-tokyo.ac.jp

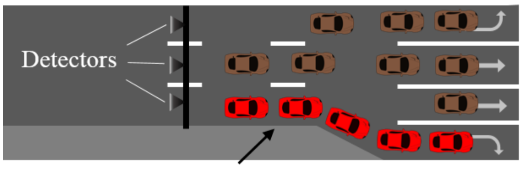
In this paper we demonstrate the application of probe data in estimating turning rates, travel time, and delay in intersections for the improvement of traffic signals. We focus on intersections with dedicated right-turn lanes whose signal phasing pattern includes a separate phase only for right-turners. The current position of detectors cannot measure overflows in the right-turn lane so right-turners often have to wait longer to cross the intersection. We introduce a simulation-based estimation method that utilizes detector and probe data from infrared beacons and present an application of the method to actual traffic data.

Key Words : *probe data, turning rate, travel time estimation, delay estimation, directional traffic*

1. INTRODUCTION

Traffic signal parameters in a number of busy Japanese intersections are based on data collected by roadside detectors, mostly ultrasonic wave detectors. According to (1), this data is used to estimate congestion length and then an algorithm that minimizes total delay computes the green split between major and minor streets.

Consider a busy intersection with high enough right turn traffic such that it has a dedicated right-turn lane. A separate phase is provided for right-turning traffic. High right-turn demand quickly overflows into the adjacent through lane as shown in **Figure 1**. However, because the detectors in Japan are usually placed at 150 m, 300 m, 500 m, and 1000 m distances from the stop line as stated in (2), detectors cannot distinguish if the overflow is composed of right-turning cars or not. Thus, the traffic signal parameters are not adjusted accordingly. The effect is the green signal duration for right-turn cars is often too short that right-turners often experience more delays than left-turn and through cars. Furthermore, these increased right-turn queues will reduce the capacity of the Through lanes. A solution to this issue was proposed in (3) by introducing image processing detectors to observe the actual number of right-turners. While the study produced good results, such detectors are not available in all intersections. Other practical solutions should therefore be explored.



Overflow in right-turn lane

Fig 1. Right-turning cars (red cars) overflowing into adjacent lane

In this paper, the authors introduce a method for estimating directional volume (i.e., the number of through, left-turning, and right-turning cars), average travel time, and average delay of vehicles in an intersection by combining detector data with probe data.

What is *probe data*? In Japan, Infrared (IR) beacons are installed at entrances to road links. These IR beacons send DOWNLINK data to passing vehicles containing traffic information and other messages from the traffic control center. In addition, vehicles with a special on-board unit can transmit UPLINK data to the IR beacons containing a vehicle ID number, passing time, and information on present and previously passed beacons (4). Here, we refer to these equipped vehicles as *probe vehicles* and the UPLINK data as *probe data*. In some areas in Japan, the number of probe cars have significantly increased (~10%) and so the possibility of using probe data for adjusting traffic signals is worth considering.

There are two unique points of this research: 1) it tries to address directional traffic as opposed to many estimation methods that only consider through traffic along major and minor links and 2) we utilize detector and probe data and use them in a simulator to produce additional data needed for a thorough understanding of the existing traffic conditions. We focus on the main purpose of traffic control which is to distribute the delay equally among the directions.

In this study, we wish to explore the applicability of probe information for traffic control purposes. Since the proposed methodology involves relatively long calculation times, offline estimation is conducted. These estimates can be used to analyze the temporal trends in directional traffic so that the default signal timings can be re-adjusted.

2. ESTIMATION METHODOLOGY

A simulation-based estimation method is employed where actual traffic volume and traffic signal data are used as inputs. Basically, the vehicle arrival data is supplied by detectors. Through multiple simulations, several combinations of turning rates are simulated and for each set of turning rates, several trials are made by randomly assigning the turning behavior of non-probe cars. From the simulation results, the most likely set of turning rates are those that produced probe car travel times that are most similar to the actual values. The *AVENUE* (5) traffic simulator is utilized for this study.

