Arterial Speed Studies Based on Data from GPS Equipped Probe Vehicle

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Abstract: Due to more complicated behavior than controlled access roadway, congested estimation on arterial road network has become a challenging topic for all traffic professionals in recent years. To indicate the traffic condition, link travel speed is considered as one of the important markers for representing traffic status on roadway network and most understood pointer for all road users. This paper describes the implementation of Running Speed and Stopped Delay (RSSD) technique for investigating the urban link travel speed and discusses on the limitation of error in speed associated from each GPS device to maintain the advantages of proposed technique in travel speed estimation. The results from real observation traffic data on urban roadway also confirm that the accuracy of travel speed estimation is significantly improved when RSSD was employed as the estimation technique compared to baseline approach particularly in the links with highly congested condition.

Keywords: Travel Speed, Speed Estimation, Probe Vehicle, Urban Roadway, Arterial Road

1. INTRODUCTION

Monitoring traffic state on road network has been a challenging topic for all traffic professionals in recent years. By knowing traffic state information, the effective traffic control and guidance systems could be achieved. Moreover, with real-time information, traffic operators are able to evaluate the efficiency of road network and monitor their ongoing operational plan. Travelers can also be benefited by using traffic information in their pre-trip planning and/or rerouting their journey.

In order to provide traffic states information, the indicator should be simplest, quantitative and easy to understand for all stakeholders. Therefore, the link travel speed is considered as one of key markers for indicating the state of traffic or performance of the entire road network. For instance, Highway Capacity Manual (HCM) (2010) utilizes Level of Service (LOS) as the indicator in measuring the operational traffic status for arterial roadways. They also suggest using of “travel speed” as the only quantitative indicator in arterial LOS measurement. Link travel speed studies can be categorized by means of measurement technique into two main groups; (1) the using of fixed sensors installed on roadside such as registration plate matching, infrared sensors, inductive loop detectors or radio beacons, etc in gathering data from passage vehicles at the selected points and (2) using the movable sensors such as probe vehicle or floating car technique which traveled in the traffic stream for collecting traffic data.

The fixed sensor technique is widely used on freeways and principal roads. In this approach, the speed, volume and occupancy at selected location are typically information measured from these devices. Numbers of previous studies were employed data collected from this technique in travel speed study e.g. data from single loop detector (Wei et al.,
2012; Chen et al., 2011; Coric et al., 2011; Jin et al., 2010; Dailey, 1999) or dual loop system (Soriguera and Robuste, 2011; Rakha and Zhang, 2005). Although fixed detector systems are admired as efficient approach for gathering traffic data, there are some arguments on using data from these systems in addressing the link travel speed and time particularly on the arterial roadways. For instance, the requirement of assumptions in converting data from fixed detector to link travel speed (e.g. traffic speed-density-volume relationship, time-mean and space-mean speed relationship) which normally direct to inevitable uncertainties on the estimation results, the unavailable data of the traffic stream beyond detector’s location once the traffic queue extends over the sensor, the cost prohibitive in wide area application of fixed sensor systems, etc.

On the contrary, mobility tracking using GPS device as moving sensors traversing in the traffic stream do not require the installation of instrument along the roadway. This sensor enables to collect Geo Positioning System traces including ID of device, location, instantaneous speed and time stamp of vehicle in real time. Therefore, owing to the promising data, reliable and cost-effective from this device, it is becoming one of major sources for traffic research. In the past decades, many researchers have endeavored to estimate traffic condition and travel speed using GPS equipped probe vehicle. Poomrittigul et al. (2008) proposed the using of Non-ID of GPS-equipped vehicles technique to estimate mean travel speed (MTS) of road segment through relationship between time mean speed (TMS) and estimated space mean speed (eSMS). Although this technique provided acceptable correlation in most of the cases, however it showed the poor outcomes on the segments with congested traffic condition (travel speed less than 10 km/h). Shi and Liu (2010) suggested the using of smooth index from estimated space mean speed for urban traffic state estimation. They also proposed the map matching algorithm based on fuzzy logics and the traffic movement classification for average speed calculation. Although, the state estimation showed good agreement with the real observed data, the result about the accuracy on speed estimation was not clear.

