Vehicle speed and volume measurement using vehicle-to-infrastructure communication

Quoc Chuyen DOAN
IRSEEM-ESIGELEC
ITS division
Saint Etienne du Rouvray
76801 - FRANCE
doan@esigelec.fr

Tahar BERRADIA
IRSEEM-ESIGELEC
ITS division
Saint Etienne du Rouvray
76801 - FRANCE
berradia@esigelec.fr

Joseph MOUZNA
IRSEEM-ESIGELEC
ITS division
Saint Etienne du Rouvray
76801 - FRANCE
mouzna@esigelec.fr

Abstract: Intelligent transport system (ITS) refers to a system that manages road traffic using information and communications technology. One of the most important parts of it is the vehicle detection which provides vehicular data such as volume, density, and speed for traffic management centers. This paper proposes a vehicle detection method which measures volume and speed using Vehicle-to-Infrastructure communication and Global Positioning System. It can be implemented on roadway infrastructure with or without other vehicle detection techniques such as loop detectors.

Key–Words: Loop detector, Traffic data, GPS, Ad-hoc, V2V, V2I

1 Introduction

Today roadways are one of the major transportation systems in the world. Developing intelligent transport systems (ITS) in order to solve traffic problems is the indispensable in many countries [8], [9]. ITS includes sensors, communication and traffic control technologies. Vehicle detection and surveillance technologies are integral parts of ITS, since they gather some parts or all of the data that is used. In general, there are two vehicle detection technologies: intrusive technology (neumatic road tubes, inductive loop detectors, piezoelectric sensors) and non-intrusive technology (video image processors, microwave radars, infrared sensors, and ultrasonic sensors) [3]. Most vehicle detection techniques today rely on inductive loop detectors because of their stability and accuracy in counting vehicle volume in real time. However, installing loop detectors needs a lot of saw-cuts on roadway surfaces, which makes them difficult to deploy and maintain. This work is much more expensive for roadway sections which need a large amount of loop detectors. Moreover, loop detectors can provide data only from vehicles to infrastructure and not vice versa, thus limiting the functionality of the system. Combining or replacing loop detectors with better vehicle detection technologies is an essential issue for the future of ITS.

This paper proposes a vehicle volume and speed measurement method using wireless communications between roadside equipment and vehicles. In this model several roadways and intersections are managed by roadside equipment. Vehicles are equipped with Global Positioning System (GPS) receivers [7] and wireless communication devices, to detect there geographical location and to provide ad-hoc network connectivity with the roadside equipment respectively. The roadside equipment collects data from vehicles to calculate volume and speed at specified positions on roadways. The wireless communication system proposed in this paper is a two way data exchange system between vehicles and roadside equipment. Consequently, besides providing traffic data, it can be further developed for other information services such as Incident Notification, Vehicle Tracking or In-Car Internet Access.

The paper is organized as follows. Section 2 introduces the background of vehicle detection and ITS. Section 3 describes the method of measuring vehicle volume and speed. Simulation results will be shown in Section 4. Finally, we conclude the paper and discuss our possible future work in Section 5.

2 Background of vehicle detection and ITS

In general, a loop detector used to detect vehicles consists of three components: a loop, a loop extension cable and a detector [4]. The detector powers the loop causing a magnetic field in the loop area. The loop resonates at a constant frequency that the detector monitors. A base frequency is established when there is no vehicle over the loop. When a large metal object, such as a vehicle, moves over the loop, the resonate frequency increases. This increase in frequency is sensed to detect vehicles. Each loop detector is placed at a specified lane on roadways to measure vehicle volume. Vehicle speed is also estimated relying on the occupancy time of the vehicle on the loop. The collected traffic data is then sent to a central traffic computer via wired communication channels. In order to improve vehicle detection techniques for ITS, wireless communication has already been studied. The wireless communication used in ITS can be classified into 2 types: vehicle-to-vehicle communication (V2V) and vehicle-to-infrastructure communication (V2I). Some systems employing V2V and V2I to provide services for roadway security and management are being developed. The paper [1] proposed a vehicle tracking system using VANET (VETRAC) which aims to create a navigation system on vehicle using WiFi as inter-connection networks. Each vehicle is assigned a Mobile-IP address. The system tracks vehicle information through WiFi access points, which are established at various locations in a roadway network. The carrier is a navigation server that connects with multiple clients (vehicle). It is also responsible for the client's request data. The client control panel system (provider/consumer) running on client side helps the user to identify their current locations, destination locations, landmarks, distances to be traveled. This system can exchange information about traffic conditions such as traffic intensity, accident occurs and notify early warning of congestion, emergency responders though carrier access points. However, location of vehicles in VETRAC system does not provide accurate estimated values because it relies on the location of WiFi access poinst. In the paper [2], the author proposed a Contents Oriented Communications (COC) system on vehicular ad-hoc network (VANET) via V2V. In this system, vehicles collect original information from other vehicles surrounding them such as identification, location, traveling direction, speed, generation time. Useful information is then created by analyzing the original information and delivered to other vehicles. In other words, COC exchanges the status of vehicles and their surroundings. It analyzes the situation in the surrounding in real-time and shares the analyzed information among vehicles. This solution can only provide timely information of vehicular accidents and congestion to drivers in the surrounding areas. It does not have a connection with traffic management center in order to control the traffic for the whole roadway network.