The study area is the 4-legged intersection shown in **Figure 2**. Infrared beacons and detectors are located at the entrances to each link. There are dedicated right-turn lanes (30 meters in length) on the east and west-bound directions. In this study, we only consider vehicles in one approach, those entering the Origin link in **Figure 2**. Data from detectors are in the form of vehicle passing times per second for each lane. Probe data for each probe car contains a unique vehicle ID number, passing time (in seconds) at a specific beacon, and the beacon ID number.

It is assumed that the traffic signal settings and phasing plan over the study time period are known. Capacity (in pcu/hr/lane), critical density (in pcu/km) and free flow speed (in km/hr) are configured for each link in the simulator while saturation flow rates (in km/hr) can be set for each lane.

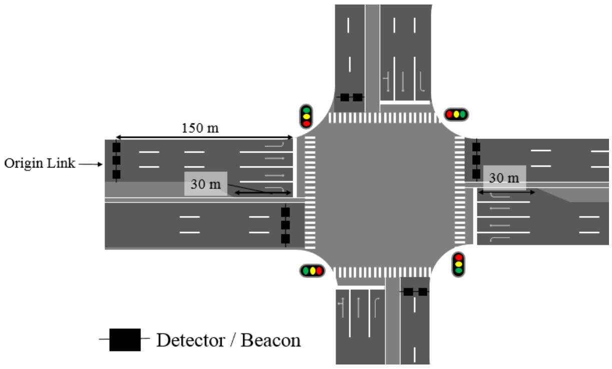


Fig. 2. Study area

(1) Simulation-based Methodology

The simulation-based methodology is conducted according to the following steps:

1. The estimation time period is selected according to the frequency at which estimates are desired as well as the amount of available probe data. For this study, we selected an estimation time period of around 30 minutes.
2. Assume turning rates. One set of turning rates constitutes one scenario. Starting with the probe car turning rates as the first scenario, other scenarios are created.
3. The detector data set is sorted into probe and non-probe cars by removing the probe car detector passing times from the detector data set. The turning behaviors of non-probe cars are randomly assigned since only probe car turning behaviors are known. This random assignment of destinations can also affect the resulting travel times. Thus, *n* trials are conducted where destinations are randomly re-assigned at each trial. **Figure 3** shows a diagram the method described.

(2) Evaluation of Simulation Results

After running each of the *n* trials for all the *s* scenarios, the travel time of all vehicles between the origin and destination beacon locations are grouped together if they passed the intersection in the same cycle. Only groups that include probe cars are evaluated. The probe car travel time dataset is compared with all probe and non-probe travel time values from the simulation to identify outliers which are excluded from the succeeding calculations.

In each group *g*, the minimum and maximum travel times are [$tt_{g,min}$, $tt_{g,max}$]. The actual travel time of probe cars in this group are most likely to fall within this range if the turning rates are correct and the destination of vehicles are assigned suitably enough. If the actual probe car travel times tt_{probe} fall outside this range, the deviation is calculated according to equation 1. Examples are illustrated in **Figure 4**.

$$\text{Probe travel time deviation} = \begin{cases} 0, & if\ tt_{g,min} \le tt_{probe} \le tt_{g,max} \\ tt_{g,min} - tt_{probe}, & if\ tt_{probe} < tt_{g,min} \\ tt_{g,max} - tt_{probe}, & if\ tt_{probe} > tt_{g,max} \end{cases} \quad (1)$$

