Evaluation of Offline and Online Speed-based Travel Time Estimation on Expressway

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Abstract: The objective of this paper is to evaluate travel time estimation techniques for offline and online applications using traffic speed. The study area was the 8.1-km Chalerm Mahanakorn Expressway Daokanong – Port section in Bangkok. Traffic speeds were collected at 7 stations. Average traffic volume of 6,140 vph was observed during the 6:00am to 22:00pm period. Four offline methods were used to convert speed into travel time for each link, namely: mid-point, section average, weighted section average, and San Antonio’s (lower speed). To aggregate link travel time into route travel time, the instantaneous and time slice methods were considered. The estimated travel time were then compared with the actual travel time observed from 1,632 vehicles. The results indicate that the accuracy depends on the time period and level of traffic congestion. Considering route travel time, the time slice method gives a slightly better accuracy than the instantaneous method. Comparing the offline (all data present) and online (short-term forecast of speed in the next time slice(s)) travel time estimation, the two methods yield similar accuracy. The findings of the research imply that the practical travel time estimation may need several methods suitable for each time period. The improved estimation can increase the accuracy over a single method, thereby decreasing the MAPE from 14-20% to 11%.

Key Words: Travel time, Estimation, Speed, Offline, Online

1. INTRODUCTION

Travel time is perhaps the most important parameter representing traffic and travel conditions. Travel time is essential for planners and operators for evaluating the operational efficiency and for determining proper traffic management. It is used as a key performance measure for Advanced Traffic Management System (ATMS). Moreover, travel time enables motorists to assess traffic condition and make better decisions when driving or when faced with rerouting. Travel time is incorporated in Advanced Traveler Information System (ATIS) such as real-time vehicle route guidance system (Nam and Drew, 1996).

Reliable and accurate travel time can be obtained by several ways, which can simply be classified into two categories namely: direct and indirect measurements. Direct travel time measurement includes probe vehicles, video license plate matching, automatic vehicle identification (AVI), and cellular phone tracking. Indirect methods estimate travel time from
collected basic traffic data, notably speed or flow data obtained from infrastructure sensors. These sensors may be inductive loop detectors, video cameras (with image processing), radar or microwave detectors. While many of these methods are costly, the estimation of travel time from infrastructure sensors seems cost-effective since these traffic sensors already exist and data are available as a part of road surveillance and management operations, especially on facilities with controlled access such as freeways or expressways.

Derived from infrastructure sensor data, travel time on expressway can be estimated by the following methods: Flow-based or Speed-based, depending on the availability of data. Flow-based travel time estimation utilizes continuous traffic stream measurement to estimate travel time over a link between two counting stations. The estimation methods employ both statistical and traffic flow theory models. The accuracy of estimation relies heavily on the errors of counts and estimation technique. Vanajakshi et al. (2009) reported that some flow-based travel time estimations which were popularly adopted in the field, could have deviations by almost 50% especially during the congestion period. Readers may refer to the paper by Nam and Drew (1996) for more details on flow-based estimation methods.

Speed-based travel time estimation methods rely on speed data provided from point detectors, normally located at counting stations. Speeds can be directly obtained from dual loop detectors, video image processing, or radar detectors. The speed-based travel time estimation is widely used due to their simplicity. However, various estimation models can be proposed, based on their assumptions, calculation methods, and data used. Li et al. (2006) categorized the models into two types; offline and online, depending on their data availability for calculation and expected application. Offline models construct the travel time in relation with historical speed data. The models are used to produce a travel time estimate if a vehicle wishes to traverse a corridor starting at time k, on a basis of data from time period k and later time periods. Online models require a short-term estimation of speed for the (future) later time periods, since these values are unknown in the real world online applications.

This paper examined several techniques that could be employed to enhance the accuracy of travel time estimation on expressway. Four estimation techniques were investigated, namely: mid-point, link-end average, weight average, and San Antonio’s or lower speed method. Two ways of travel time aggregation were computed and compared: instantaneous and time slice. Finally, the models’ accuracy was evaluated for offline and online methods.