3 Method description

In the proposed system, vehicles and roadside equipment form an ad-hoc network which has no prearranged infrastructure. The vehicles which are considered as nodes in the network are mobile, so a vehicular ad-hoc network is created. Each roadside equipment called V2I station manages offline data which refers to the information of roadway infrastructure within its direct radio range. We assume the transmission range of vehicles is long enough for the connection to V2I stations, whenever vehicles are in the range of V2I stations. In fact, the overlap between coverage areas of V2I stations can lead to an inaccurate detection of vehicles. Therefore, we define an effective range for each V2I station instead of using its direct radio range (see Fig. 1). The effective range is smaller than or equal to the direct radio range so that there is no overlap between effective areas. In order to carry out the functions of a loop detector, V2I station detects locations of vehicles periodically and then counts the number of vehicles passing a given position in a period. These given positions are considered as emulated detectors which provide vehicle volumes using V2I communication. Every query period T_{query}, V2I stations broadcast a query message to all vehicles in their effective range. Vehicles reply to the query with a "Hello" message. This message contains vehicle information such as identification number (ID), location, sending date and speed. We assume each vehicle has a different ID. The vehicle speed is given by the on-car speedometer and vehicle location is detected by the GPS receiver. The vehicular data called online data is updated and stored in V2I stations. Volume and speed of vehicles are measured every data-extract period.

3.1 Query period

Query period T_{query} is an interval of time between two successive times when V2I stations send query messages to vehicles. To ensure the update of vehicular data, T_{query} must be longer than the transmission delay between vehicles and V2I stations. Before dealing with T_{query}, we first need to estimate the maximum transmission delay. We assume the size of exchanged messages does not exceed 50 bytes or 400 bits. If the communication follows the wireless local area network standard 802.11 at a bit rate of 11Mbps, the transmission delay for each message is : $\frac{400}{11} = 36(\mu s)$. This delay increases if there are several vehicles communicating with a V2I station at the same time. In the case where the effective range (R) of the V2I station is 100 (m), its coverage area is given by $\pi * R^2 = 31400(m^2)$. We also assume

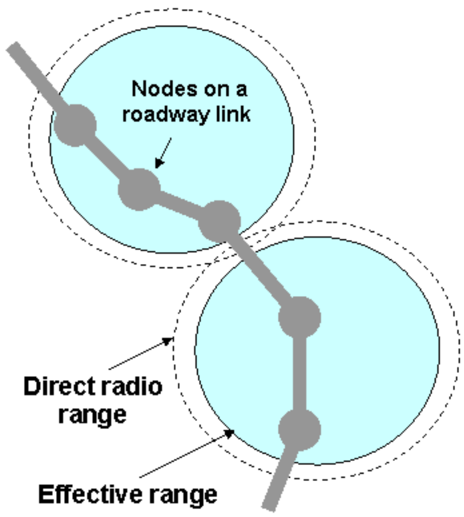

Figure 1: Effective range of V2I stations

the average space size for a vehicle is 5 m in length and 3.5 m in width (equals to the lane width). The maximum number of vehicles present in this area is $N = \frac{31400}{3.5 * 5} = 1794$. So the maximum transmission delay is $D = 1794 * 36 * 10^{-6} \approx 0.065(s)$. In this paper, T_{query} is set to 0.1 second which is longer than the maximum transmission delay.

3.2 Roadway design

The roadway system model in this paper consists of links and connectors [6]. Each element has a different ID. A connector joins up two links. Roadways may have only one link (one-way street) or two links (2-way street). A link refers to one side of a roadway where vehicles move in the same direction. A link may have one or more lanes. Lanes are defined areas on a link which generally allow only one type of vehicle to travel. Lanes of a link are assigned a number starting from 1. Lane 1 is the rightmost one in the link direction (see Fig. 2). We define nodes (way-points) which are also numbered starting from 1 along the imaginary central line of a link in its direction. Nodes are chosen in such a way that the shape of the imaginary line that joins them is most similar to the shape of the link. In addition, the distance between nodes is greater than the average length of vehicles (5 m).

The proposed solution aims to detect the volume and speed of vehicles at specified positions on roadways. We assume, at each of these positions, that there is an emulated detector which is defined by an ID and a location. Emulated detectors of a V2I station must be located within a smaller range (R-d) compared with the effective range (R) (see Fig.