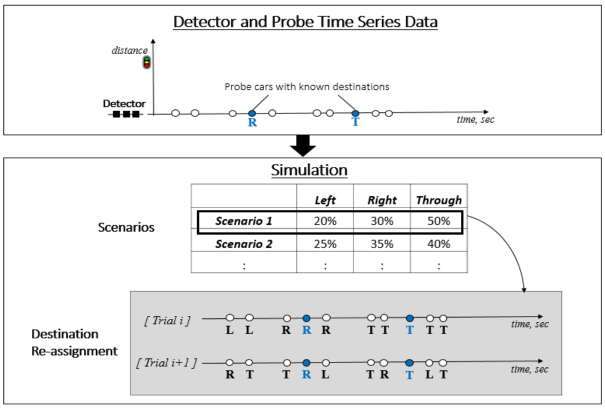


Fig. 3. Outline of Simulation-based Method

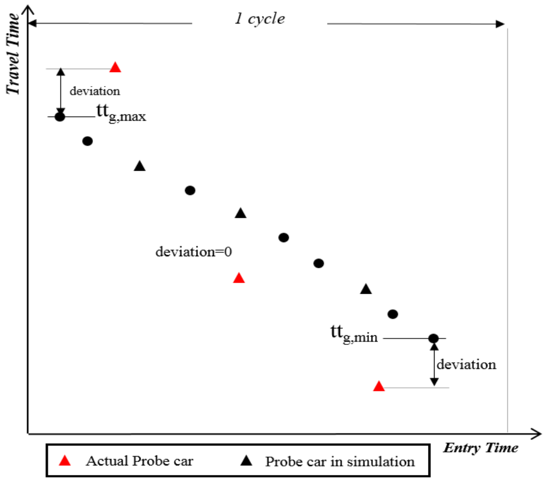


Fig. 4. Calculation of Deviation

Considering all scenarios *S*, the trial with the least total deviation is obtained using equation 2.

$$min \left\{ D_{t,s} = \sqrt{\textstyle\sum_{i=1}^{n} d_{i,t,s}^2}\ ; t \in T, s \in S \right\} \quad (2)$$

where:
$D_{t,s}$= root square sum of deviations for trial *t*, scenario *s*
$d_{i,t,s}$= deviation of probe car *i* in trial *t* and scenario *s*
n = total number of probe cars (L, R, and T)
T= set of all trials in one scenario
S = set of scenarios

This trial is considered to have the closest similarity to the actual traffic condition. The turning rates assumed in this trial are considered the estimated turning rates. Consequently, the estimated average travel time and delay are obtained from the simulation output of this trial. Delay is defined here as the difference between the travel time and free flow travel time.

3. EXPERIMENTAL RESULTS

The estimation methodology depends on simulator output so we test the simulator's capability to replicate the traffic conditions in a video survey we conducted to determine the appropriate parameters that require calibration. This is test is referred to as the "reproducibility test". The later part of this section presents the application of the estimation methodology to actual field data.

(1) Field Survey Data

The data for the reproducibility test was obtained from a field survey conducted in a Japanese intersection. Two cameras were positioned in an elevated walkway upstream of the chosen intersection. Camera A captured a closer view of the vehicles around 40 meters from the stop line while Camera B captured a wider view which includes the cars passing near the detector. The layout of the intersection and corresponding locations of the cameras are shown in **Figure 5.**

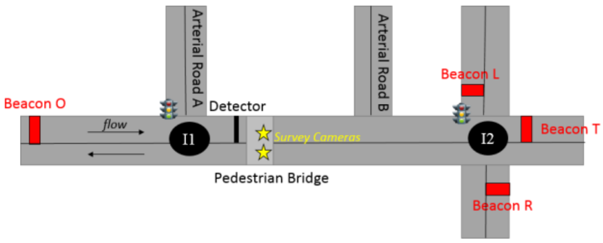


Fig. 5. Layout of Survey Area

Referring to **Figure 5**, intersection I1 and its upstream link are not considered in this study because the turning behavior of the cars approach I1 cannot be determined. The simulation area starts from the detector location until the positions of beacons L, T, and R. The upstream beacon is thereby transferred to the detector location in the simulation.

Detector passing times per second were obtained from video data. Since the location of the survey cameras did not cover the detector, a reference line was selected in Camera B's footage and the passing times of the cars on this line was recorded. The detector passing time was estimated by subtracting a constant value equal to the travel time between the detector and the reference line at a cruising speed of 55 km/h. The entry time of the probe cars at the detector location were also extracted from video data. The vehicles entering and exiting through Arterial Road B are neglected in this study.

