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RESEARCH ARTICLE

The frequency of CFVD speed report for highway traffic

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ABSTRACT

The control signals of cellular networks have been used to infer the traffic conditions of the road network. In particular, consecutive handover events are being used to estimate the traffic speed. During traffic congestion, consecutive handover events may be rare because vehicles move slowly, and thus very few or no speed reports would be generated from the congested area.However, the traffic speed report rate during traffic congestion has not been investigated in the literature. In this paper, we present an analytic model to estimate the speed report rate from cellular network signaling in steady traffic conditions, that is, the traffic speed and flow are assumed constant. Real field trial data were used to validate our analytic model. In addition, computer simulations were conducted to study how speed reports are generated in dynamic traffic conditions when traffic speed and flow change rapidly. Our study indicates that in a typical cell of length 1.5 km with a typical expected call holding time of 1 min, no speed report was generated from a congested three-lane highway. Our study demonstrates that the lack of speed reports from consecutive handover events during rush hours indicates severe traffic congestion, and new methods that can estimate traffic speed from cellular network data during severe traffic congestion need to be developed. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS
traffic information; floating vehicle; CFVD

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1. INTRODUCTION

Traffic information systems provide road users and traffic managers with accurate and reliable real-time traffic information, such as traffic speed and flow, travel time, and accident events. The real-time traffic information can be used to support on-vehicle navigation system, vehicle dispatch system, and traffic control. Traffic information has traditionally been gathered by public agencies such as Departments of Transportation via stationary *vehicle detectors* (VDs) installed on the roadways. The most common stationary VDs are inductive loops installed in roadbeds. Other VD technologies, such as radar devices and video image processor, have also been developed [1]. Each VD requires a communications link back to the *traffic information center* (TIC). Moreover, because of outdoor weather exposure, the failure rates of VDs are usually high [1]. Therefore, stationary VDs are very expensive to install, operate, and maintain, and their installations are typically limited to freeway or highway surveillance.

Alternatively, traffic information can be collected from vehicles equipped with *Global Positioning System* (GPS) receivers and wireless communication capability as probes on the road network. The GPS-equipped probe cars transmit their positions and speeds to a traffic information center periodically [1]. As taxis are more likely to be constantly moving, they are the most common choice for probe cars. For example, San Francisco taxis have been used as probes to collect and forecast the traffic conditions [2]. The GPS receivers and wireless communication devices are moderately expensive. However, a large number of probe cars must be equipped, or the amount of collected data may not be enough to generate real-time traffic information for a large road network. Herrera *et al*. studied the traffic data obtained from 100 vehicles carrying GPS-enabled mobiles phones driving round trips on a highway [3]. The vehicles record their speeds and locations when they pass predetermined locations. Their study suggests that a 2–3% penetration is enough to provide accurate measurements of the traffic speed.

Cellular phones or *mobile stations* (MSs) are all-pervasive nowadays. As MSs constantly register their locations to the cellular network, MSs on moving vehicles can be used as probes to gather traffic information. This approach is referred to as *cellular floating vehicle data* (CFVD) because cellular network signalings are used to infer real-time traffic information [4–11]. In a cellular network, the service area is populated with *base stations* (BSs), where the radio coverage of a BS or a sector of a BS is called a cell. When a communicating MS is moving from one cell to another, the handover procedure is executed so that the call can be continued. Caceres *et al*. used inter-cell handover signalings to estimate the vehicular volumes on road network [5]. The mean absolute relative error of their estimations compared with the VD recorded volumes is 20%. When an active, busy MS on a moving vehicle performs two consecutive handovers, the vehicle's speed can be estimated according to the distance of the two handover locations and the time difference of the two handovers. Compared with the conventional probe vehicles, the CFVD approach does not require any additional on-vehicle devices, and there are sufficient probes because MSs are so pervasively used. Moreover, the CFVD approach is a passive traffic detection method, as no modification on MSs is needed.

Several research projects have been undertaken to study CFVD using two consecutive handover signalings from the cellular network to estimate the traffic speed and travel time. Gundlegard and Karlsson localized the handover locations with high accuracy for both the *Global System for Mobile Communications* (GSM) and *Universal Mobile Telecommunications System* (UMTS) [6]. Their results indicate that the traffic speed estimation is more accurate in UMTS than in GSM. Thiessenhusen *et al*. measured the traffic speeds obtained from two consecutive handover records of GSM and compared with those obtained by stationary VDs and GPS-equipped probe cars [7]. The errors were between 20 and 30 km/h. On the other hand, Maerivoet and Logghe showed that the CFVD technology has a very good accuracy on motorways with free flow traffic [8]. In addition, the CFVD study by Bar-Gera demonstrated that the discrepancies between travel times obtained from stationary VDs and CFVD is 10.7% in average [9]. Fiadino *et al*. presented a full data-processing chain of extracting traffic information from UMTS signaling data in details [10]. The whole process includes preprocessing raw signaling data, route detection, and traffic monitoring. Chiang *et al*. explored multiple handover patterns of MSs on freeway to estimate the traffic speed [11]. They obtained a mean relative error of 14%, compared with the speed measured by VDs. However, about 24% of their estimations are of errors more than 20 km/h.