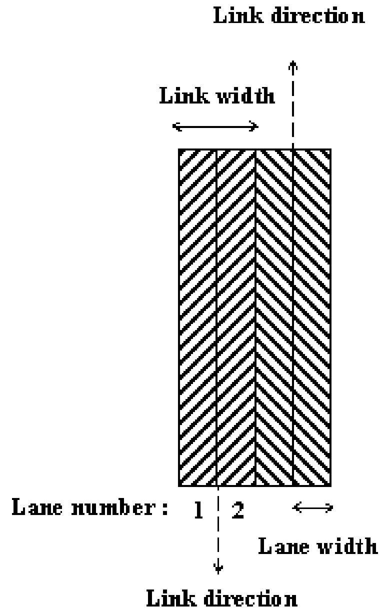

Figure 2: Distribution of lanes on a roadway

3). If there is an emulated detector very close to the outer limit of the effective range, the V2I station may receive "Hello" messages from vehicles after they have passed this detector. This will make an error in measuring vehicle volume. The distance d is long enough for a vehicle traveling at the top speed limit to go through within T_{query} which is given by $d \geq T_{query} * (Maximum\ of\ vehicle\ speed)$.

3.3 Offline data processing

Offline data which is available at V2I stations consists of all parameters of nodes, links, and emulated

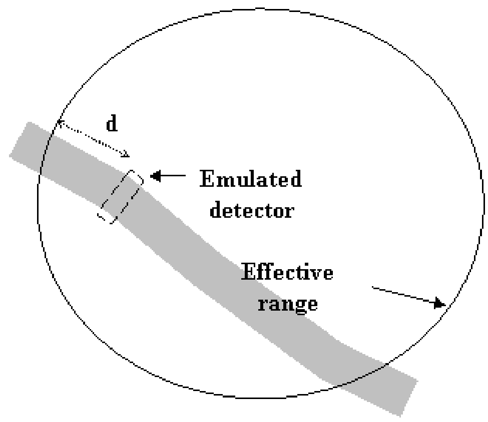

Figure 3: Distribution of emulated detectors in the coverage range of a V2I station

detectors in the coverage range of V2I stations. It is collected from roadway infrastructure and stored in form of separated data tables as follows:

- Node_table = {X_node,Y_node, node ID, link ID, lane width, number of lane}
- Station_table = {Node_table{}, X_station, Y_station, station ID, transmission range}
- Detector_table ={X_detector, Y_detector, detector ID, link ID, lane number}

Location parameter is defined as a 2 dimensions coordinate (X,Y). Lane and link parameters in Node_table and Detector_table refer to the link and lane where nodes and emulated detectors are located. For example, Node_table = {20.5,69.2, 5, 3, 3.5, 2} refers to a node 5 located at coordinate {X=20.5,Y=69.2} on the link 3 which has 2 lanes of 3.5m width.

3.4 Online data processing

Online data which refers to vehicular data is collected and updated at V2I stations every T_{query}. We keep only data from vehicles which are located within the effective range of V2I stations relying on their locations. Online data is also stored in form of Vehicle_tables as follows:

- Vehicle_table = { X_vehicle, Y_vehicle, vehicle ID, transmitted time, speed, station ID }

V2I stations analyze online and offline data to calculate volume and speed. The calculation process can be divided to 3 sub-processes: link checking, lane checking, speed and volume measurement. The first two sub-processes determine the lanes and links where vehicles are located. The last sub-process calculates volume and speed of vehicles at specific emulated detectors.

3.5 Link checking

This sub-process determines the link where vehicles are located to update Vehicle_tables. Firstly, we compare the current location of a vehicle with the location of every two successive nodes on a link. We repeat this comparison at other links until we find the closest link segment to the vehicle. If the distance from the vehicle to that closest link segment is smaller than the link width, the vehicle is located on that link. Fig. 4 shows how we determine the closest link segment. We assume that A_1 and A_2 are two successive nodes on link A. M is a vehicle in

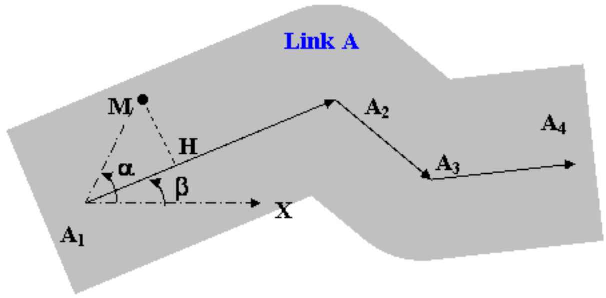

Figure 4: Localization of vehicle M

the V2I station area containing link A. The coordinates of these three nodes are respectively given by: $M(x_1, y_1)$; $A_1(x_{A_1}, y_{A_1})$; $A_2(x_{A_2}, y_{A_2})$.