2. THEORETICAL BACKGROUND AND CONSTRUCTION OF TRAVEL TIME ESTIMATION METHOD

2.1 Travel Time Estimation
Travel time is defined as the time duration for a vehicle or traffic (group of vehicles) in traversing a section of road. More specifically, a link travel time is the time spent on a link originating at an upstream node and ending at a downstream node. Since many links are connected to form a corridor or route, a route travel time is basically the summation of link travel times of all links on the route. In other words, the route travel time is the time spent from the first end of origin node (of the first link) to the end of the destination node (of the last link) on the route.

Travel time has a clear relationship with speed. For a vehicle, travel time on a link from an
upstream node to a downstream node which has a distance $S$ apart, can be expressed as:

$$T = \frac{v}{S}$$  \hspace{1cm} (1)$$

where $T$ is the travel time on the link and $v$ is the speed of the vehicle traversing the link (space speed). Since $S$ is fixed, the travel time is known when the speed is estimated.

For a specific consideration on speed in relation to travel time, let $t_u$ be the departure time from upstream node and $t_d$ be the arrival time to any distance on the road link. $T$ denotes the travel time from the upstream node. The travel distance $x$, corresponding to the speed profile $v(t)$ is expressed by

$$\Delta x = \int_{t_u}^{t_d} v(t) \, dt$$  \hspace{1cm} (2)$$

Figure 1 shows a simple illustration of two vehicles traversing two links on a route. Let $t_i^u$ be the arrival time of vehicle $i$ at node 1 (upstream node) and $t_i^d$ be the departure time of vehicle $i$ at node 2 (downstream node).

Figure 1 shows speed profiles of two vehicles traveling on a route. Vehicle 1 enters node 1, upstream on link 1 at time $t_u^1$ and leaves link 1 at downstream node 2 at time $t_d^1$. The travel time of this vehicle traversing link 1, $t_d^1 - t_u^1$, is the integral of instantaneous speed(s) during $t_u^1$ and $t_d^1$ as shown in equation (2). Vehicle 2 enters node 1 at time $t_u^2$ and leaves node 2 at time $t_d^2$. The travel time of this second vehicle is $t_d^2 - t_u^2$. The travel time calculation employs entire speed profile during the travel on the link between $x_u$ and $x_d$. With the point data available at nodes 1 and 2, only the traffic speeds at these locations are known. The travel time estimation is then the approximation of the speed profile of travel between the upstream and downstream nodes of link 1. The average speeds at $x_u$ and $x_d$ are equal to $(v_u^i + v_d^i)/2$ and $(v_u^i + v_d^i)/2$ in case of time mean speed, and $2/(1/v_u^i + 1/v_d^i)$ and $2/(1/v_u^i + 1/v_d^i)$ in case of space mean speed regardless of the speed profile between $x_u$ and $x_d$. The travel time estimation from speed at upstream and downstream nodes must hold any assumption regarding the speed profile (and
its speed alteration) on the link. This assumption becomes a unique characteristic of the link since each link has different physical and traffic conditions.

Speed is normally aggregated to be a representative speed for a given time period (time slice). The speed is practically averaged over a specified time at a given reference station (i.e. upstream node) without considering the vehicle passage onto the next node (downstream node) for more precise travel time determination. Chu et al. (2005) illustrated the determination of average speed considering the arrival and departure time of vehicles (traffic) traversing a link. The average speed must be determined for the time period (t, t+1) for those vehicles traversing a corresponding distance, not just those traversing between upstream and downstream nodes at distance (x_u, x_d). The theoretical average speed accounts for all vehicles entering the upstream node or leaving the downstream node during (t, t+1). The average speed (space mean) is expressed as:

\[
\bar{v} = \frac{\sum_{n=1}^{N} \left\{ \min\left(x^n_{t+1}, x^n_d\right) - \max\left(x^n_u, x^n_d\right) \right\}}{\sum_{n=1}^{N} \left\{ \min\left(t + 1, t^n_d\right) - \max\left(t, t^n_u\right) \right\}}
\]  

(3)

Where
- \( N \) = number of vehicles passing the link
- \( x^n_t \) = distance of vehicle \( n \) at time \( t \)
- \( x^n_u \) = distance of upstream node
- \( x^n_d \) = distance of downstream node
- \( t^n_u \) = time when vehicle \( n \) passes the upstream node
- \( t^n_d \) = time when vehicle \( n \) passes the downstream node.