The aforementioned studies have shown that CFVD can be useful in estimating traffic speed and travel time. However, when road traffic is congested and vehicles move slowly, consecutive handover events are rare, and thus very few speed reports would be generated from CFVD. CFVD may tell that there is a traffic jam because no speed report is generated, but cannot tell how bad the traffic jam is. The issue of rare speed reports from CFVD during traffic congestion has not been investigated in the literature. In this paper, we present an analytic model to estimate the frequency of CFVD speed reports in steady traffic conditions. Real anonymized signaling traces of a cellular network have been used to study the effects of rare consecutive handover events during traffic congestion. The signaling traces are used to validate our analytic model. Moreover, we have conducted computer simulations to determine whether CFVD can generate speed reports when the traffic becomes congested rapidly because of a traffic accident.

The remainder of the paper is organized as follows. In Section 2, we briefly describe how speed reports can be generated from two consecutive handover events. In Section 3, we present an analytic model to estimate speed report rate from CFVD and compare the analytic results with the real signaling traces from a cellular network. Section 4 describes a computer simulation model of speed reports generated from CFVD and the simulation results. Finally, conclusions are given in Section 5.

2. SPEED ESTIMATION FROM HANDOVER EVENTS

In a cellular network, such as GSM or UMTS, every cell is identified by a unique *Cell Global Identification* (CGI). The BS broadcasts its CGI periodically. When an MS attaches to the mobile network, it camps on a BS and stores the BS's CGI. The MS makes or accepts a call through the camped-on BS. When the MS moves from a cell to another during a call, the ongoing call is handed over to the new BS. For example, an MS (Figure 1(a)) moving along a road makes or receives a phone call through the BS of Cell_1 at time t_0. When the MS enters Cell_2 at t_1, it executes the handover procedure to switch the voice connection from Cell_1 to Cell_2.

The speed of the MS can be estimated by utilizing the information provided by the standard handover procedure described earlier. When the MS camps on or is handed over to a BS, it obtains the BS's CGI. Therefore, from the two consecutive handover events depicted in Figure 1, we obtain handover pair (Cell_1, Cell_2) for the first handover at time t_1 and (Cell_2, Cell_3) for the second handover at time t_2. If we can map handover pair (Cell_1, Cell_2) to location L_1 and handover pair (Cell_2, Cell_3) to location L_2, then we can compute the speed of the MS as $v = \frac{d(L_1,L_2)}{t_2-t_1}$ in the period $[t_1, t_2]$, where $d(L_1, L_2)$ denotes the travel distance on the roadway between L_1 and L_2.

In general, a handover occurs in a small area, which is referred to as a handover area, in the overlapping serving area of the two cells (Figure 1(b)). The handover areas and the distance between two handover areas on a roadway need to be determined first in a learning phase [12] before they can be used to compute the traffic speed. In practice, the handover locations on a roadway can be

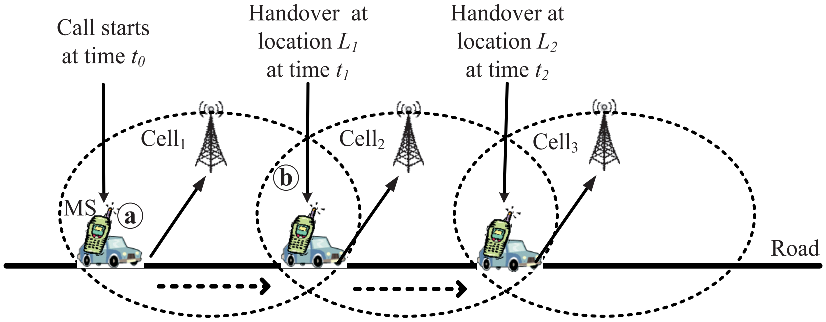


Figure 1. The cell switching of a moving MS on a highway.

measured by an MS having an ongoing call on a moving vehicle equipped with a GPS receiver. As the vehicle moves along the roadway and the MS is handed over from one cell to another, as we know, the time when each handover occurs and the handover locations can be obtained from the GPS receiver. The handover locations can be matched with the roadway's geographic information to determine the travel distance between two handover locations. As the handovers between Cell_i and Cell_{i+1} do not occur at an exact location, but in a small area, we can conduct a number of position measurements and use the average as the position of L_i. The coverage area of a handover area may be too large such that the discrepancy between the CFVD speeds obtained from the handover area and the actual traffic speeds is unacceptable. In this case, this handover area cannot be used for CFVD speed estimation. In general, the two handover events used for CFVD speed estimation need not be consecutive; any two handover events of an MS can be used. Two far-apart handover events can be used to obtain traffic speed reports with higher accuracy, as the effect of handover location inaccuracy is reduced by the larger distance between the two handovers.