Study from Quiroga and Bullock (1998) has demonstrated the technique for travel time and speed estimation based on probe data by using the relationship between average speed and the segment length to estimate segment travel time. They verified their proposed methodology with the real traffic data observed from highway network. Many of works have applied this concept in various purposes, for instance, Zou et al. (2005) applied this technique and developed the new methodology for performing arterial speed study from GPS data, Quiroga (2000) used this concept in measuring the performance of congestion management systems, Jiang et al. (2009) analyzed and evaluated the travel time estimation from this concept compare with the direct method. Bai and Zhao (2010) integrated this technique for travel speed estimation in their traffic state identification procedure.

However, due to the advantages of probe data in which the running and stopped delay behavior can be extracted from recorded instantaneous speed, therefore we have proposed the modification technique so called “Running Speed and Stopped Delay Method (RSSD)” to tackle the link travel time estimation problem (Puangprakhon and Narupiti, 2013). The accuracy of proposed technique in travel time estimation was tested and compared with the benchmark approach (Quiroga and Bullock, 1998) by using real observation data from urban roadways in Bangkok. The results indicated that the accuracy of estimated travel time is significantly improved by RSSD method, particularly in the highly congested condition (the segment with high stopped delay time per total travel time ratio).

This paper illustrates the application of RSSD concept in estimating of link travel speed which is considered as key indicator for representing traffic condition on arterial roadways. This paper also providing the discussion on the limiting error associated with each GPS measurement to maintain the advantages of proposed technique over the widely used
approach. The paper begins with the formulations of existing algorithm and concepts of the RSSD technique. Details of the study area and technique for gathering data are described. The verification and evaluation of proposed technique compared with the baseline approach. The results and main conclusions of the study are finally presented.

2. THEORETICAL BACKGROUND

2.1 Recording from GPS and Link Travel Time

Data from probe vehicles is considered as one of the promising sources of information for travel speed and time studies on road networks. In this data collecting system, the moveable sensors that travel in the traffic stream, such as vehicle equipped with GPS device, were acted as the tracking instruments for collecting the real-time location and instantaneous speed of vehicle along the travel route. However, due to the polling positions or sampled points of probe-based data are randomly distributed and not necessary to be corresponded with the end point of links on the road network (see Figure 1). As a consequent, the allocating of travel time between two consecutive sampled GPS points across the end point of link to individual link is considered as one of the crucial tasks in the link travel speed and time estimation procedure.

One of the simplest and widely implemented ideas for estimating link travel time is by searching the closet GPS point to the end points of link (both upstream and downstream nodes) and consider as the entrance and exit times of link, or else, by assuming the constant driving speed among two consecutive sampled points. The decomposed travel time in each link can be determined by direct interpolation between times stamped and reported positions of each vehicle. This technique delivers reasonable results in the traffic with nearly constant speed profile such as on freeways or motorways with the under-saturated traffic condition (Neumann, 2013). However, in reality particularly in urban context which comprises traffic signals, intersections and numerous of access points where the speed profiles are generally fluctuated and far from constant, the estimation technique based on constant speed assumption has difficulty in providing precise outcomes (Puangprakhon and Narupiti, 2014).

![Figure 1. Time-space diagram of GPS points along the traveled segment](image)
2.2 Estimating of Link Travel Speed and Time from Average Speed Technique

In general, Traffic data collected from GPS receiver including: ID of GPS, location, speed, and time stamp of tracked vehicle. As the speed is calculated from the receivers poll pseudorange data (distance between satellite and GPS receiver) and pseudorange data, therefore speed and position recorded from GPS receivers are independent. This allows calculating traveled distance from GPS speed and also permits to calculate the segment speed (Quiroga and Bullock, 1998).

From Figure 1, let $d$ be the traversal distance covered by probe vehicle during time $t_0$ and $t_p$. In case of recorded time interval among GPS points is small enough and distance between two adjacent GPS points are much smaller than the segment length, the distance traveled can be expressed by applying the trapezoidal approximation as:

$$d = \int_{t_0}^{t_p} v(t) \, dt \approx v_0 \left( \frac{t_1 - t_0}{2} \right) + \sum_{k=1}^{p-1} v_k \left( \frac{t_{k+1} - t_{k-1}}{2} \right) + v_p \left( \frac{t_p - t_{p-1}}{2} \right)$$

(1)

where $v_k$ is the instantaneous speed data from GPS at time $k$. The average speed $u_d$ associated with distance traveled $d$ can be expressed as:

$$u_d = \frac{d}{t_d} = \frac{d}{t_p - t_0}$$

(2)

where $t_d$ denotes travel time spent for traversing distance $d$.