(2) Reproducibility Test

Probe travel times collected over a period of 16 cycles (29 minutes and 49 seconds) is considered for the reproducibility test. The cycles were chosen such that they begin at an under saturated traffic condition and gradually develop to an oversaturated condition. The first cycle chosen was preceded by a cycle with no queue spillover (i.e. the queue was completely cleared at the green times), eliminating the need to set-up initial traffic conditions corresponding to existing queues.

Default values were used for the Link Capacity and Critical Density. Saturation flow rates were observed from video data. Sensitivity tests conducted showed that average observed values of saturation flow rates are adequate for proper representation in the simulator. **Table 1** shows a summary of the parameters used in the simulator. The left lane's saturation flow rate was set to 1500 pcu/hr due to the conflict with pedestrians. The traffic signal durations were adjusted according to the length of the effective green times because during congested conditions, vehicles still tried to cross the intersection at the onset of amber.

Table 1 Simulation Parameters

Link Capacity	1800 pcu/hr/lane
Critical Density	140 pcu/km
Free flow Speed	55 km/hr
Saturation Flow Rates (per lane)	
Left lane	1500 pcu/hr
Through lanes	1800 pcu/hr
Right lane	1800 pcu/hr

1000 trials were conducted and the trial with the least total deviation was obtained. **Figures 6a to 6c** are plots of travel times between the upstream and downstream beacon points belonging to the minimum deviation trial grouped by cycle. **Figure 7** shows the distribution of deviations for the trial with the least total deviation.

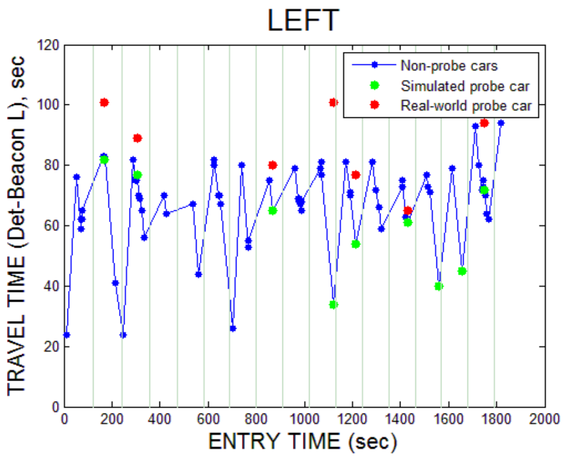


Fig. 6a. Minimum total deviation case out of 1000 trials showing left-turn travel times

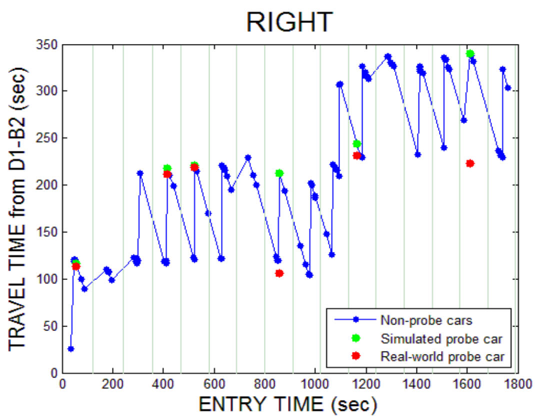


Fig. 6b. Minimum total deviation case out of 1000 trials showing right-turn travel times

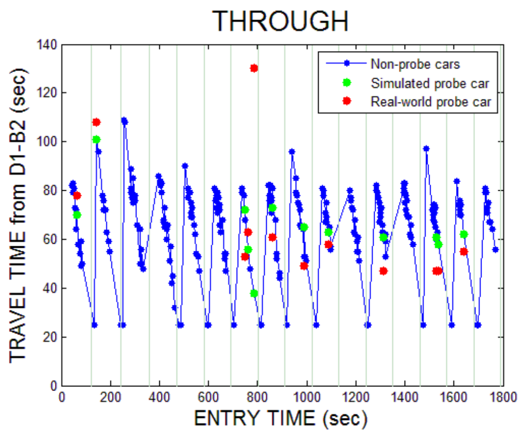


Fig. 6c. Minimum total deviation case out of 1000 trials showing through travel times