3. AN ANALYTIC MODEL FOR SPEED REPORT RATE UNDER STEADY TRAFFIC

On the basis of the CFVD approach described in Section 2, we propose an analytic model to investigate how often speed reports can be generated from CFVD under steady traffic conditions, that is, how often two consecutive handovers occur. The traffic conditions that we study are real traffic on a highway, which is measured by roadside stationary VDs. In other words, the inputs of our model are the highway traffic flow (the volume of passing vehicles per unit time) and traffic speed.

3.1. The analytic model

In addition to the traffic flow and speed, three other factors affect the rate of the traffic speed reports generated from two consecutive handover locations. First, the shorter the distance between the two handover locations, the more often speed reports can be generated because it takes less time to travel through. Second, a longer call is more likely to perform consecutive handovers and generate speed reports. Third, the more calls occurring in the moving vehicles, the more speed reports can be generated. Our analytic model makes the following assumptions. There is an MS on each moving vehicle. The call arrivals, including originating (outgoing) calls and terminating (incoming) calls, to the MS form a Poisson process with rate λ. The call holding time (CHT) is exponentially distributed with mean $1/\mu$ [13].

Figure 2 depicts the timing diagram of a speed report generated by two consecutive handovers. An MS on a moving vehicle initiates or receives a call at time t_0, and its distance to the next handover location, L_1, is x. The MS performs the first handover at L_1 at time t_1 and the second handover at L_2 at time t_2 before the call ends at time t_3. It is clear that time interval (t_0, t_3) is the CHT, whose length can be determined by its distribution. Given the location where the call initiates and the handover locations, time t_2 can be determined by the speed of the vehicle, denoted by v. We have

$$t_2 = t_0 + \frac{x + d(L_1, L_2)}{v} \tag{1}$$

Given the traffic flow f and traffic speed v measured by a VD, the traffic density, that is, the number of vehicles per

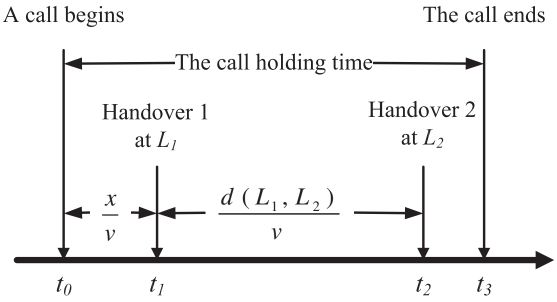


Figure 2. The timing diagram of a speed report generated.

unit distance on the roadway, is $\frac{f}{v}$. As the call arrival rate (CAR) to each vehicle is λ, the CAR per unit distance on the roadway is $\frac{f\lambda}{v}$. As depicted in Figure 2, a speed report is generated by a passing vehicle if a call begins before L_1 (i.e., $x > 0$) and the call ends after L_2 (i.e., $t_2 < t_3$). Let r denote the speed report rate; r can be obtained as follows.

$$r = \int_{x=0}^{\infty} \left(\frac{f\lambda}{v}\right) \int_{t=\frac{x+d(L_1,L_2)}{v}}^{\infty} \mu e^{-\mu t} \mathrm{d}t\,\mathrm{d}x \qquad (2)$$

$$= \left(\frac{f\lambda}{\mu}\right) \times e^{-\frac{\mu \cdot d(L_1,L_2)}{v}} \qquad (3)$$

There may be more than one cellular operator. As each operator can only obtain the CFVD of its own, only a fraction of the traffic flow contributes to the speed reports of the operator. In this case, the traffic flow f in Equation (3) needs to be multiplied by the market share percentage.

Note that our analysis assumes constant traffic flow and constant traffic speed. In reality, both traffic flow and speed may vary with respect to time and location. Equation (2) can be generalized if the function of traffic flow with respect to location is known. In this case, let $f(x)$ denote the traffic flow at the location where the distance to L_1 is x. We can obtain

$$r = \int_{x=0}^{\infty} \left(\frac{f(x)\lambda}{v}\right) \int_{t=\frac{x+d(L_1,L_2)}{v}}^{\infty} \mu e^{-\mu t} \mathrm{d}t\,\mathrm{d}x$$

$$= \frac{\lambda}{v} \times e^{-\frac{\mu \cdot d(L_1,L_2)}{v}} f^*\left(\frac{\mu}{v}\right) \qquad (4)$$

where $f^*(\mu/v)$ is the Laplace transform of the traffic flow with respect to location.