The mean travel time for a time period (t, t+1) is calculated from:

\[
T_s = \frac{x_d - x_u}{\bar{v}} = \frac{Ax}{v}
\]  

(4)

The theoretical determination of travel time for a time period (t, t+1) shows difficulties in exact calculation of travel time in practice. First, it is unknown which vehicles enter the upstream node and leave the downstream node during (t, t+1). Although many attempts were made to approximate this using knowledge of traffic flow, the approximation relies on the
traffic flow condition on the link (the level of congestion) and the variation of traffic movements on the link. In reality, therefore, the known traffic flow data are mainly the traffic flow during \((t, t+1)\) and the associated speed of all vehicles in the same time period.

### 2.2 Speed-based Travel Time Estimation Model

Several studies suggest various calculation methods for determining link travel time from spot speed data. These travel time estimation methods range from a simple model using speed representative of a section to a complicated model which takes into account the dynamic traffic speed in different time slices. Four methods of travel time estimation from speed are described below:

1. **Travel time calculation from mid-section speed,** \(T_{mid}\). Travel time is calculated from the average speed at the midpoint of the road link. The traffic speed over the entire link section is approximated by the average speed measured at the mid-point of the link. Therefore, \(v_{SMS}\) can be the representative of average speed of the entire section, \(\bar{v}_{mid}\), and thus,

\[
\bar{v}_{mid} \approx v_{SMS}
\]

\[
T_{mid} = \frac{S}{\bar{v}_{mid}}
\]

where \(S\) is the distance of the road link, km
\(\bar{v}_{mid}\) is the average speed at the midpoint of the road link (km/h).

2. **Travel time from link-end speed average,** \(T_{avg}\). Travel time for each link is computed from the average of the speeds at upstream and downstream sections of the link.

\[
\bar{v}_{avg} = \frac{v_u + v_d}{2}
\]

\[
T_{avg} = \frac{2 \times S}{v_u + v_d} = \frac{S}{\bar{v}_{avg}}
\]

where \(v_u\) is average speed at upstream node (km/h)
\(v_d\) is average speed at downstream node (km/h).

3. **Travel time from weighted average link-end speed,** \(T_{weight}\). Travel time for each link is computed from the weighted average of speeds at upstream and downstream sections of the link by the traffic volumes at upstream and downstream sections.

\[
\bar{v}_q = \bar{v}_{weight} = \frac{q_u v_u + q_d v_d}{q_u + q_d}
\]

\[
T_{weight} = \frac{S}{\left\{v_u \times \left(\frac{q_u}{q_u + q_d}\right) + v_d \times \left(\frac{q_d}{q_u + q_d}\right)\right\}}
\]

where \(q_u\) is traffic volume at the upstream node (veh)
\(q_d\) is traffic volume at the upstream node (veh).
4. San Antonio’s or Travel time from lower speed calculation, $T_{San}$. Travel time is calculated from the lower speed, measured at upstream and downstream sections.

$$\bar{v}_{San} = \min \{v_u, v_d\}$$  \hspace{1cm} (11)

$$T_{San} = \frac{S}{\bar{v}_{San}}$$ \hspace{1cm} (12)

where $v_{San}$ is the lower speed between the two speeds calculated at the upstream and downstream nodes.

2.3 Instantaneous and Time Slice Travel Time Estimation

The above speed-based travel time estimation models, with the exception of the mid-point model, consider the manipulation of average speeds at upstream and downstream ends of the link. Referring to Li et al. (2006), if the average speeds at both nodes come from the same time period, then the model is based on the instantaneous travel time estimation.

Let $v(x, k)$ represent an average speed of traffic at a node of distance $x$ and the data are averaged for time period $k$. Travel time for a link $i$ at time period $k$ can be expressed in an instantaneous model (link-end speed average model) as

$$T(i,k) = \frac{2S}{v(x_u,k) + v(x_d,k)}$$ \hspace{1cm} (13)

where $x_u$ and $x_d$ is the distance of upstream and downstream nodes of link $i$, respectively.

The route travel time is calculated from the summation of travel time of $n$ links forming the route.

$$RT(k) = \sum_{i=1}^{n} T(i,k)$$ \hspace{1cm} (14)

The instantaneous model requires only speed data at time period $k$ at all nodes (counting station). An intrinsic assumption is that the speeds will not change dramatically over time it takes the vehicles to traverse from the origin to the end of the route. This assumption may be plausible during the uncongested flow condition. The discernable advantage of this model is that it can be used for online application. This model is widely used in the United States and Australia for providing real-time travel time information (Oz Engineering and Motive Maps, 2004 and Kloot, 1999).