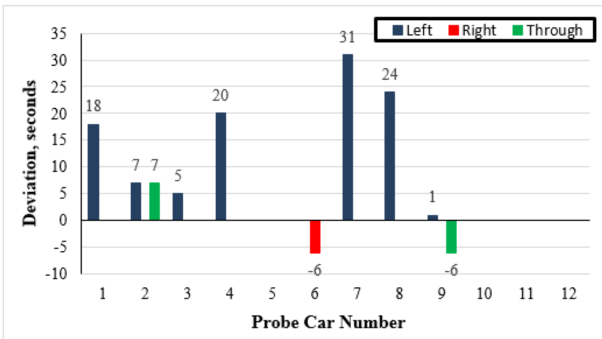


Fig.7. Distribution of deviations for trial with minimum D_t.

The value of $D_{t,s}$ in this trial where s=0 since no other scenarios were considered is 49.6 seconds. The left turn direction has high deviations reaching upto 31 seconds but the deviations for the Right and Through directions were both at 6 seconds. The left turn travel times may have been affected by Arterial Road B. Due to the high demand in Arterial Road B, there were times when left-turn vehicles joined the arterial road's queue before realizing that they can overtake this queue and advance to the head of the left-turn lane. As such, some additional delays may have been incurred which were not reflected in the simulation. Seeing that the Right-turn and Through traffic probe data had small deviations, we accept this result and conclude that the simulator can replicate the real world probe car travel times.

(3) Turning Rate Estimation

The estimation method was applied to the same detector passing time data used in the reproducibility test. The table below shows the ground truth data for the 16-cycle duration observed from the video.

Table 2. Ground Truth Data (Duration: 29 min, 49 sec)

	Volume		
	Left	Right	Through
Probe Cars	9	6	13
Non-Probe Cars	71	106	243
Total	**80**	**112**	**256**
	Turning Rate		
	Left	Right	Through
Probe Cars	32%	21%	46%
Non-Probe Cars	17%	25%	58%
Total	**18%**	**25%**	**57%**

Seven scenarios were considered (**Table 3**). To reduce the number of calculations, only the right turning rates and the sum of Left turning and Through rates were increased/decreased. A ratio of 1:2 was maintained for the left and through traffic volumes, corresponding to the number of lanes available for each of them. Starting from the ground truth right-turn probe proportions Scenario 4, the Right turning rates were gradually decreased by 2% from Scenarios 3 to 1 and increased by 2% from Scenario 5 to 7. As the Right turning rates were decreased, the sum of Left and Through turning rates were simultaneously increased. They were subsequently decreased when the Right tuning rates were increased.

Table 3. Simulation Scenarios

Scenario number	Turning Rates	
	Left + Through	Right
1	85%	15%
2	83%	17%
3	81%	19%
4 (=Probe)	79%	21%
5	77%	23%
6(=Ground Truth)	75%	25%
7	73%	27%

1000 trials were conducted for each of the scenarios. The table below summarizes the minimum root sum square values per direction for each scenario. The minimum total value belongs Case 6, Trial number 121. Thus, the estimated turning rates are equal to 75% Left+Through traffic and 25% Right-turn traffic. This coincides with the ground truth data.

Table 4. Summary of trials in each scenario with minimum total deviation

Scenario	Minimum $D_{t,s}$				Trial #
	Left	Right	Through	**Total**	
1	20.9	112.5	49.9	**124.9**	108
2	21.6	109.6	50.9	**122.8**	78
3	20.5	38.0	54.6	**69.6**	262
4	20.5	16.1	53.9	**59.9**	262
5	20.1	7.1	13.9	**25.5**	108
6	20.0	5.0	9.9	**22.9**	121
7	23.4	7.0	9.2	**25.6**	179

Figure 8 shows the distribution of the probe car deviations for the minimum deviation trial. The average travel time and delay estimates are summarized in **Figure 9**. Notice that the results show that the right-turn traffic's average delay is more than twice as much as that of the left and through traffic. For the 16-cycle period considered, the green duration allotted for the right-turn traffic was only 13 seconds on average which is merely 25% of the total green time allotted for the left/through and right-turn traffic (phase 1 and phase 2, respectively). Knowing this information, the green time durations can be adjusted to reduce the overall delay.