3.2. Investigation on rare report issue

Figure 3 depicts the flow–speed data recorded by a VD located at the 41.5-km mark on the north-bound Number 1 Highway in Taiwan, during 6–24 h in the days of a month. Each dot represents the average traffic flow and vehicle speed detected by the VD in a 5-min interval. As shown in Figure 3, the recorded data display a typical flow–velocity curve in an arch shape. The left foot of the arch represents traffic congestions where the traffic flow is moderate and the speed is low. The right foot of the arch represents free flow (i.e., light traffic) where the flow is low and the speed is high. The top of the arch represents the maximum capacity of the road, that is, the saturated traffic flow. The curve indicates that the traffic is saturated when the flow is around 5000 cars per hour; at that flow, the traffic speed is around 60 km/h.

For each VD record, that is, a data pair of traffic flow and speed, displayed in Figure 3, we can estimate the speed report rate from CFVD using Equation (3). In our analysis, we assume that the CAR $\lambda = 0.5$ calls/h and the average CHT $1/\mu = 1$ min. The assumptions are based on the statistics of real field trial data described later in this paper. The market share percentage of the mobile operator under study is assumed to be 38%, that is, 38% of the vehicles carrying MSs that can be measured in the cellular network. The remaining 62% of the vehicles do not contribute to speed report measurement, but would contribute to the road traffic. The distance between two handover locations is 1.5 km, which is a typical length of a cell diameter. Figure 4 depicts that the rates of CFVD speed reports that can be generated from the real traffic recorded by the VD. The report rate versus speed curve also displays an arch shape, but tilted to the right. This means that the speed reports from CFVD are rare both at traffic congestions and at very light traffic. As we can see from the curve, the lack of speed reports is more severe during traffic congestions; the expected report rate can be as low as 0.04 per hour. This means that when the traffic is severely congested, there is virtually no speed report at all. The maximum report rate is about 4.4 reports per hour, which occurs when the traffic speed is around 90 km/h, that is, when the flow is around 3000 per hour as indicated in Figure 3.

The CFVD speed report rate improves when the CHT increases. Figure 5 depicts the effects of CHT on the speed report rate. Three different average CHTs have been used, $1/\mu = 1$, 2, and 3 min. The cell diameter is 1.5 km, and 38% of the vehicles are carrying MSs that can be measured in the cellular network. The analytic results in Figure 5 indicate that the speed report rate improves significantly

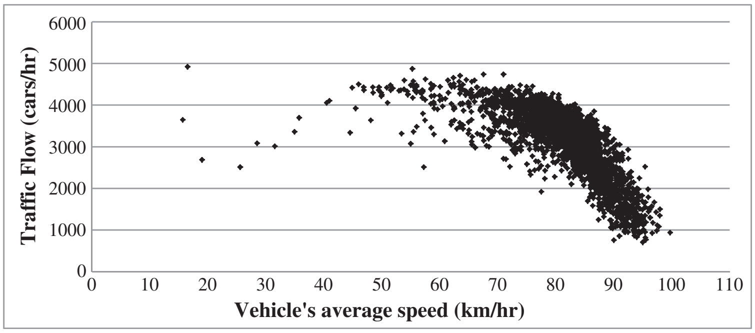


Figure 3. The flow–velocity curve recorded by a VD on Number 1 Highway, Taiwan.

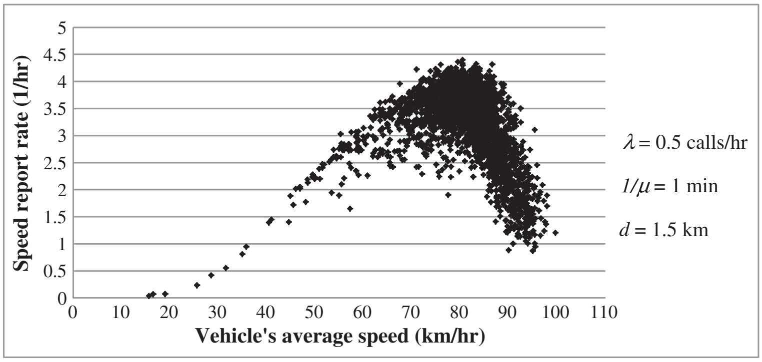


Figure 4. The speed report rate of CFVD.