We determine the coordinate of H which is a projection of M on line A_1A_2. The condition $\overrightarrow{MH} \perp \overrightarrow{A_1A_2}$ can be mathematically represented by

$$x_{MH} * x_{A_1A_2} = y_{MH} * y_{A_1A_2} \quad (1)$$

Moreover, H is also on line A_1A_2 leading to:

$$x_{A_2H} * y_{A_1A_2} = y_{A_2H} * x_{A_1A_2} \quad (2)$$

Resolving (1) and (2), we obtain the coordinate of H:

$$x_H = \frac{1}{x^2_{A_1A_2} + y^2_{A_1A_2}} * [x_M * x^2_{A_1A_2} + + y_{A_2M} * x_{A_1A_2} * y_{A_1A_2} + x_{A_2} * y^2_{A_1A_2}] \quad (3)$$

$$y_H = y_M + \frac{x_{MH} * x_{A_1A_2}}{y_{A_1A_2}}. \quad (4)$$

The distance d_{MH} from M to line A_1A_2 is given by:

$$d_{MH} = \sqrt{(x_{MH})^2 + (y_{MH})^2}. \quad (5)$$

where

$$x_{A_iA_{i+1}} = (x_{A_{i+1}} - x_{A_i}) \quad (6)$$
$$y_{A_iA_{i+1}} = (y_{A_{i+1}} - y_{A_i}). \quad (7)$$

The two following conditions ensure that vehicle M is on segment A_1A_2 or M is located on link A:

- H is between A_1 and A_2;
- d_{MH} is shorter than the link width.

In this example, we start to check segment A_1A_2 then continue with A_2A_3, A_3A_4... and segments on other links until we find the segment containing vehicle M. Then we continue the lane checking sub-process. If there is no segment matched this checking, vehicle M will be removed from the system. The link checking algorithm is shown in Fig. 5.

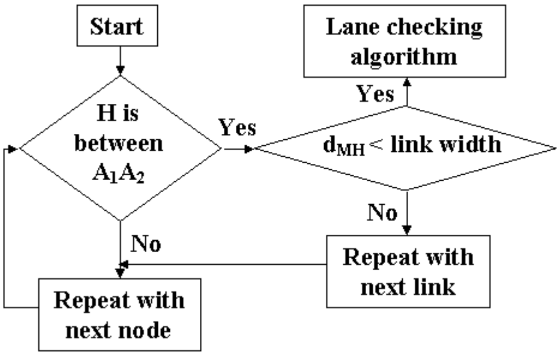

Figure 5: Link checking algorithm

3.6 Lane checking

After determining links where vehicles are located, we determine lane number of vehicles and update Vehicle_tables. This sub-process is described as follows, going back to the example in Fig. 4. Angle α between $\overrightarrow{A_1M}$ and horizontal axis is given by:

$$tan(\alpha) = \frac{y_{A_1M}}{x_{A_1M}} \quad (8)$$

Angle β between $\overrightarrow{A_1A_2}$ and horizontal axis is given by:

$$tan(\beta) = \frac{y_{A_1A_2}}{x_{A_1A_2}} \quad (9)$$

The angle difference $(\alpha - \beta)$ between 2 vectors $\overrightarrow{A_1M}$ and $\overrightarrow{A_1A_2}$ which is given by:

$$tan(\alpha-\beta) = \frac{y_{A_1M} * x_{A_1A_2} - y_{A_1A_2} * x_{A_1M}}{x_{A_1M} * x_{A_1A_2} + y_{A_1M} * y_{A_1A_2}} \quad (10)$$

A_1 and A_2 are on the central line which divides the surface of link A to 2 sides: left and right along its direction. The left side contains higher number lanes and lower number lanes are on the right side. Lane checking sub-process consists of 2 steps. The first step determines the side of link A containing vehicle M relying on the angle difference $(\alpha-\beta)$. The second step will calculate lane number by comparing the distance from vehicle M to the central line of link A with the lane width. The lane number of vehicle M is determined for four cases as described in the lane checking algorithm in Fig. 6.

If $(\alpha-\beta) \geq 0$, vehicle M is on the left-hand side. Depending on whether the number of lanes (N_{lanes}) of link A is odd or even, the lane number of vehicle M is given by (11) and (12) respectively.

$$Case\ 1 = \frac{N_{lanes}+1}{2} + \left[\frac{d_{MH}}{lane\ width}\right] \quad (11)$$

$$Case\ 2 = \frac{N_{lanes}}{2} + \left[\frac{d_{MH}}{lane\ width} - \frac{1}{2}\right] + 1 \quad (12)$$

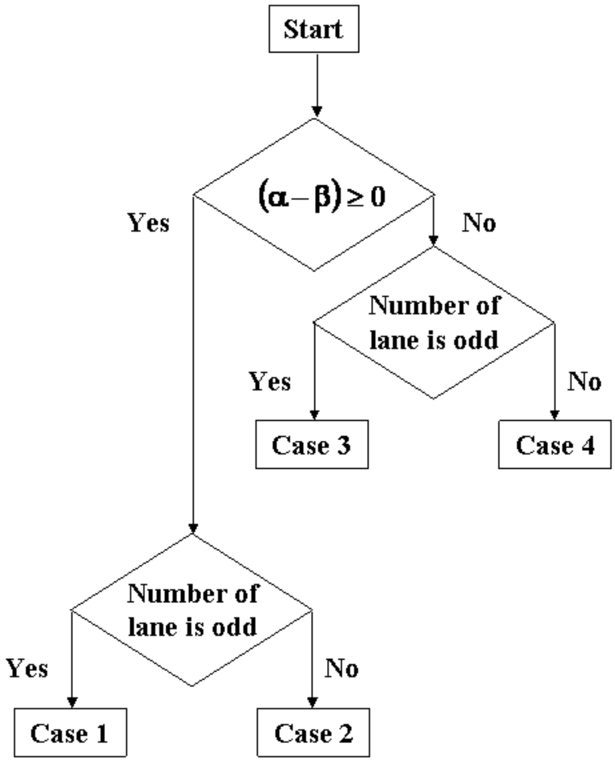

Figure 6: Lane checking algorithm

Otherwise, if $(\alpha - \beta) < 0$, vehicle M is on the right-hand side. There are also two sub-cases for odd (13) and even (14) numbers of lanes.