An improvement to account for the variation in speed over time is the consideration of expected travel time on the route. When a vehicle starts its journey at time $k$ at the entering node, it would incur travel time of $T(n,k)$ in link $n$ before reaching the link $n+1$. When this vehicle leaves link $i$, this vehicle spends a total of $\sum_{i=1}^{n} T(i,k)$. Thus, the time that this vehicle enters the subsequent link may fall in the next time period $k+1$. In this manner, the travel time calculation for link at time $t_k (i, t_k)$ is called Time slice model and can be written as

$$T(i,t_k) = \frac{2S}{v(x_u,k) + v(x_d,k + t(i,k))}$$ \hspace{1cm} (15)

This model can be further refined through an iterative method as suggested by Cortes et al.
2.4 Offline vs. Online Travel Time Prediction
Unlike instantaneous models, the time slice travel time estimation requires an average speed of the traffic at the downstream node for the next time period, when necessary, to compute travel time. In real application, the average speed in the next time period is unknown. Therefore, it is necessary to predict the average speed in the next time period using available speed data. In this research, a simple moving average is proposed since it utilizes the knowledge on traffic speed at the corresponding node. This short-term past data can be a good indicator for estimating the speed close to reality. Similar to the instantaneous model, an intrinsic assumption is that the traffic condition will not change drastically in the next time period.

2.5 Comparison on Performance of Travel Time Estimation
Tufte et al. (2008) proposed several indicators to examine the accuracy of travel time estimation. Nonetheless, the accuracy is typically measured using the Mean Absolute Percent Error (MAPE). Statistically, MAPE is defined as the average of percentage errors. MAPE is also often useful for purposes of reporting, because it is expressed in generic percentage terms. The MAPE can only be computed with respect to data that are guaranteed to be strictly positive.

\[
MAPE = \frac{1}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right| * 100
\]

where \( A_t \) and \( F_t \) are actual value and estimated value for time period \( t \), respectively, and \( n \) is the number of data to be computed (i.e., number of time periods).

3. RESEARCH DESIGN AND METHODOLOGY

3.1 Study Location
The study obtained traffic data from Chalerm Mahanakorn Expressway in Bangkok, Thailand. The Daokanong-Port section has been equipped with 11 image processing camera units but data from only 7 units were used in this study. The layout of the study site is shown in Figure 3.

The traffic on this expressway section varies by time of day. The peak period took place in the morning during 6:00-10:00am. The speed data were obtained directly from image processing units. These speed sensors did not detect the data for all vehicles, rather they captured the samples of speed when vehicles passed the virtual detection zones.

The study route is 8.1 km, some sections of which have 4 lanes and others have 6 lanes. The traffic sensors have been installed at intervals ranging from 400m to 2,000 m. The locations of speed sensors are illustrated in Figure 4.
The data were collected during 6:00am-22:00pm on June 9, 2010. Video image processing cameras provided real-time data of flow, speed, and occupancy of traffic at each counting station (node). Figure 5 shows the collected traffic speed data. Note that speed from each station differs greatly due to several physical factors such as on-ramp, steep bridge, off-ramp, and traffic conditions. Note that traffic congestion occurred during 6:00am-10:00am. This period is considered to be the morning peak. Station 10 (EXAT10), the last speed measurement station, experienced a slow queue back up from the downstream link, causing a slowdown during the 17:30pm-19:00pm period.

The actual route travel time data were obtained from video extraction. The total travel times of approximately 1,700 vehicles were collected. This amount of data guaranteed more than 95% of statistical significance and was sufficient for representing the actual travel time. The actual travel time on the expressway is shown in Figure 6.
3.2 Evaluation Plan
This study evaluated speed-based travel time estimation in three aspects. First, the methods for average speed calculation were evaluated. Four speed-based estimation models were tested and compared using the real travel time data on the Expressway. Second, the instantaneous and time slice models were determined and compared. Third, the last evaluation was the test of on-line applications when some travel times in the coming time period had to be estimated for the time slice estimation model. The evaluation plan is shown in Figure 7.