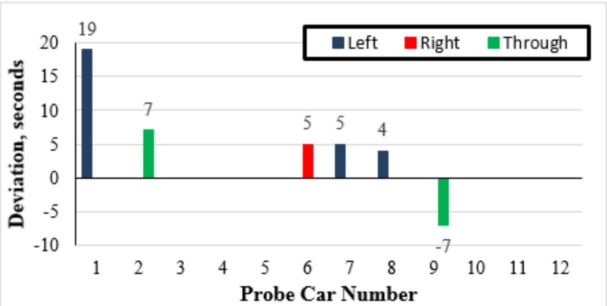


Fig.8. Minimum total deviation case (Scenario 6, Trial 121)

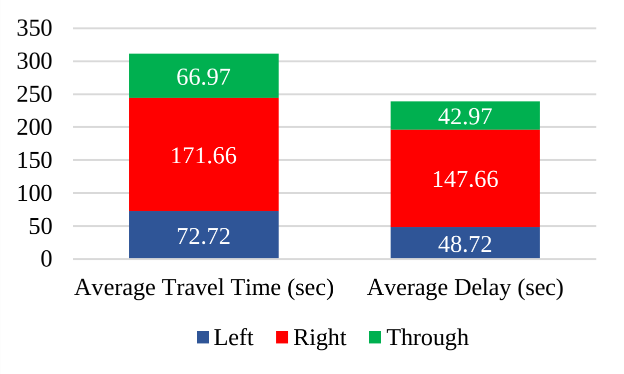


Fig. 9. Average Travel Time and Delay Estimation Results

(4) Discussion

Recall that minimum calibration was needed for this simulator and default values were mostly used except for cruising speed and left-turn saturation flow rate which are easy to observe on the field. The effect of the pedestrians on saturation flow rate can significantly affect the throughput of the left-turn lane. Thus, saturation flow rates must be carefully considered.

We expect that some errors/non-zero deviations are caused by the variation between driver behavior in real life and those in the simulation. Varying driver behavior leads to different cruising speeds, saturation flow rates, effective green times, etc. Another significant source of error is the uncertainty due to the random nature by which destinations are assigned to the non-probe cars. Thus, we can expect deviations to occur and in our methodology look for the trial which has the closest possible set of probe car travel times to the actual values.

It is also possible, however, for more than one scenario to have zero total deviations. This can happen especially when the turning rate scenarios are within the same flow regime (e.g., turning rates for several scenarios all reflect undersaturated conditions). For these cases, additional criteria can be set to select the best scenario. Other parameters such as standard deviation of values can be considered.

An important consideration in the application of this methodology is the selection of the estimation time period. If shorter time periods will be chosen, say, every 5 minutes, it is possible for queue spill-overs to be present at the start of the estimation time interval. Under these circumstances, the simulator must be pre-set to the traffic condition prior to the time interval being considered. It is also important to address the effect of neglecting the arterial traffic. Given existing infrastructure, it is difficult to precisely estimate arterial traffic. If the traffic conditions are too heavy, inaccurate estimates of the arterial traffic could cause significant errors in the estimation results. Data issues such as detector data errors and outlier probe car travel times were dealt with by relying on the data obtained with the video data.

4. CONCLUSIONS

In this study, we introduced a simulation-based method for offline estimation of directional demand (or turning rates), travel time, and delay using probe data from Infrared Beacons. We demonstrated that the simulator used was able to reproduce actual probe car travel times using minimal calibration. The methodology was applied to the estimation of volume, travel time and delay for directional traffic. It was able to estimate the true turning rate correctly. For future work, further analysis will be conducted to investigate the methodology's performance under varying degrees of saturation for different directions, different estimation time interval durations, and different probe penetration rates.

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