$$Case\ 3 = \frac{N_{lanes}+1}{2} - \left[\frac{d_{MH}}{lane\ width}\right] \quad (13)$$

$$Case\ 4 = \frac{N_{lanes}}{2} - \left[\frac{d_{MH}}{lane\ width} - \frac{1}{2}\right] \quad (14)$$

From (11) to (14), operator [] is used to round off the value to the nearest integer value.

3.7 Speed and volume measurement

After determining link and lane number of vehicles, this sub-process will check whether vehicles have passed any emulated detectors since the last time they were detected. The passing status of vehicles is then added to Vehicle_table. ID of emulated detectors are contained in "detector ID" parameters, and passing status ("YES" or "NO") of vehicles is stored in "passing status" parameters.

- Vehicle_table = { X_vehicle, Y_vehicle, vehicle ID, transmitted time, speed, station ID, link ID, lane number, detector ID, passing status}

This step completes the online data update for vehicles. At the end of each data-extraction period (30 seconds), we calculate the average value of vehicle speeds within this period. Vehicle volume which is the number of vehicles passed at a specific emulated detector during the data-extraction period is determined relying on ”passing status” parameters. There are some following error cases associated with this way.

In Fig. 7, Fig. 8, Fig. 9 each link A and B contains an emulated detector D1, D2 respectively. A and B connect with each other at an intersection. Two successive positions of vehicle M which is always on link A: M(t) and M(t-1) are captured at t and (t-1). If M is located right at the intersection, the V2I station may detect incorrectly whether it is on link A or B.

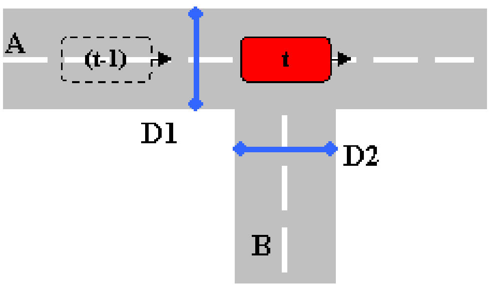

Figure 7: Wrong detection case 1

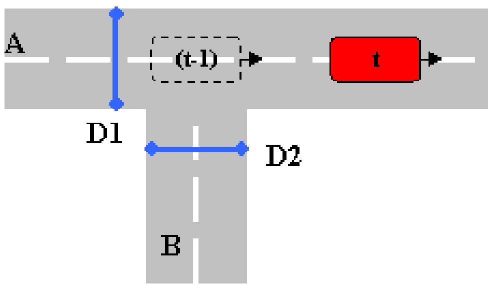

Figure 8: Wrong detection case 2

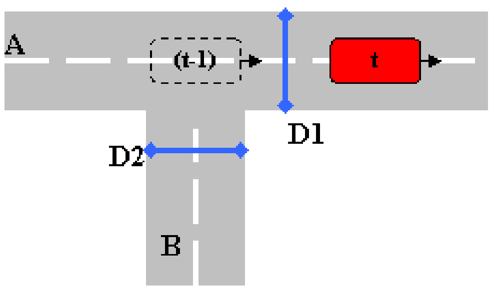

Figure 9: Wrong detection case 3

In the first case, the V2I station detects incorrectly that M(t) passes the detector D2 on link B although it is on link A. In the second and third case, V2I station incorrectly inferences that M(t-1) passes D2 on link B. We can correct these wrong detections for two cases. If the ”Detector ID” of M(t) is the same as M(t-1), we’ll check the ”passing status” of M(t) and M(t-1) as discussed above. Otherwise, if M(t-1) did not pass a detector D_i, which is also between two positions of M(t-1) and M(t), M(t) passed D_i.

4 Evaluation of method

The proposed solution is implemented in VISSIM 4.30 (microscopic, behavior-based multi-purpose traffic simulation program developed by PTV AG Germany) [5] on Windows platform. We use VISSIM to create a roadway network which can provide online and offline data. An external module which carries out the calculation of vehicle volume and speed is also developed using Visual Basic programming language. Every T_{query}, the external module receives online and offline data from VISSIM. Then it calculates vehicle volume and speed every data-extraction period (Fig. 10).

