A Cell Probe-Based Method for Vehicle Speed Estimation

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1. Introduction

Constructing intelligent transportation systems (ITS) to obtain real-time traffic information (e.g., average vehicle speed, travel time, traffic flow, and traffic condition) are important issues for the developments of smart cities. The real-time traffic information collection methods can be grouped into three categories: vehicle detector (VD), global position system (GPS)-based probe car, and cellular floating vehicle data (CFVD). Although the precise traffic information can be estimated and collected by VDs, the deployment and maintenance fees are very expensive. GPS-based probe cars can report the vehicle speed and travel time, but the penetration rate of GPS-based probe cars is usually not high enough to infer precise real-time traffic information. The number of people owning cell phones has been increased, so using mobile stations (MSs) as probes for tracking the locations of MSs and obtaining CFVD is feasible.

Some studies proposed analytical models based on CFVD to estimate traffic information (e.g., traffic flow, vehicle speed, vehicle density, and travel time). For instance, when a MS moves from a location area (LA) to another LA, the normal location update (NLU) procedure is performed. Therefore, the NLU events can be used to estimate traffic flow. Furthermore, two consecutive NLU events can be collected and used for the estimations of vehicle speed and travel time [1]. However, the traffic information estimation methods based on two consecutive NLU events are only suitable for long road segments. Therefore, traffic information estimation methods based on two consecutive handoff (HO) events have been proposed for shorter road segments [2]. Although these methods can obtain precise traffic information for shorter road segments, the availability ratios of these methods may be very lower.

Therefore, this study tracks and analyses the locations of mobile user signals through interfaces of cellular networks. Firstly, this study monitors the network interfaces (e.g., A and IuCS) and designs an ITS server to retrieve the network signals (e.g., NLUs, HOs, and call arrivals (CAs)) and estimate the traffic condition information. When a call is initialized, the processes of CA will be performed by a calling party and a called party; the number of CA which is associated with vehicle density [3] can be used for vehicle speed estimation. This study designs a regression-based method and considers the NLU-based method and HO-based method to propose a vehicle speed estimation algorithm which is called CP-based method (shown in Fig. 1).

2. Vehicle Speed Estimation

2.1 NLU-Based Speed

For the estimation of NLU-based speed, Fig. 2 illustrates the space diagram for vehicle movement and NLU on a road. This study supposes that there is a road covered by three LAs and a MS in a car on the road. The detail steps are as follows.

**Step 1:** When the car moves from LA1 to LA2, the NLU procedure is performed. A NLU signal is sent to core network, and the ITS server can retrieve the signal which contains the location of NLU L1 and NLU time t1.

**Step 2:** When the car moves from LA2 to LA3, the NLU procedure is also performed. The ITS server also retrieves...
the signal which contains the location of NLU $L_5$ and NLU time $t_5$. Then the NLU-based speed of the MS can be computed as $u_n = \frac{d(L_5, L_4)}{t_5 - t_4}$ in the period $[t_4, t_5]$, where $d(L_1, L_5)$ denotes the geographic distance between $L_1$ and $L_5$.

2.2 HO-Based Speed

For the estimation of HO-based speed, Fig. 2 illustrates the space diagram for vehicle movement and HO on a road. This study supposes that there is a road covered by six cells and a MS in a car on the road. The detail steps are as follows.

**Step 1:** A CA is performed by the MS in the car at time $t_2$, and the car keeps moving on the road.

**Step 2:** When the communicating MS in the car moves from Cell$_1$ to Cell$_4$, the HO procedure is performed. A HO signal is sent to core network, and the ITS server can retrieve the signal which contains the location of HO $L_3$ and HO time $t_3$. 

**Step 3:** When communicating MS in the car moves from Cell$_4$ to Cell$_5$, the HO procedure is also performed. The ITS server also retrieves the signal which contains the location of HO $L_4$ and HO time $t_4$. Then the HO-based speed of the MS can be computed as $u_n = \frac{d(L_4, L_3)}{t_4 - t_3}$ in the period $[t_3, t_4]$, where $d(L_3, L_4)$ denotes the geographic distance between $L_3$ and $L_4$.

2.3 Regression-Based Speed

In accordance with Ref. [3], the amount of CAs is related with traffic density, which means the amount of CAs is the reciprocal of vehicle speed. Moreover, this study proposes a regression model to analyse the parameters (i.e., $\alpha$ and $\beta$) in Formula (1) [4] from vehicle speed and the amount of CAs. There are $N$ cycles in history data, and the practical vehicle speed $U_i$ and the amount of CAs $a_i$ are recorded in the $i$-th cycle for estimating the vehicle speed $u_i$. Then the NLU-based speed, the HO-based speed, and the estimated vehicle speed from regression model are considered and analysed by CP-based algorithm to estimate CP-based vehicle speed.

$$u_r = \alpha \times a + \beta,$$

where

$$\alpha = \frac{N \left( \sum_{i=1}^{N} a_i U_i \right) - \left( \sum_{i=1}^{N} a_i \right) \left( \sum_{i=1}^{N} U_i \right)}{N \left( \sum_{i=1}^{N} (a_i)^2 \right) - \left( \sum_{i=1}^{N} a_i \right)^2}$$

$$\beta = \frac{1}{N} \left( \sum_{i=1}^{N} U_i - \alpha \sum_{i=1}^{N} a_i \right)$$

2.4 CP-Based Method

Figure 3 shows the CP-based method to analyse the NLU-based speed, HO-based speed, and regression-based speed for vehicle speed estimation. In accordance with the experiment results in previous studies, NLU-based method can provide high vehicle speed estimation accuracy when the traffic state is free flow [1]. Therefore, the NLU-based speed is adopted when the NLU-based speed is faster than the threshold of free flow speed ($\eta_f$). However, NLU-based method cannot immediately estimate the vehicle speed of the short road segment. Therefore, the HO-based speed and the regression-based speed in accordance with the amount of CAs are considered in this paper. The HO-based speed report is not always available in accordance with the call holding time, so it should be checked in each cycle. Moreover, the HO-based method can provide high vehicle speed estimation accuracy when the traffic state is congestion or free flow. Therefore, HO-based speed is adopted when it is faster than the threshold of high speed ($\eta_h$) or is slower than the threshold of low speed ($\eta_l$); otherwise the regression-based speed in accordance with the amount of CAs is adopted.