The distance traveled $d$ and segment length $L$ should be very similar in the case that the first and last GPS point corresponded to the segment are sufficiently close to the entrance and exit points of segment, respectively. As a result, the average segment speed $u$ from $u_d$ can be approximated and equation (2) can be rewritten as:

$$u \approx \frac{1}{t_p - t_0} \left[ v_0 \left( \frac{t_1 - t_0}{2} \right) + \sum_{k=1}^{p-1} v_k \left( \frac{t_{k+1} - t_{k-1}}{2} \right) + v_p \left( \frac{t_p - t_{p-1}}{2} \right) \right]$$

(3)

In general, the real segment length $L$ is the known, consequently, segment travel time, $T_S$ then becomes

$$T_S \approx \frac{L}{u}$$

(4)

2.3 Running Speed and Stopped Delay Concept in Link Travel Speed and Time Estimation

Travel time is typically defined as the time spent for traveling between any two points and is basically composed of running and stopped delay times. Regarding to the definition of travel time, segment travel time, $T_S$ or the time spent for traversing any road segment can be expressed in terms of running and stopped delay time as:
where $t_R$ is running time, $t_D$ is stopped delay time, $L$ is length of the roadway segment, and $v_R$ is the average running speed.

As aforementioned, link travel time consists of two parts: the running time and stopped delay periods. Recall equation (2), the traversal distance covered by probe vehicle can be expressed as:

$$d = t_d \times u_d$$

(7)

Since the distance traveled is arisen only in running period (vehicle cannot move during the stopping period), therefore the traveled distance can be rewritten in terms of running speed and running time as:

$$d = t_{R,d} \times v_{R,d}$$

(8)

where $t_{R,d}$ denotes running time spent for traversing through distance $d$ and $v_{r,d}$ denotes the average running speed associated with distance traveled $d$.

Equation (3) can then be rewritten in terms of running speed and stopped delay as:

$$v_{r,d} \approx \frac{1}{(t_p - t_o) - t_{D,d}} \left[ v_o \left( \frac{t_1 - t_o}{2} \right) + \sum_{k=1}^{p-1} v_k \left( \frac{t_{k+1} - t_{k-1}}{2} \right) \right] + v_p \left( \frac{t_p - t_{p-1}}{2} \right)$$

(9)

where $t_{o,d}$ denotes stopped delay time during the vehicle was traversing through distance $d$.

In the arterial road network which generally comprises signalized intersection, the segment or link is typically partitioned at the intersection. At those points, transferring of vehicle from one to another segment occurs after the vehicle has passed the signal (intersection) and occupies the next road section and it is theoretically recognized that while a vehicle transferring from one road segment to nearby segment, the vehicle speed needs to be more than zero, or in other words it must be in the running state (stopped vehicle cannot move). Furthermore, in case that the sampling time interval of GPS is small, the speed between the last GPS point in the upstream segment and the first GPS point in the downstream segment is generally more than zero (no stopped delay time between two contiguous GPS points which lie on different segments).

Let reconsider the concept of travel time estimation in Figure 1, the segment travel time $T_S$ is estimated from the relationship between known traveled distance $d$ and segment length $L$ (shorten or lengthen the known distance around the edge of segment to the segment length) together with the average speed $u$ (which comprises running speed and stopped). However, from the above argument, it is reasonably to employ the running speed instead of average speed in performing travel time estimation. Due to the time changed respect to shorten or lengthen distance is governed only from running period. With this manner, the segment travel time can be rewritten in terms of running time and stopped delay time as:
Consequently, average segment speed can be computed by

\[ u \approx v_{R,d} \frac{t_{R,d} + (T_S - t_d)}{T_S} \approx v_{R,d} \left( \frac{t_d - t_{D,d}}{T_S} + \frac{T_S - t_d}{T_S} \right) \]  

\[ u \approx v_{R,d} \frac{T_S - t_{D,d}}{T_S} \approx v_{R,d} \left( 1 - \frac{t_{D,d}}{T_S} \right) \]  

(11a)

(11b)

It could be noticed from equation (11b) that in case of no stopped delay time during traversing road segment, the value of running speed must be equivalent to average speed. As stopped delay time enhances the running speed increases accordingly.