The simulation area is considered as shown in Fig. 11. The road topology consists of 5 roadways: A, B, C, D, E which form a traffic circle and a three-legged intersection. Each input at A, B, C, E has 1 lane; input at D has 2 lanes. Between the intersection and the traffic circle, there is a two-way pedestrian crossing. A 50m effective range V2I station covers the traffic circle area and the 100m one manages

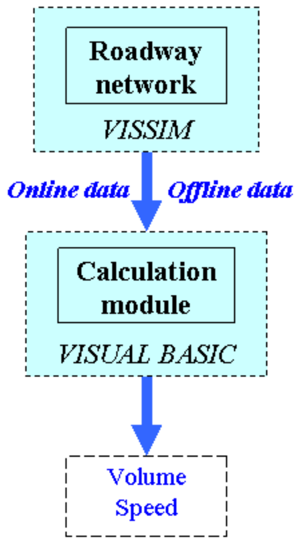

Figure 10: Method implementation

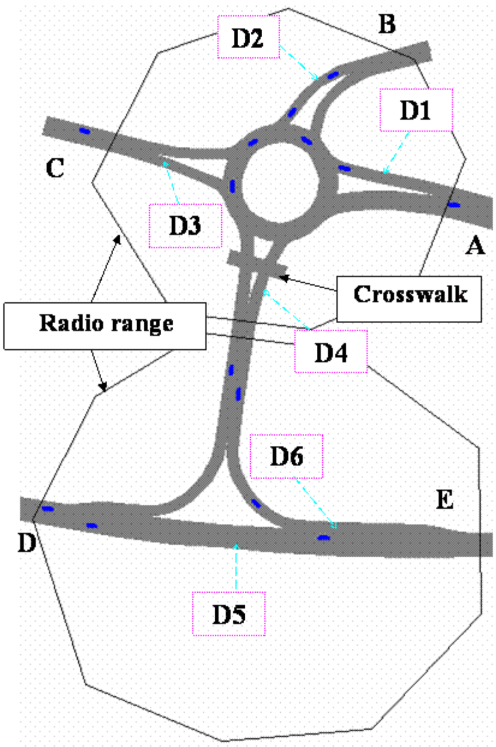

Figure 11: Simulation roadway network

the intersection area. Six loop detectors from D1 to D6 are placed within these 2 areas to directly detect volume and speed. In addition, volume and speed are also indirectly measured using the wireless communication. Vehicles are set to move through this roadway network at speed up to 36 m/s with a static routing decision. Pedestrians are given the right of way at the crosswalk. The simulation is run for 600 seconds. Both the direct traffic data from loop detectors and the indirect data from V2I stations are collected every 30-second data-extraction period. We note that because D1 is located in front of the pedestrian crossing, vehicle volume and speed at D1 are lower than at other detectors. The simulation parameters are shown in Table 1.

Fig. from 12 to 17 represent the speed measured by loop detectors from D1 to D6 respectively and by the V2I stations. The green line with small triangles represents the difference value of speed measured by loop detectors and by V2I stations. The horizontal axis is 20 periods of 30 second each, during the 600-second simulation.

Table 1: Simulation parameters

Parameters	Value
Total simulation time (s)	600
Query period (s)	0.1
Data-extraction period (s)	30
Lane width (m)	3.5
Loop detector size (m)	2.1 x 5
Vehicle length (m)	5
Effective range (m)	50 & 100
Maximum vehicle speed (m/s)	36
Input volume A (vehicle/h)	200
Input volume B (vehicle/h)	500
Input volume C (vehicle/h)	50
Input volume D (vehicle/h)	629
Input volume E (vehicle/h)	758
Pedestrian volume (people/h)	200