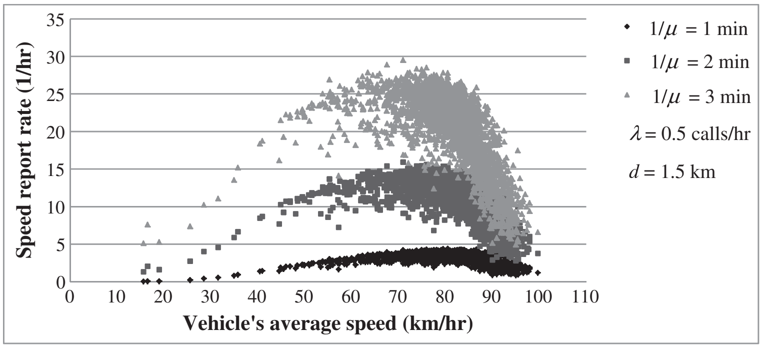


Figure 5. The effects of call holding time on the speed report rates of CFVD.

as the CHT increases. When the traffic is severely congested and the average CHT is 3 min, more than six speed reports per hour can be obtained from CFVD, that is, in average, a speed report every 10-min interval, which is satisfactory for traffic information systems applications. The maximum report rates are around 5, 16, and 29 for CHTs 1, 2, and 3 min, respectively. This indicates that the report rate increases at a faster rate than the CHT increases. However, the average CHT is about 1 min on the cellular networks in Taiwan. This suggests that CFVD would not generate speed reports on a severely congested highway. We believe that the lack of CFVD speed reports during congestion would be more severe on surface streets because both the traffic flow and speed are lower.

3.3. The field trial data

In general, the CARs and the CHTs for the calls originated or terminated in moving vehicles may change when traffic speeds change. For example, in a highway congestion, people may start calling, and hence the number of originating calls increases. On the other hand, during congestion, the time taken to travel the same distance between two handovers is longer. As a result, real field trial data need to be analyzed first before fully investigating the speed report rate during traffic congestion.

The UMTS network with wideband code division multiple access air interface of Chunghwa Telecom was used in our experiments. The control signals on Iu-CS were collected for a period of 2 weeks. Iu-CS is the interface between radio network controllers (RNC) and mobile switching centers. As the UMTS implements soft handover, an MS may maintain connections with up to six cells. However, the RNC only informs the mobile switching centers of the connected cell with the best signal strength. When the RNC indicates that the connected cell with the best signal strength changes, the MS is assumed to be handed over to the new cell. The collected control signals on Iu-CS include normal location update (NLU), call arrival, call completion, and handover. A 10-km segment of Number 3 Highway, Taiwan, was considered in our experiment. As the highway segment crosses a location area, MSs on the vehicles passing the road segment would perform two NLUs, one when entering the segment and the other when leaving. The time interval between the two NLUs was used to determine if the MSs were on the vehicles traveling on the highway; if an MS's time interval matches the traffic speed obtained by the highway VDs within 25% error margin, the MS is assumed to be on the highway. The CARs, the CHTs of the MSs moving on the highway, and the traffic speed obtained by the VDs were recorded. As we are interested in the effects of traffic speed on CHT and CAR, for each 10-km/h bracket of the traffic speeds, the average CHTs and CARs were computed.

Figure 6 depicts the effects of traffic speed on CHT and CAR. The results indicate that both CHT and CAR increase as traffic speed drops below 50 km/h, that is, people make or receive more and longer phone calls during traffic congestions on the highway. The CHT increases from about 60 s during free flow traffic to about 80 s during traffic congestions. Similarly, the CAR increase from 0.43 to 0.52 per hour. This may partially alleviate the effects of few CFVD speed reports during traffic congestion. However, when the traffic speed drops from 30 to 15 km/h, the CHT drops from 78 to 60 s. This is because when vehicles move in a stop-and-go traffic, the drivers need to pay more attention to brake frequently. This may result in a shorter CHT.

From the results depicted in Figure 6, we have the CHT and CAR for each traffic speed bracket. We can plug the CHTs, CARs, and traffic speeds into Equation (3) to obtain the analytic speed report rates, and we can compare the analytic results with the field trial data. Two selected handover areas are used in our analysis; they are selected because the areas are relatively small and more accurate CFVD speeds can be obtained. The distance between the two selected handover areas is 1.7 km. Because of the soft-handover design of UMTS, only 75% of the passing MSs with ongoing voice communications perform the first handover and 88% of the second handover. Therefore, the report rate obtained from our analytic model must be multiplied by $0.66(= 0.75 * 0.88)$, that is, only the calls that perform both handovers generate speed reports. Figure 7 plots the CFVD speed report rates from the analytic model and from the field trial data against traffic speeds. We observe that the analytic results match the field trial data in most cases, except that the analytic model underestimates the report rate by 60% when the traffic speed is only 30 km/h. This phenomenon is because the CHTs are not exponentially distributed, and more phone calls last long enough to perform two consecutive handovers. However, both the analytic results and the field trial data indicate that there is no CFVD speed report when the traffic speed is in the 15-km/h bracket, that is, the traffic is severely jammed.