2.4 Error in Travel Speed estimation (Baseline Approach)

From Figure 1, average speed on each segment, \( u \) can be approximated from the relationship between segment length and the segment travel time as follow:

\[ u \approx \frac{L}{t_{exit} - t_{ent}} = \frac{L}{T_S} \]  

(12)

The upper bound for error of speed, \( \varepsilon_u \) in term of positional accuracy of individual GPS point, \( \varepsilon \) and segment travel time, \( T_S \) can be express by assuming the error associated with \( t_{ent} \) and \( t_{exit} \) are independent (In practical, \( \varepsilon_u \) values may be lower if the errors associated with \( t_{ent} \) and \( t_{exit} \) are both of the same sign and magnitude) and using the error propagation theory as:

\[ \varepsilon_u \approx \frac{\sqrt{2} \varepsilon}{t_{exit} - t_{ent}} = \frac{\sqrt{2} \varepsilon}{T_S} \]  

(13)

Error of average speed computed from equation (3) can also be expressed using error propagation theory and assuming constant sampling time interval \( \Delta t \) between two contiguous GPS points as:

\[ \varepsilon_u \approx \frac{\sqrt{p - 0.5}}{p} \varepsilon_v \approx \frac{\sqrt{\Delta t (T_S - 0.5 \Delta t)}}{T_S} \varepsilon_v \]  

(14)

where \( p \) denotes the number of GPS points within the segment (in addition to \( p_0 \)), \( \varepsilon_v \) is the error in speed associated with each GPS points.

Due to equation (13) and equation (14) measure error in segment speed occurred from error in positional and speed measurement respectively. Therefore by combining equation (13) and (14), the threshold which equation (3) would be preferable for estimating average segment speed can be express as:

\[ \varepsilon_v < \frac{\sqrt{2} \varepsilon}{\sqrt{\Delta t (T_S - 0.5 \Delta t)}} \]  

(15)
Table 1. Limiting error $\varepsilon_v$ from baseline approach as function of $T_s$ and $\varepsilon$.
(Assuming $\Delta t = 1$ s.) [Equation (15)]

<table>
<thead>
<tr>
<th>$T_s$ (s)</th>
<th>$\varepsilon = 0.1$ m</th>
<th>$\varepsilon = 0.5$ m</th>
<th>$\varepsilon = 1$ m</th>
<th>$\varepsilon = 3$ m</th>
<th>$\varepsilon = 10$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.17</td>
<td>0.83</td>
<td>1.65</td>
<td>4.96</td>
<td>16.52</td>
</tr>
<tr>
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<td>0.12</td>
<td>0.58</td>
<td>1.15</td>
<td>3.46</td>
<td>11.53</td>
</tr>
<tr>
<td>50</td>
<td>0.07</td>
<td>0.36</td>
<td>0.72</td>
<td>2.17</td>
<td>7.24</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
<td>0.26</td>
<td>0.51</td>
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<td>5.10</td>
</tr>
<tr>
<td>200</td>
<td>0.04</td>
<td>0.18</td>
<td>0.36</td>
<td>1.08</td>
<td>3.60</td>
</tr>
<tr>
<td>500</td>
<td>0.02</td>
<td>0.11</td>
<td>0.23</td>
<td>0.68</td>
<td>2.28</td>
</tr>
<tr>
<td>1000</td>
<td>0.02</td>
<td>0.08</td>
<td>0.16</td>
<td>0.48</td>
<td>1.61</td>
</tr>
</tbody>
</table>

Table 1 demonstrates some sample values of $\varepsilon_v$ calculated from equation (15) for several combinations among $\varepsilon$ and $T_s$ by assuming constant sampling time interval, $\Delta t = 1$ sec. As could be noticed from Table 1, $\varepsilon_v$ has direct proportional to $\varepsilon$ which indicates that as the positional accuracy of GPS device increases ($\varepsilon$ decreases), the accuracy on speed must also increase ($\varepsilon_v$ decreases) in order to maintain the advantage of equation (3) over equation (12). Moreover, $\varepsilon_v$ is inversely proportional to $T_s$ and $\Delta t$ which signifies that as the segment travel time or sampling time interval increases, the effect of positional error will be lower. In our study, we used the GPS devices which had 3 m positional accuracy and 0.36 km/h speed accuracy as the data collecting instruments. From Table 1, by assuming $\varepsilon = 3$ m, the limiting error for $\varepsilon_v$ is much larger than 0.36 km/h this means that equation (3) provides more accurate segment speed estimation result than equation (12).