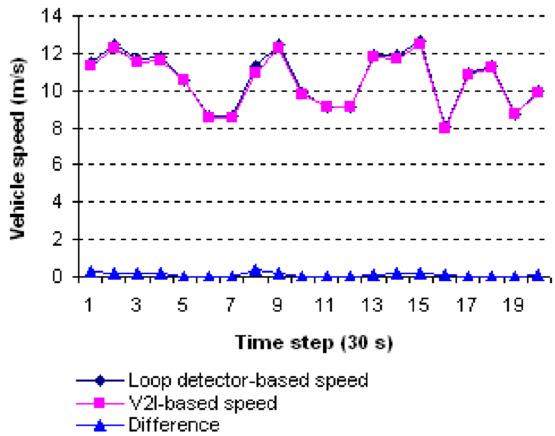

Figure 12: Vehicle speed at detector D1

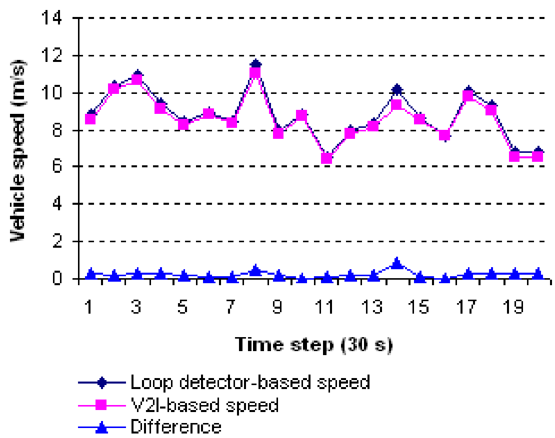

Figure 13: Vehicle speed at detector D2

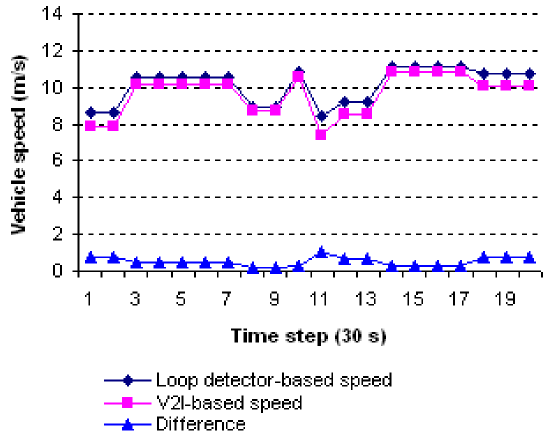

Figure 14: Vehicle speed at detector D3

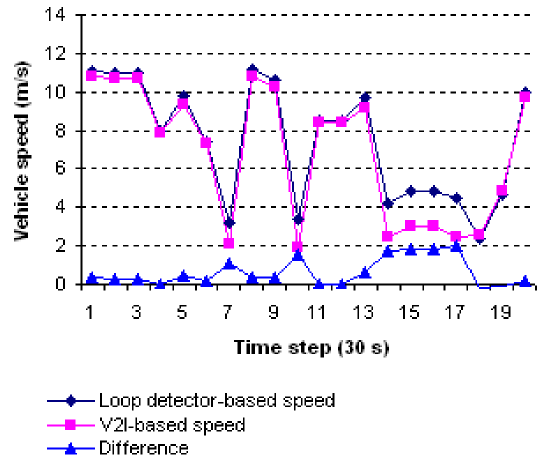

Figure 15: Vehicle speed at detector D4

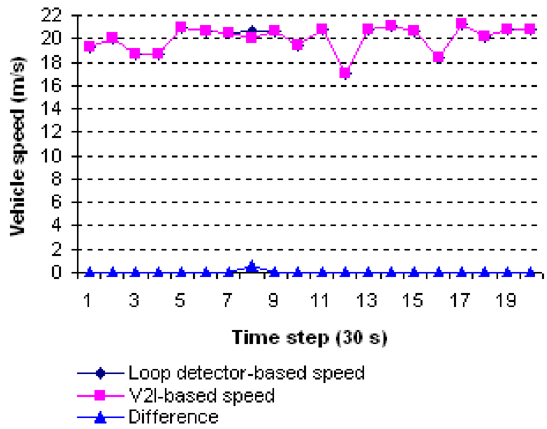

Figure 16: Vehicle speed at detector D5

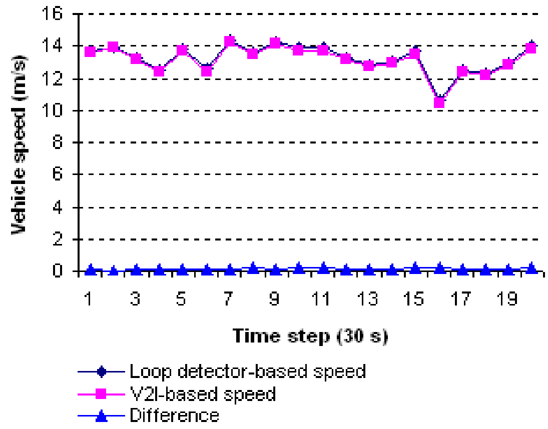

Figure 17: Vehicle speed at detector D6

We can see that the difference of speed data in the two methods increases when vehicle speed decreases (see the result at D4). This is because V2I stations determine the average speed of a vehicle within the time it cover an emulated detector while loop detectors return the instant speed whenever a vehicle occupies them. When vehicles move slowly, the time interval that vehicles cover a detector increases. Therefore, the difference between average speed and instant speed increases.

Fig. from 18 to 23 are histograms of the volume detected by detectors from D1 to D6 respectively and by the V2I stations. The horizontal axis is also 20 periods of 30 seconds each. The histograms show the V2I-based volume is very precise compared with that of loop detectors. Although in some cases there is a difference of detected volume when we look at some periods, the total volume does not change.