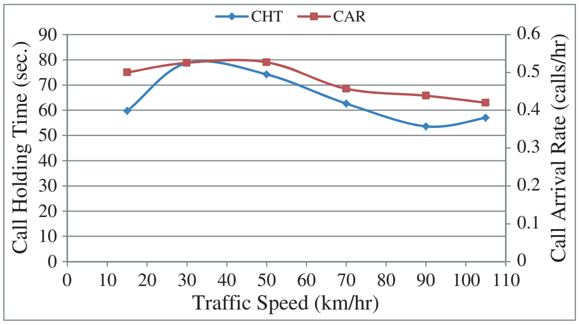


Figure 6. The effects of traffic speed on the CHT and CAR.

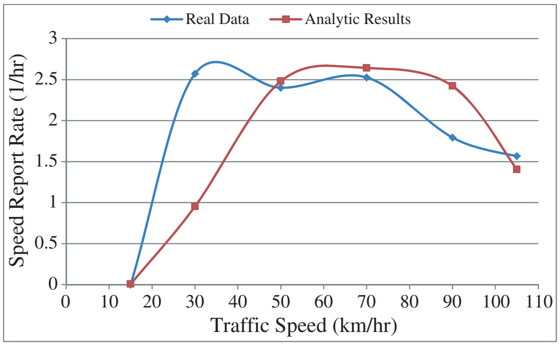


Figure 7. The effects of traffic speed on the CFVD speed report rate.

4. COMPUTER SIMULATION FOR CAR ACCIDENT SCENARIOS

The analytic model described in Section 3 assumes constant traffic flow and constant traffic speed. However, the study of steady traffic flow does not provide information for situations such as car accidents, which rapidly collapse the traffic into congestion. When the traffic congestion occurs, both traffic flow and speed may change rapidly. This section uses computer simulations to study dynamic traffic conditions to learn if the speed reports generated by CFVD can detect the rapid changes in traffic conditions.

Our simulation consists of three steps. In step 1, a microscopic multi-modal traffic flow simulation software VISSIM [14] is used to generate vehicle trajectories on a simulated highway. Second, call arrival patterns are generated for each vehicle under simulation. Given the handover locations on the simulated highway, the vehicle trajectories and the call arrival patterns are examined to check if speed reports are generated, that is, if two consecutive handovers occur. VISSIM can simulate many aspects of a road network, including road conditions, vehicle types, driver behavior, and statistical data collection [14]. *Data collection points* (DCPs) can be inserted on the simulated road to record the simulation time, the vehicle's ID, and the speed of each vehicle passing the DCPs. In our simulations, DCPs are inserted at the handover locations of the simulated road, so that the time when a vehicle passes each handover location is recorded.

In step 2, we generate the cellular communication behaviors of the simulated vehicles. We assume that the call arrivals (including originating calls and terminating calls) to each MS form a Poisson process with rate λ, and the CHTs are exponentially distributed with mean $1/\mu$. When a vehicle enters the simulated road segment, our simulator acts as a random observer for the MS on the vehicle. Therefore, with probability λ/μ, the MS has an

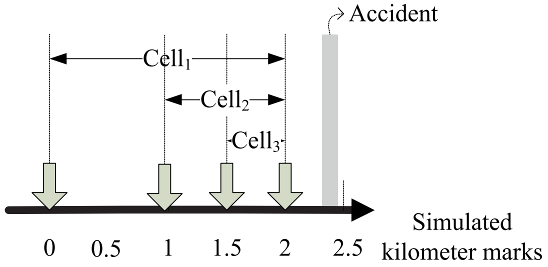


Figure 8. The handover locations and the affected area of a traffic accident.

ongoing call, and the time interval to the next call arrival is exponentially distributed with mean $1/\lambda$. The simulator repeatedly generates the inter-arrival times and CHTs of the subsequent calls until the vehicle leaves the simulated road segment.

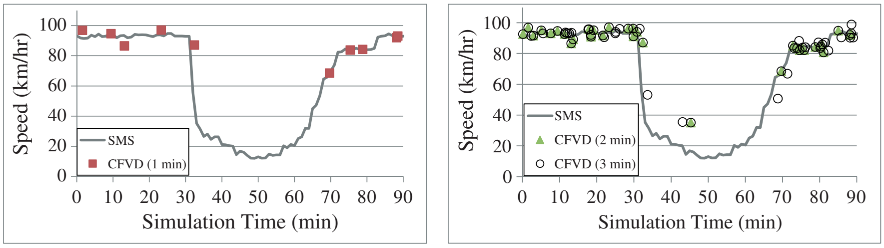
In step 3, we generate speed reports from handover events. Each record collected by the DCPs of VISSIM indicates the time when a vehicle passes a handover location. Given the VISSIM records and the calling patterns generated earlier, it is straightforward to check whether two consecutive handovers occur or not. When they occur, a traffic speed report is created from CFVD by dividing the distance of the handover locations by the time difference of the two VISSIM records.

To obtain the ground-truth speed, the simulator also computes the average speed of all vehicles passing each cell. This ground-truth speed will be compared with the speed reported from CFVD to check the quality of the CFVD's reports. The ground-truth speed will be referred to as *space mean speed* because it is the mean speed of the vehicles driving through a cell.