4. RESULTS AND DISCUSSIONS

4.1 Comparison of Travel Time Estimation Methods
Figure 8 gives one example of link travel time estimation. The travel time can be estimated for all links to provide the examination on the differences in the estimation by various methods.

In summary, \( T_{avg} \) and \( T_{weight} \) give close values while \( T_{san} \) and \( T_{mid} \) tend to give large differences from each other. \( T_{san} \) is the highest, especially during congestion periods (6:00am-10:00am and 17:30pm-19:00pm) because these time periods had a sudden change in traffic flow speed. The \( T_{san} \) results in longer travel time as it selects the lower speed. \( T_{mid} \) has higher value compared to \( T_{avg} \) and \( T_{weight} \) and has low variation. \( T_{avg} \) and \( T_{weight} \) are similar but the travel time from \( T_{san} \) is always higher than travel times from other methods.
Figure 9 illustrates the results of route travel time from the four methods, using both instantaneous and time slice methods. These results can be used to compute Mean Absolute Percentage Error (MAPE), to evaluate the accuracy of the estimation. The results of the comparison are shown in Table 1. During morning peak hour period, MAPE ranges from 10-30%. Travel time from mid-point method gives the lowest errors, especially with the time slice method (MAPE 12% compared to 23-26% from other methods). During the afternoon peak period, where the end of the route was affected by slow queue from downstream road section, traffic congestion on the last link of the route produced irregular travel time estimation and thus resulted in high MAPE. During off peak period, the MAPE is low. This means that the estimation is close to the actual value. Travel time from San Antonio’s gives the best accuracy (MAPE 11% compared to 14-15% from other methods).

4.2 Practical Improvement of Travel Time Estimation
The previous findings of travel time estimation reveal that the calculation of travel time from various methods yield different levels of accuracy. Thus, a practical improvement of the travel time estimation is to select appropriate estimation method for a particular traffic condition. In this research, two improvement methods were selected and tested; the first was the selection of the best estimation method according to time of day, and the second was the selection of the best estimation method according to the level of traffic congestion (speed).

The first practical improvement method (D1) selected the best travel time estimation method from the results of the previous analysis. The practical travel times were estimated from mid-point average, end-link speed average, and San Antonio’s, during the morning peak, afternoon peak, and off-peak, respectively. The results show that the selection of the best estimation method according to time of day improves the overall accuracy from 14-19% by single method to 11%.
The second practical improvement method (D2) was the selection of travel time estimation method from the amount of travel time. First, the travel times of the entire duration were sorted and categorized and the MAPE for each travel time category was determined. Then the best estimation method was selected based on the minimum MAPE for each class.

A question may be asked as to what value of travel time should be used to be the representative travel time for each category (period). In reality, the actual travel time is not available and therefore in practice, a value of travel time from an estimation method must be used. In this research, an investigation was conducted to find the best representative of travel time. Several combinations of the representative travel time were tested. Table 2 displays the results of the accuracy when using various ways of averaging estimated travel time(s).

The result in Table 2 suggested that the travel time from mid-point speed should be used for two reasons. First, the travel time from mid-point speed required simple calculation utilizing an average of speed of the section. This travel time estimate would not produce extreme high or low travel time (in case of San Antonio’s). Second, considering MAPE in the previous analysis, the travel time from mid-point speed produced the highest accuracy among all
methods for the entire day. Thus, the travel time from mid-point speed was first used to classify travel time into categories before assigning the proper estimation method for each category.

Table 2. Mean Absolute Percentage Error (MAPE) of the average of travel times from various estimation methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Tawsm</th>
<th>Taws</th>
<th>Tawm</th>
<th>Tasm</th>
<th>Taw</th>
<th>Tas</th>
<th>Tws</th>
<th>Tsm</th>
<th>Ta</th>
<th>Tw</th>
<th>Ts</th>
<th>Tm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MAPE</td>
<td>13.7</td>
<td>13.7</td>
<td>16.2</td>
<td>14.6</td>
<td>14.9</td>
<td>17.2</td>
<td>15.8</td>
<td>15.8</td>
<td>15.9</td>
<td>14.8</td>
<td>16.0</td>
<td>16.9</td>
</tr>
</tbody>
</table>

a = average, w=weight, s=San Antonio’s, m=mid-point

Figure 10 and Table 3 summarize the results of MAPE for each travel time category. When the instantaneous travel time estimation is used, the San Antonio’s method gives the greatest accuracy when the speed is high (i.e., off-peak or uncongested condition), while generally the travel time estimation from mid-point speed is the best method when travel time ranges from 9 to 17 minutes (35 to 66 kph). At lower speed, the travel time from speed average or weighted speed average gives the best results. The trend is also similar when the time slice travel time estimation is used. The San Antonio’s method is the best when traffic speed is high. At middle range of speed (35-60 kph), travel time from mid-point speed gives the best estimate, and at low speed (less than 35 kph), travel time estimated from average speed or weighted average speed gives the best result.