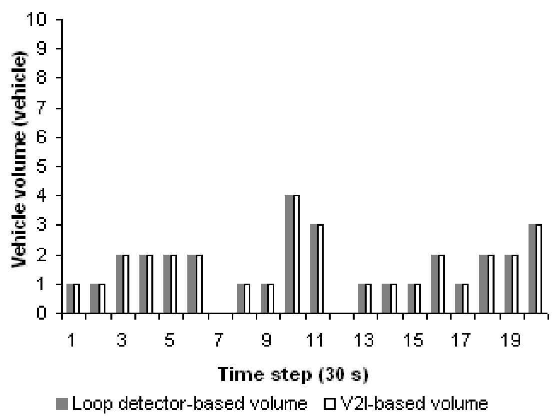

Figure 18: Vehicle volume at detector D1

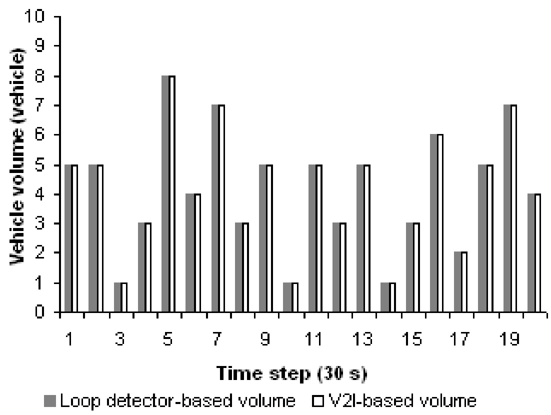

Figure 19: Vehicle volume at detector D2

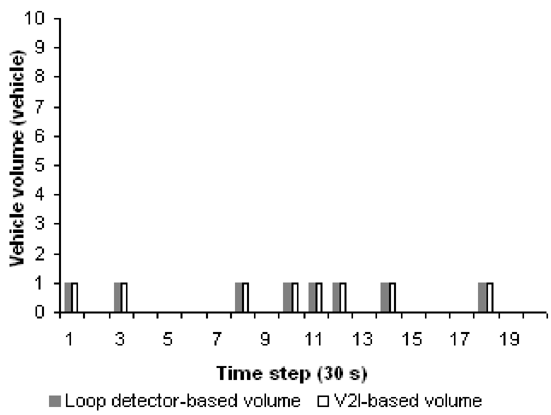

Figure 20: Vehicle volume at detector D3

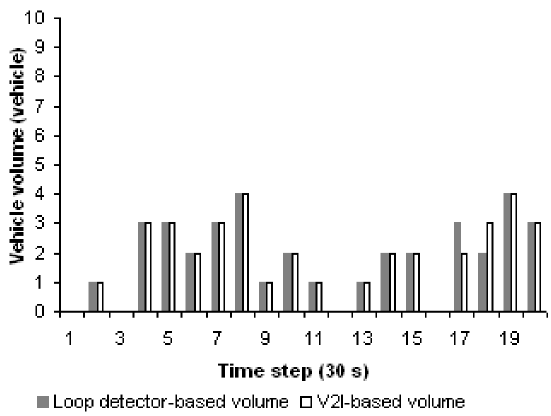

Figure 21: Vehicle volume at detector D4

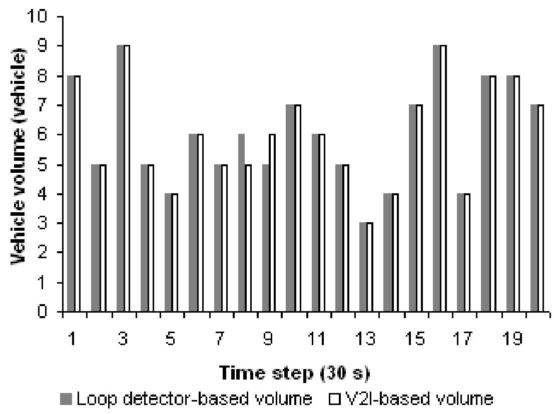

Figure 22: Vehicle volume at detector D5

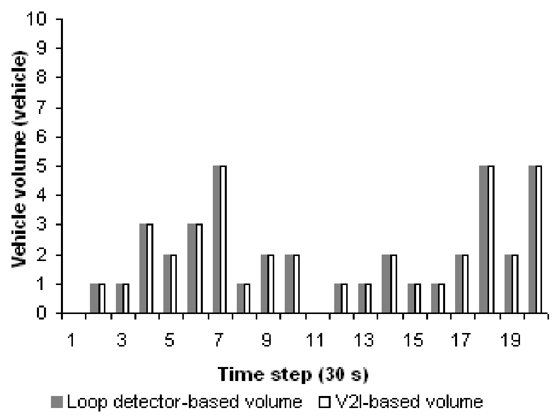

Figure 23: Vehicle volume at detector D6

The reason for this difference is that the V2I stations sometimes register detected vehicles on the volume data of the following data-extraction period depending on when they receive "Hello" messages. For example, looking at time steps 17 and 18 in Fig. 21 we see that detector D4 detected 3 and 2 vehicles in each time step respectively, the V2I station detected 2 and 3 vehicles respectively. The sum of detected vehicles over the two periods is 5 in both cases.

5 Conclusion

The traffic data measurement based on the V2I communication and GPS is an efficient method which can be used for future ITS. The proposed method can provide the volume and speed of vehicles at any position of any roadway lane in the transmission range of V2I station. However, the GPS errors must be less than the lane width because we identify vehicle locations at the lane level. In this paper, we assume that all vehicles are equipped with GPS receivers which is not always possible in real conditions. In the future work, we will reduce the number of vehicles equipped with GPS and apply an approximation method to evaluate vehicular data.

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