A Cell Probe-Based Method for Vehicle Speed Estimation

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SUMMARY   Information and communication technologies have improved the quality of intelligent transportation systems (ITS). By estimating from cellular floating vehicle data (CFVD) is more cost-effective, and easier to acquire than traditional ways. This study proposes a cell probe (CP)-based method to analyse the cellular network signals (e.g., call arrival, handoff, and location update), and regression models are trained for vehicle speed estimation. In experiments, this study compares the practical traffic information of vehicle detector (VD) with the estimated traffic information by the proposed methods. The experiment results show that the accuracy of vehicle speed estimation by CP-based method is 97.63%. Therefore, the CP-based method can be used to estimate vehicle speed from CFVD for ITS.

key words: intelligent transportation systems, cellular floating vehicle data, cellular networks, vehicle speed estimation, regression

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 city. The real-time traffic information collection methods can be grouped into three classes: 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 maintain fees are very expensive. GPS-based probe car 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 analysed for the estimations of vehicle speed and travel time [1]. However, the traffic information estimation methods based on two consecutive NLU events are only
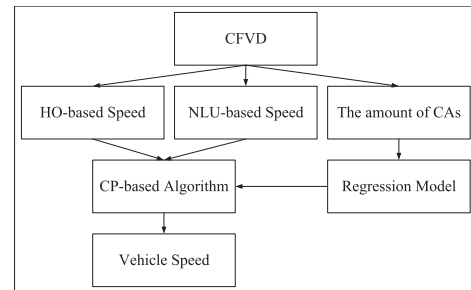
Fig. 1   The considered factors in CP-based method.

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 LA_1 to LA_2, 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 L_1 and NLU time t_1.

Step 2: When the car moves from LA_2 to LA_3, the NLU procedure is also performed. The ITS server also retrieves
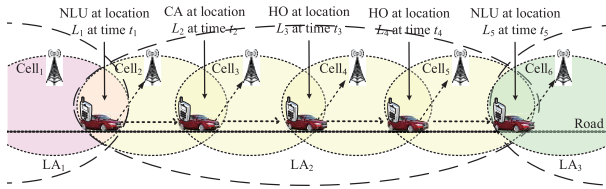
Fig. 2 The cell switching of a moving MS on a road.

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 $u_n = \frac{d(L_1,L_5)}{t_5-t_1}$ in the period $[t_1, t_5]$, 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$_3$ 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 $u_n = \frac{d(L_3,L_4)}{t_4-t_3}$ 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., α and β) 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_r. 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.

$$u_r = \alpha \times a + \beta, \text{ where}$$

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

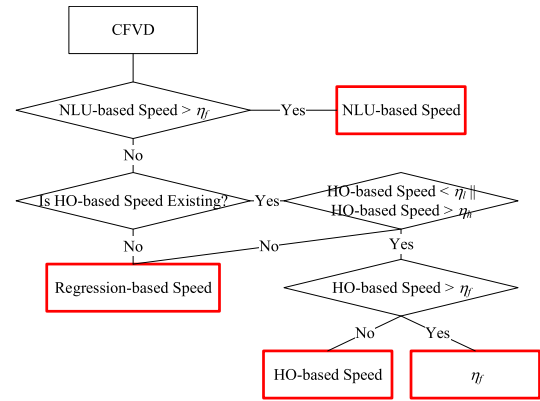$$\beta = \frac{1}{N}\left(\sum_{i=1}^{N} U_i - \alpha \sum_{i=1}^{N} a_i\right)$$

(1)

Fig. 3 CP-based method.

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 (η_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 (η_h) or is slower than the threshold of low speed (η_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_i)) by Formula (2).

$$R_h = \min\left(\frac{|U - u|}{U}, 1\right) \times 100\%$$

(2)

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.

Day	Vehicle Speed Estimation Accuracy
Sunday	96.06%
Monday	98.57%
Tuesday	98.19%
Wednesday	98.63%
Thursday	98.01%
Friday	96.64%
Saturday	97.33%
Average	97.63%

Table 2   The speed estimation accuracy comparisons of methods.

	NLU-based [1]	HO-based [2]	FPA-based [5]	CP-based
Accuracy	93%	89%	96%	98%
Availability ratio	100%	19%	100%	100%

Table 3   The cost comparisons of methods.

	NLU-based [1]	HO-based [2]	FPA-based [5]	CP-based
Monitored Interfaces	A and IuCS	A and IuCS	A-bis and Iub	A and IuCS
The number of required servers	< 100	< 100	> 10000	< 100

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 Iub 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 Iub 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.

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