We simulated traffic congestion caused by a traffic accident on a highway. Figure 8 depicts the simulated highway. The highway was 2.5 km long, three lanes wide, and crossed three artificially overlapping cells. We intended to study the effects of cell diameter; the overlapping cells of length 1.5, 1, and 0.5 km, respectively, were studied. A traffic flow of 5000 cars per hour, which is a typical peak flow of a three-lane highway, were injected into the road during 1.5 simulation hours, and only 38% (the market share percentage of the mobile operator under study) of the vehicles contribute to CFVD reports. The desired speeds of the vehicles were uniformly distributed in 85–120 km/h. A simulated traffic accident occurred at the 2.4-km mark at an elapsed time of 30 min after simulation starts and affected two lanes between the 2.3-km and 2.4-km marks. The desired speed of the affected area was set to 4–6 km/h. The accident was cleared at the elapsed time of 60 min by setting the desired speeds back to 85–120 km/h. The CAR to each vehicle was assumed to be one call per hour, which is about double the average CAR measured from the field trial data. Three CHTs (1, 2, and 3 min) were simulated.

Figure 9(a) depicts the simulation results of Cell_1, which is 1.5 km wide, when the expected CHT is 1 min. Each square dot represents a speed report from two consecutive handovers from the CFVD, and the curve represents the ground truth, that is, the average space mean speed of all the simulated vehicles passing Cell_1 in 1-min intervals. The steep dive of the space mean speed curve indicates that traffic collapses into congestion quickly in Cell_1. The results indicate that CFVD generates no speed report after the traffic starts to collapse and during the congestion. It is not until the congestion is fully cleared can CFVD generate speed reports. Figure 9(b) depicts the simulation results of Cell_1 when the expected CHTs are 2 and 3 min. Each triangle dot represents a speed report in the scenario with 2-min CHT, and each circle that of 3-min CHT. As we have expected, the speed reports are generated much more frequently when traffic is not congested. When the expected CHT is 2 min, only one speed report is generated during the congestion. By contrast, when the expected CHT is 3 min, only two reports are generated during the 30-min congestion interval. In addition, during the simulation time interval 47–68 min, no speed report is generated.

Figure 10 depicts the simulation results of Cell_2, and Figure 11 the simulation results of Cell_3. Cell_2 is 1 km wide, and Cell_3 0.5-km wide. It is clear that as the cell diameter decreases, more speed reports are generated. However, the results in Figures 10(a) and 11(a) indicate that when the expected CHT is 1 min, no speed report is generated in either cell during the 30-min congestion period. It is not until the congestion is fully cleared can speed reports be generated. Figures 10(b) and 11(b) depict the simulation results when the expected CHTs are 2 and 3 min. The results also indicate that as the cell diameter decreases, the number of speed reports generated increases.



(a) 1-min call holding time (b) 2-min and 3-min call holding times

Figure 9. The speed reports from the CFVD of Cell_1 of length 1.5 km.

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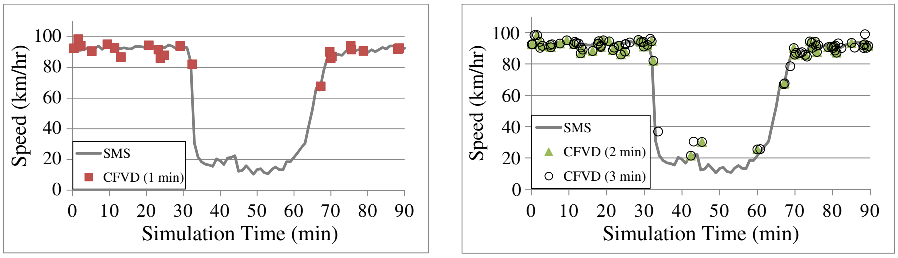
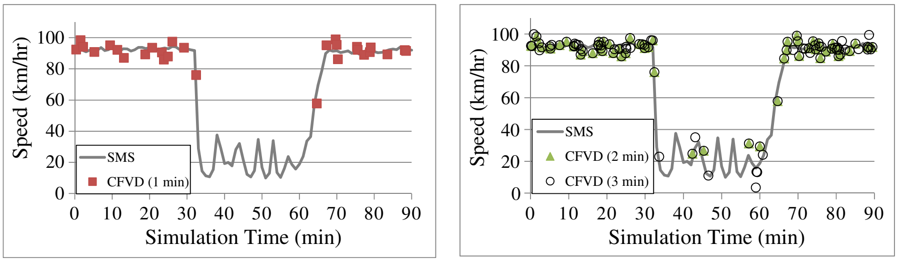


(a) 1-min call holding time (b) 2-min and 3-min call holding times

Figure 10. The speed reports from the CFVD of Cell_2 of length 1 km.