Figure 10. Mean Absolute Percentage Error (MAPE) for each travel time estimation method

Table 3. Tabular Mean Absolute Percentage Error (MAPE) by travel time estimation method

<table>
<thead>
<tr>
<th>Travel Time</th>
<th>Instantaneous</th>
<th>Timeslice</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Minute)</td>
<td>(Sec)</td>
<td>Tavg</td>
</tr>
<tr>
<td>0-6</td>
<td>0-360</td>
<td>14.7</td>
</tr>
<tr>
<td>6-7</td>
<td>360-419</td>
<td>16.4</td>
</tr>
<tr>
<td>7-8</td>
<td>420-479</td>
<td>20.3</td>
</tr>
<tr>
<td>8-9</td>
<td>480-539</td>
<td>30.0</td>
</tr>
<tr>
<td>9-10</td>
<td>540-599</td>
<td>34.7</td>
</tr>
<tr>
<td>10-11</td>
<td>600-659</td>
<td>24.7</td>
</tr>
<tr>
<td>11-12</td>
<td>660-719</td>
<td>9.9</td>
</tr>
<tr>
<td>12-13</td>
<td>720-779</td>
<td>72.0</td>
</tr>
<tr>
<td>13-14</td>
<td>780-839</td>
<td>66.0</td>
</tr>
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<td>14-15</td>
<td>840-899</td>
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<td>900-959</td>
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<td>16-17</td>
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<td>17-18</td>
<td>1020-1079</td>
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</tr>
<tr>
<td>18-19</td>
<td>1080-1139</td>
<td>13.2</td>
</tr>
<tr>
<td>19-20</td>
<td>1140-1199</td>
<td>20.2</td>
</tr>
<tr>
<td>&gt;20</td>
<td>&gt;1200</td>
<td>42.0</td>
</tr>
</tbody>
</table>
4.3 Performance of Online Travel Time Estimation Models

The previous section describes the investigation of the best offline travel time estimation method in case that the traffic speed data in all time periods are known. The investigation can determine the best estimation method that yields the highest accuracy, compared to the actual travel time. In reality, the time slice estimation requires short-term future traffic speed in the subsequent sections, whenever necessary. Thus, this travel time in the subsequent period needs to be predicted.

The objective of this investigation was to observe the change in accuracy when the unavailable travel time in the subsequent period(s) was estimated. The technique for short-term forecast was the moving average for the future speed in the subsequent time period. This technique is simple but powerful in producing the prediction using the most up-to-date speed information in the current and past time periods.

Two methods of online short-term speed forecast using moving average were tested. In the first method, the speed data in the first time period was assumed to have the same value as the previous time period. Then the speeds in the subsequent link(s) were predicted. This method was herein called “previous data”. The other method was to forecast the unavailable speed on the first link, when rules applied. This method was called “predict data”. Using the four fundamental methods of travel time estimation, and the two improvement methods (D1, D2), the results could be compared with those travel times estimated by offline methods. The results of MAPE used for accuracy comparison are shown in Table 4.

Table 4. Mean Absolute Percentage Error (MAPE) of offline and online travel time estimation