3. Practical Experimental Results and Discussions

The aim of the practical experiments is to analyse the accuracies of vehicle speed estimation. The practical experiments were carried out on a 30 km long highway segment in the Highway No. 1 in Taiwan. For the evaluation of speed estimation, this study collected the actual speed ($U$) information obtained from VD and analysed the error ratio ($R_h$) for the evaluation of estimated speed $u$ (e.g., $u_h$, $u_n$, and $u_l$) by Formula (2).

$$R_h = \min \left( \left| \frac{U - u}{U} \right| \right) \times 100\%$$

For CP-based method, this study adopted some parameters as follows to estimate the vehicle speed: $\eta_f = 90$ km/hr, $\eta_l = 50$ km/hr, and $\eta_h = 85$ km/hr. The CFVD from Chunghwa Telecom and the VD data from Taiwan Area National Freeway Bureau during September and November in
Table 1  The speed estimation accuracies of the CP-based method.

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<thead>
<tr>
<th>Day</th>
<th>Vehicle Speed Estimation Accuracy</th>
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<tbody>
<tr>
<td>Sunday</td>
<td>96.06%</td>
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<tr>
<td>Monday</td>
<td>98.57%</td>
</tr>
<tr>
<td>Tuesday</td>
<td>98.19%</td>
</tr>
<tr>
<td>Wednesday</td>
<td>98.63%</td>
</tr>
<tr>
<td>Thursday</td>
<td>98.01%</td>
</tr>
<tr>
<td>Friday</td>
<td>96.64%</td>
</tr>
<tr>
<td>Saturday</td>
<td>97.33%</td>
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<tr>
<td><strong>Average</strong></td>
<td>97.63%</td>
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Table 2  The speed estimation accuracy comparisons of methods.

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<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>93%</td>
<td>89%</td>
<td>96%</td>
<td>98%</td>
</tr>
<tr>
<td><strong>Availability ratio</strong></td>
<td>100%</td>
<td>19%</td>
<td>100%</td>
<td>100%</td>
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Table 3  The cost comparisons of methods.

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<td><strong>The number of required servers</strong></td>
<td>A and IuCS</td>
<td>A and IuCS</td>
<td>A-bis and Iu</td>
<td>A and IuCS</td>
</tr>
<tr>
<td></td>
<td>&lt; 100</td>
<td>&lt; 100</td>
<td>&gt; 10000</td>
<td>&lt; 100</td>
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last year were recorded and analysed for the evaluation of the proposed method in the offline environments. Table 1 shows that the average accuracy of the CP-based method is 97.63%.

For the comparisons of vehicle speed estimation accuracy, this study analysed the cellular network signals from Chunghwa Telecom and provides the comparison with NLU-based method [1], HO-based method [2], FPA-based method [5], and CP-based method. The aim of the practical experiments was to analyse the accuracies of vehicles speed estimation based on the different methods. The collected control signals included NLU, CA and HO, and the traffic information reporting cycle is 5 min/cycle (i.e., 288 cycles in one day). The practical results of NLU-based method, HO-based method, FPA-based method, and CP-based method are showed in Table 2. In the practical experimental results, the accuracy of NLU-based speed is about 93%, but this method only obtains precise estimated speed with free flow. Although HO-based method can provide good accuracy for shorter road segment, the availability ratio is about 19%. Moreover, the speed estimation accuracy of the CP-based method is about 98%, and the availability ratio of this method is 100%. In the CP-based method, the average usage ratio of NLU-based, HO-based and Regression-based algorithms are 91%, 1% and 8%, respectively. Therefore, the CP-based method is more suitable for ITS.

For deployment and computation cost, A-bis and IuCS interfaces are needed to be monitored for FPA-based method (shown in Table 3). The number of these interfaces in Taiwan is larger than 10000, and more monitor servers are required. Although the FPA-based method can provide the lower error ratio of vehicle speed estimation than HO-based method, the cost of FPA-based method is too expensive. However, the number of A and IuCS interfaces in Taiwan is smaller than 100. Therefore in the view of cost, the proposed CP-based method is more suitable for ITS.

4. Conclusions

This study proposed a CP-based method to analyse cellular network signals (i.e., NLUs, HOs, and CAs) for estimating vehicle speeds. In practical experiments, this study compared the practical traffic information of VD with the estimated traffic information by the proposed methods. Although FPA-based method can provide good vehicle speed estimation accuracy, it needs to retrieve the cellular network signals via A-bis and IuCS interfaces. However, HO-based method and CP-based method need to retrieve the cellular network signals via A and IuCS interfaces which are usually monitored in each telecom company. Therefore, the deployment and computation cost of FPA-based method is too expensive and is not suitable for vehicle speed estimation. Furthermore, the results showed that the accuracy of vehicle speed estimation by CP-based method which is 97.63% is higher than NLU-based, HO-based and FPA-based methods. Therefore, the CP-based method can be used to estimate vehicle speed from CFVD for ITS.

Acknowledgments

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References