(a) 1-min call holding time (b) 2-min and 3-min call holding times

Figure 11. The speed reports from the CFVD of Cell_3 of length 0.5 km.

When the CHT is 2 min, during the 30-min congestion interval, three speed reports are generated in Cell_2, and five reports in Cell_3. When the CHT is 3 min, more speed reports are generated in both cells. In brief, our simulation results indicate that when the traffic is severely jammed because of a car accident on a three-lane highway, no speed report is generated during the congestion when the average CHT is 1 min, even for a small cell of length 0.5 km.

5. CONCLUSIONS

Two consecutive handover events of CFVD have been used to estimate traffic speed of the road network. We suspected that when road traffic is congested, consecutive handover events may be rare, and thus very few speed reports would be generated from CFVD. We developed an analytic model to study the frequency of CFVD traffic speed report for highway traffic from two consecutive handover events. Using the real traffic flow recorded by a VD on a three-lane highway, our analytic results indicate that when the traffic is congested and the average CHT is 1 min, speed reports from a cell of length 1.5 km are indeed rare, less than 0.1 reports per hour. In addition, field trial data on a three-lane highway from a mobile telecommunication operator were analyzed. The field data indicate that both the CAR and CHT increase slightly when the highway traffic speed drops below 50 km/h. However, when the traffic is severely jammed, no CFVD speed report was generated from two selected handover areas 1.7 km apart. Computer simulations have also been developed to study how many speed reports can be generated when traffic collapses into congestion because of car accidents. Our simulation results indicate that when the expected CHT is 1 min and the CAR to each vehicle is one call per hour, no CFVD speed report is generated from a small cell of length 0.5 km on a severely congested three-lane highway. However, when the expected CHT is 3 min, the problem of no speed report disappears. As the average CHT on the cellular networks in Taiwan is only 1 min, we need to develop new CFVD methods that can estimate traffic speed during severe congestions.

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REFERENCES

1. Martin PT, Feng Y, Wang X. *Detector Technology Evaluation*. Department of Civil Environmental Engineering, University of Utah-Traffic Lab: Salt Lake City, UT, 2003.

2. Hunter T, Herring R, Abbeel P, Bayen A. Path and Travel Time Inference from GPS Probe Vehicle Data, In *Proceedings of Neural Information Processing Systems foundation (NIPS)*, 2009; 1–8.
3. Herrera J-C, Work D, Ban X, Herring R, Jacobson Q, Bayen A. Evaluation of traffic data obtained via GPS-enabled mobile phones: the Mobile Century field experiment. *Transportation Research Part C* 2010; **18**: 568–583.
4. Ygnace J, Drane C, Yim Y-B, de Lacvivier R. Travel time estimation on the San Francisco bay area network using cellular phones as probes, *PATH Working Paper UCB-ITS-PWP-2000-18*, University of California, Berkeley, 2000.
5. Caceres N. Traffic flow estimation models using cellular phone data. *IEEE Transactions on Intelligent Transportation Systems* 2012; **13**(3): 1430–1441.
6. Gundlegard D, Karlsson JM. Handover location accuracy for travel time estimation in GSM and UMTS. *IET Intelligent Transport Systems* 2009; **3**(1): 87–94.
7. Thiessenhusen KU, Schafer RP, Lang T. *Traffic Data From Cell Phones: A Comparison with Loops and Probe Vehicle Data*. Institute of Transport Research German Aerospace Center: Germany, 2003.
8. Maerivoet S, Loggh S. Validation of travel times based on cellular floating vehicle data, In *Proceedings of the 6th European Congress and Exhibition on Intelligent Transportation Systems*, Aalborg, Denmark, 2007; 2–9.
9. Bar-Gera H. Evaluation of a cellular phone-based system for measurements of traffic speeds and travel times: a case study from Israel. *Transportation Research Part C* 2007; **15**: 380–391.
10. Fiadino P. Steps towards the extraction of vehicular mobility patterns from 3G signaling data. *Traffic Monitoring and Analysis* 2012; **7198**: 66–80.
11. Chiang CY, Chuang J-Y, Chen J-K, Hung C-C, Chen W-H, Lo K-R. Estimating instant traffic information by identifying handover patterns of UMTS signals, In *Proceedings of International IEEE Conference on Intelligent Transportation Systems*, Washington, USA, 2011; 390-395.
12. Kaplan Y, Avni O. Method for measuring road traffic load based on analyzing cellular communications, 2010. *US patent 7783296*.
13. Bolotin VA. Modeling call holding time distributions for CCS network design and performance analysis. *IEEE Journal on Selected Areas in Communications* 1994; **12**(3): 433–438.
14. Planung Transport Verkehr AG. VISSIM user manual—V.5.20, 2009. Karlsruhe, Germany.

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