2.5 Error in Travel Speed estimation (RSSD Approach)

As demonstrated in equation (11b) that average speed can be approximated by using the relationship among running speed, stopped delay time and total travel time. Consequently, from equation (9) and (11b), error of average speed calculated from RSSD technique can be computed by using error propagation theory and assuming sampling time interval $\Delta t$ between two contiguous GPS points is constant as:

$$
\varepsilon_u \approx \varepsilon_R (1 - \frac{t_{D,d}}{T_s}) \approx \frac{\sqrt{\Delta t(T_s - t_{D,d} - 0.5\Delta t)}}{T_s - t_{D,d}} (1 - \frac{t_{D,d}}{T_s})\varepsilon_v
$$

(16)

Noted that in reality the detected vehicle speeds from GPS data are normally comprise discrepancies due to the limitation of device accuracy. As a result, even though the vehicle was in stopped delay period, the detected speeds from GPS at those points are generally fluctuated and not perfectly equal to zero. However, the error from discrepancies during these stopped delay times could be mitigated by setting up the threshold for detecting the stopped delay behavior of vehicle (e.g. by setting 0.5 km/h as the threshold and consider all the speed values lower than 0.5 km/h as the absolutely stop behavior, 0 km/h) and filtering out the error in speed measurement during this period. This procedure leads higher accuracy to the RSSD technique due to some errors were diminished during this process.

By comparing equation (13) and (16), the threshold which equation (11b) would be preferable for estimating average speed can be express as:
\[ \varepsilon_v < \frac{\sqrt{2} \varepsilon}{\sqrt{\Delta t (T_S - t_{D,d} - 0.5 \Delta t)}} \]  

(17)

Table 2 demonstrates sample values of \( \varepsilon_v \) calculated from equation (17), in terms of congestion level or ratio between stopped delay time and travel time, \( (t_{D,d} / T_S) \) by assuming sampling time interval is 1 sec and the positional error of GPS is 3 m. It could be observed that in the uncongested segment or without stopped delay time, the \( \varepsilon_v \) values calculated from the average speed technique (equation (15)) are equal to the ones from RSSD technique (equation (17)). However, since the congestion increases (ratio of stopped delay time per section travel time, \( t_{D,d} / T_S \) increases) the effect of positional error increases leads to higher limitation of error in speed associated with each GPS points, \( \varepsilon_v \) for providing the advantages of speed estimation by equation (11) over equation (12).

Table 2. Limiting error \( \varepsilon_v \) from RSSD approach as function of \( T_S \) and \( t_{D,d} \cdot \)

(Assuming \( \Delta t = 1 \) s and \( \varepsilon = 3 \) m)[Equation (17)]