<table>
<thead>
<tr>
<th>Method</th>
<th>Peak Time 1 (6:00am–10:00am)</th>
<th>Instantaneous</th>
<th>Timeslice</th>
<th>Previous data</th>
<th>Predict Data</th>
<th>Offline Previous data</th>
<th>Predict Data</th>
<th>Offline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tavg</td>
<td>24.7</td>
<td>25.5</td>
<td>23.9</td>
<td>26.2</td>
<td>25.4</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tweight</td>
<td>24.4</td>
<td>25.9</td>
<td>23.8</td>
<td>26.0</td>
<td>25.8</td>
<td>23.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSan</td>
<td>26.3</td>
<td>23.1</td>
<td>25.6</td>
<td>24.2</td>
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<td>13.3</td>
<td>14.2</td>
<td>11.9</td>
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<td>14.2</td>
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<th>Predict Data</th>
<th>Offline Previous data</th>
<th>Predict Data</th>
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<td>9.1</td>
<td>6.7</td>
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<td>19.1</td>
<td>23.3</td>
<td>22.9</td>
<td>19.3</td>
<td>23.3</td>
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<tr>
<td></td>
<td>D1</td>
<td>6.9</td>
<td>5.4</td>
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<td>5.4</td>
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<th>Timeslice</th>
<th>Previous data</th>
<th>Predict Data</th>
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<th>Predict Data</th>
<th>Offline</th>
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<tr>
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<td>15.9</td>
<td>16.1</td>
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<td>15.3</td>
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<td>TSan</td>
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<td>9.0</td>
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<td>9.0</td>
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<td>14.2</td>
<td>14.0</td>
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<td>14.2</td>
<td>13.9</td>
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<tr>
<td></td>
<td>D1</td>
<td>11.0</td>
<td>9.0</td>
<td>10.9</td>
<td>10.8</td>
<td>9.0</td>
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<tr>
<td></td>
<td>D2</td>
<td>9.5</td>
<td>8.0</td>
<td>9.6</td>
<td>9.5</td>
<td>8.1</td>
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<table>
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<th>Instantaneous</th>
<th>Timeslice</th>
<th>Previous data</th>
<th>Predict Data</th>
<th>Offline Previous data</th>
<th>Predict Data</th>
<th>Offline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tavg</td>
<td>16.7</td>
<td>17.4</td>
<td>16.5</td>
<td>17.0</td>
<td>17.4</td>
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<tr>
<td></td>
<td>Tweight</td>
<td>16.2</td>
<td>17.1</td>
<td>16.1</td>
<td>16.7</td>
<td>17.1</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSan</td>
<td>19.4</td>
<td>16.6</td>
<td>19.2</td>
<td>18.8</td>
<td>16.8</td>
<td>19.5</td>
<td></td>
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<tr>
<td></td>
<td>Tmid</td>
<td>14.9</td>
<td>14.7</td>
<td>14.7</td>
<td>14.8</td>
<td>14.7</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D1</td>
<td>11.3</td>
<td>10.0</td>
<td>11.2</td>
<td>11.1</td>
<td>10.0</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>13.8</td>
<td>13.1</td>
<td>13.9</td>
<td>13.9</td>
<td>13.2</td>
<td>13.8</td>
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</table>
Comparing the two methods of online estimation, both produce similar accuracy. The MAPE does not differ more than 3%. Tavg, Tweight, and Tmid have the same trend of accuracy, as they give the higher accuracy using previous data. Comparing the instantaneous and time slice methods, the two methods do not show any difference in accuracy in travel time estimation when the traffic congestion is low. During morning peak period however, the time slice method shows some accuracy improvement over the instantaneous method when using Tsan and Tmid estimation method.

The results in Table 4 imply that in general, the online travel time estimation produces minor different accuracy from the offline method. During morning peak period, offline estimation performs better than online estimation. In contrast, during afternoon peak period, the online estimation performs better. During off-peak periods, the accuracies from both methods are generally comparable.

**4.4 Discussions**

The study (Table 1 and Table 4) reveals several interesting findings. First, for this specific expressway, the best accuracy of offline travel time estimation ranges from 7-15%. The time slice method, which considers appropriate link travel time calculation based on arrival time at the corresponding link, does not improve much the accuracy. The improvement ranges 0-1.4% over the instantaneous method. Among the four travel time estimation methods, travel time calculated from mid-point speed provides the best accuracy during the morning peak period, while travel time from San Antonio’s gives the best accuracy during off-peak period. It shows that during the off-peak period, when the traffic speed is high and with less variation, a simple method of travel time estimation still works well.

Second, since a travel estimation method works well for a particular time period(s), it is suggested that the alteration of estimation method by time of day (D1) will improve the accuracy of the estimates by 3% over the whole day, compared to the single best estimation method. Nonetheless, during some time period, D1 can improve greatly (e.g. during afternoon peak, MAPE of Tsan and D1 is 40% and 7%, respectively). The selection of estimation method by travel time class (D2) is somewhat complicated and does not improve the accuracy better than the selection by time of day (D1). Therefore, it is suggested that the practical travel time estimation can employ appropriate methods for specific time period(s). As suggested by the results of the study, Tmid should be used during morning peak period, Tavg during afternoon peak period, and Tsan during off-peak period.