<table>
<thead>
<tr>
<th>( T_S ) (s)</th>
<th>( \frac{t_{D,d}}{T_S} = 0 )</th>
<th>( \frac{t_{D,d}}{T_S} = 0.2 )</th>
<th>( \frac{t_{D,d}}{T_S} = 0.4 )</th>
<th>( \frac{t_{D,d}}{T_S} = 0.6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.96</td>
<td>5.58</td>
<td>6.51</td>
<td>8.16</td>
</tr>
<tr>
<td>20</td>
<td>3.46</td>
<td>3.88</td>
<td>4.50</td>
<td>5.58</td>
</tr>
<tr>
<td>50</td>
<td>2.17</td>
<td>2.43</td>
<td>2.81</td>
<td>3.46</td>
</tr>
<tr>
<td>100</td>
<td>1.53</td>
<td>1.71</td>
<td>1.98</td>
<td>2.43</td>
</tr>
<tr>
<td>200</td>
<td>1.08</td>
<td>1.21</td>
<td>1.40</td>
<td>1.71</td>
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<td>500</td>
<td>0.68</td>
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<td>0.88</td>
<td>1.08</td>
</tr>
<tr>
<td>1000</td>
<td>0.48</td>
<td>0.54</td>
<td>0.62</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 2. Limiting error in speed associated with each GPS device from baseline and RSSD approach. (Assuming \( \Delta t = 1 \) s and \( \varepsilon = 3 \) m)
Furthermore, the advantages of RSSD over baseline approach in addressing speed estimation can be demonstrated by the limiting error in speed associated with each GPS device as presented in Figure 2 and 3. In the case that no stopped delay time (DT = 0) experienced during traversing throughout road segment, the limiting of GPS speed error from both techniques are equivalent represented by the bold line in Figure 2. However, as the congestion level increases (ratio of stopped delay time per travel time (DT/TT) increases) the limiting error of GPS for RSSD technique enhances while baseline method provides the same values as in the case of uncongested condition (due to the limiting error of baseline technique does not consider the effect of delay time, as illustrated in equation (15)). The abovementioned points out that in congested traffic condition RSSD technique allows the using of lower accuracy device than baseline approach to maintain the accuracy level of travel speed estimation over equation (12). In other word, with the same device, travel speed estimation from RSSD technique offers higher accuracy than baseline approach particularly in highly congested traffic condition.

Figure 3. Surface plotting of limiting error in speed associated with each GPS device in various traffic congestion levels from RSSD approach. (Assuming Δt = 1 s and ɛ = 3 m)
3. EXPERIMENTS AND METHODOLOGY

3.1 Study Corridor and Sampling Technique

In our experiments, we used probe vehicle data collected from urban arterial roadway in Bangkok to verify and compare proposed technique with the baseline method in addressing link travel speed estimation problem. The in-bound arterial route comprises 5 segments partitioned at signalized intersection with different segment length ranging from 0.5 km to 1.47 km was selected as the study corridor. Number of lanes of each segment also varies, some have 3 lanes and others have 4 lanes per direction.

The GPS equipped vehicles were used as tracking device in our study. For gathering ground truth, the sampling time interval of each GPS was set to highest frequency as possible, in this study it was set to every 1 second. Each recorded data point from GPS tracking system comprises the vehicle ID, sampling time, location, and instantaneous speed and acceleration of vehicle at regular sampling periods. The totally 9 probe vehicle runs throughout the study corridor in both congested period during the morning peak and the off-peak period in the late morning and afternoon were collected and used as the dataset for testing the applicability of proposed method in various scenarios. In addition, the GPS receiver used in this study had accuracy in position and speed within the range of 3 m and 0.36 km/hr (0.1 m/s) respectively.

3.2. Evaluation Method

In order to examine the accuracy of both techniques in travel speed estimation, Absolute Percentage Error (APE), Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE) were used to investigate the amount of estimation error compared with the ground truth from observation since MAPE can express the estimation error in generic percentage terms and is often useful as the accuracy indicator while RMSE can measure the differences between estimated values and the values actually observed.

\[
APE = \left| \frac{u_{est} - u_{obs}}{u_{obs}} \right| \times 100
\]

\[
MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{u_{est}(i) - u_{obs}(i)}{u_{obs}(i)} \right|
\]

\[
RMSE = \sqrt{\frac{\sum(u_{est}(i) - u_{obs}(i))^2}{n}}
\]

where \(u_{est}(i)\) is the estimated travel speed of segment \(i\), \(u_{obs}(i)\) denotes the observed travel speed of segment \(i\) and \(n\) is the number of data to be computed.

4. RESULTS FROM FIELD STUDY AND DISCUSSIONS

In this section, the performance and accuracy of RSSD technique in segment travel speed estimation were investigated and compared with the benchmark method. For representing the sampling time interval in reality, three testing scenarios with different sampling time intervals (1, 3 and 10 seconds) were simulated from the high resolution observed field data and used to address the correctness and applicability of proposed technique on different scenarios.
Table 3 demonstrates results of travel speed estimation from both techniques in different sampling time intervals. Noted that, each value in this table was summarized from totally 45 study cases (from 9 runs throughout 5 segments with different congestion levels). As shown in Table 3, the using of RSSD method as the estimation technique provides better agreement with observed field data than baseline approach in all cases. It is clearly confirmed by the lower MAPE and RMSE values in all sampling time intervals. Furthermore, the sampling time interval affects the level of accuracy from both techniques, longer sampling periods direct to lower in accuracy level. As the sampling period increases from every 1 second to 3 seconds and 10 seconds, the MAPE values from baseline method increase from 1.43% to 1.74% and 4.14%, while those MAPE of RSSD method increase from 0.87% to 1.19% and 3.08%, respectively.