Third, the online estimation does not lose much accuracy when compared to the offline method. A simple speed forecast for the subsequent time period can give relatively sufficient travel time estimation accuracy. The accuracy of online method is lower than that of offline method by no more than 3% (MAPE) for each time period, and no more than 1.8% for the whole day.

The results of travel time estimation in this study may be compared to those from other studies in other locations. Keep in mind that travel time estimation in each study differs from one another in the physical layout of detectors, and amount and interval of traffic speed data. Table 5 is the comparison of MAPE between this study and another study in Australia (Li et al., 2006)
Table 5. Comparison of Mean Absolute Percentage Error (MAPE) of travel time estimation in Thailand and Australia

<table>
<thead>
<tr>
<th>Method</th>
<th>Time Period</th>
<th>Citylink, Australia</th>
<th>Bangkok, Thailand (Tmid, Online single method): Offline (previous data)</th>
<th>Bangkok, Thailand (D1, Time of day): Offline (previous data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous</td>
<td>Morning</td>
<td>12.9</td>
<td>13.3 (14.0)</td>
<td>13.3 (14.0)</td>
</tr>
<tr>
<td></td>
<td>Afternoon</td>
<td>11.1</td>
<td>23.3 (22.9)</td>
<td>7.3 (6.9)</td>
</tr>
<tr>
<td></td>
<td>Off-peak</td>
<td>6.3</td>
<td>14.0 (14.1)</td>
<td>14.0 (14.1)</td>
</tr>
<tr>
<td>Time slice</td>
<td>Morning</td>
<td>12.2</td>
<td>11.9 (13.3)</td>
<td>11.9 (13.3)</td>
</tr>
<tr>
<td>(dynamic)</td>
<td>Afternoon</td>
<td>10.4</td>
<td>23.3 (22.9)</td>
<td>7.3 (6.9)</td>
</tr>
<tr>
<td></td>
<td>Off-peak</td>
<td>5.9</td>
<td>13.9 (14.2)</td>
<td>11.2 (10.8)</td>
</tr>
</tbody>
</table>

Note: In Australia, the term Mean Absolute Relative Error (MARE) is used.

Data in Table 5 may be difficult to be directly compared since the data come from different location and setting. It may be pointed out that the travel estimation method works well to estimate travel time during off-peak in Australia, with MAPE value as low as 5.9% using dynamic time slice method. In Thailand, a simple method of travel time from mid-point can estimate the travel time during morning peak period as good as 12%. In both studies, the (dynamic) time slice method provides better accuracy than the instantaneous method. The improvement in Australia is approximate 0.7% MAPE, while the improvement in Thailand is as much as 2.8% during off-peak period.

Another implication from the study is that the estimated travel time is approximately 7.5-14% for the expressway in Bangkok, Thailand. With the distance of 8 km and the travel time during peak hour of about 18 minutes, the calculated travel time will deviate from the true travel time by approximately 2-3 minutes. This level of accuracy is acceptable for many traveler information system applications. In the United States, a general acceptance on the accuracy of travel time estimation is about 20%.

5. CONCLUSION

This paper evaluated various speed-based travel time estimation methods. These methods were constructed with various methods of average speed determination and dynamic of time periods for calculation of link and route travel time. Four methods of travel time calculation, namely: mid-point, end-link average, weight average, and lower speed (San Antonio’s), were evaluated with data from an expressway in Bangkok, Thailand. Each method gives different accuracy. The time slice method, which considers dynamic travel time on links, gives higher estimation accuracy than the instantaneous method. Improvement in accuracy over a single estimation method can be achieved by selecting an appropriate estimation method for a given time period. The improvement can be as much as 3.5% compared to the best single estimation method.

The online estimation method is compared with the offline method. The online method requires some short-term forecast of speed in the next time period. With the use of simple moving average technique, the online estimation method produces comparable accuracy. The findings of the research could assist the development of appropriate travel time estimation method with sufficient level of accuracy for many applications.
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REFERENCES