The effects of segment travel time on accuracy of travel speed estimation from both methods are illustrated in Figure 4. It could be observed that as segment travel time increases the error of estimated speed decreases, which conforms to equation (14). For instance, in the case that using 3 second sampling time, the errors in speed on the shorter segments or segments with travel time less than 100 seconds vary within ±3 km/h more than those in the longer segments with travel times over 100 seconds which the error of estimated speeds lies within the range of ±1.5 km/h. Additionally, the estimation error from RSSD technique tends to be lower than that of the baseline approach, which is shown by the narrower distribution trends particularly on the longer segments or in the segments with higher travel time which generally contain stopped delay behavior (congested traffic condition).

<table>
<thead>
<tr>
<th>Sampling time interval</th>
<th>Baseline approach</th>
<th>RSSD approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAPE (%)</td>
<td>RMSE (km/h)</td>
</tr>
<tr>
<td>Sampling time = 1 second</td>
<td>1.43</td>
<td>0.38</td>
</tr>
<tr>
<td>Sampling time = 3 seconds</td>
<td>1.74</td>
<td>0.53</td>
</tr>
<tr>
<td>Sampling time = 10 seconds</td>
<td>4.13</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Figure 4. Relationship between error in speed estimation and travel time when using sampling time interval = 1 and 3 seconds
The more details about the effect of traffic conditions on the accuracy level of estimation is illustrated in Figure 5 through the relationship between APE from both techniques and the ratio between stopped delay time and travel time. In the case that uncongested condition (or no stopped delay time during traversing road segment), both techniques provide the same level of accuracy signified by the equivalent APE value (approximately 1%). However, once the congestion increases (stopped delay time/travel time increases), the RSSD technique offers superior estimation results which can be perceived by the lower trend of APE value, while APE values from baseline technique increases and provides lower accuracy. This is due to in RSSD technique the effects of stopped delay are mitigated during the travel speed estimation therefore the associated error from speed measurement at those periods were diminished. As the result, the accuracy of RSSD estimation outstandingly increases on the highly congested traffic conditions which conform to equation (16). Additionally, in the same segment, once the stopped delay time increases (higher congested), the RSSD technique provides better speed estimation than the estimation in the uncongested situation.
5. CONCLUSION

Estimating of link travel speed on urban arterials is difficult task but as one of the key indicators for representing traffic state, it is considered as the imperative procedure in developing traffic information. In this paper, we have proposed the algorithm for calculating travel speed on urban roadways from probe data called “Running Speed and Stopped Delay (RSSD) method”. This technique employs the advantage of moveable sensor in which the location and speed of tracked vehicle can be automatically detected. Consequently, the running speed and stopped delay time of probe vehicle during traversing any road segment could be extracted from recorded data. Moreover, for illustrating the applicability range of RSSD technique, we also provide some discussions on the limiting of error in speed associated from each GPS device to maintain the advantage of proposed technique in travel speed estimation.

Result from the analysis indicates the advantages of RSSD over baseline approach in addressing speed estimation which can be demonstrated by the higher limiting error in speed associated with each GPS device and also points out the higher accuracy level when RSSD approach was employed as the travel speed estimation technique particularly in the highly congested traffic conditions.

Furthermore, the high resolution field data collected from urban arterial roadways in Bangkok was used to verify the accuracy of proposed technique and compare with the baseline approach. Results from field observations demonstrate that the accuracy of RSSD method on travel speed estimation outperforms baseline method in all test scenarios. Although, both techniques provide the same estimation result on the uncongested segments (segment without stopped delay time), study result illustrates the remarkably improvement when RSSD technique was employed in the congested condition.

The segment length also affects the correctness of speed estimation, as the segment length or segment travel time increases the accuracy of speed estimation increases. In addition, in the same segment, once the congestion enhances, the RSSD technique provides higher accuracy than in the uncongested traffic.

REFERENCES


