

Research Article

Evaluating the Accuracy of Bluetooth-Based Travel Time on Arterial Roads: A Case Study of Perth, Western Australia

Yuchen Liu ¹, Jianhong (Cecilia) Xia ¹ and Alope Phatak ²

¹Department of Spatial Sciences, Curtin University, Bentley Campus, Kent Street, GPO Box U1987, Perth, WA 6845, Australia

²Centre for Transforming Maintenance Through Data Science, Curtin University, Bentley Campus, Kent Street, GPO Box U1987, Perth, WA 6845, Australia

Correspondence should be addressed to Yuchen Liu; yuchen.liu@postgrad.curtin.edu.au

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Bluetooth (BT) time-stamped media access control (MAC) address data have been used for traffic studies worldwide. Although Bluetooth (BT) technology has been widely recognised as an effective, low-cost traffic data source in freeway traffic contexts, it is still unclear whether BT technology can provide accurate travel time (TT) information in complex urban traffic environments. Therefore, this empirical study aims to systematically evaluate the accuracy of BT travel time estimates in urban arterial contexts. There are two major hurdles to deriving accurate TT information for arterial roads: the multiple detection problem and noise in BT estimates. To date, they have not been fully investigated, nor have well-accepted solutions been found. Using approximately two million records of BT time-stamped MAC address data from twenty weekdays, this study uses five different BT TT-matching methods to investigate and quantify the impact of multiple detection problems and the noise in BT TT estimates on the accuracy of average BT travel times. Our work shows that accurate Bluetooth-based travel time information on signalised arterial roads can be derived if an appropriate matching method can be selected to smooth out the remaining noise in the filtered travel time estimates. Overall, average-to-average and last-to-last matching methods are best for long (>1 km) and short (≤ 1 km) signalised arterial road segments, respectively. Furthermore, our results show that the differences between BT and ground truth average TTs or speeds are systematic, and adding a calibration is a pragmatic method to correct inaccurate BT average TTs or speeds. The results of this research can help researchers and road operators to better understand BT technology for TT analysis and consequently to optimise the deployment location and configuration of BT MAC address scanners.

1. Introduction

Accurate travel time (TT) or speed measures, such as average TTs or average travel speeds, are critical for road operators to monitor, evaluate, and manage the performance of a road network, and for road users to make well-informed route choices [1, 2]. However, collecting such information by using traditional methods and technologies, such as floating car survey and automatic number-plate recognition technology, is a cumbersome and resource-intensive task, even for a single road [3].

Recently, Bluetooth (BT) technology has been recognised as an alternative, cost-effective method to supply TT and other valuable traffic information [4–6], such as origin-

destination [7, 8], routing choice [5, 9], and vehicle trajectories [10]. BT traffic monitoring systems rely on the identification of unique BT media access control (MAC) addresses of in-vehicle discoverable BT devices, such as onboard stereos, hands-free kits, and global positioning system (GPS) navigation modules. Because of their low capital and installation costs, BT MAC address scanners (BMSs) can be installed on a massive scale at critical locations of a road network, such as signalised intersections along arterial roads, to detect MAC addresses at different times and locations [11] and provide network-wide performance indicators in real time [12]. This enables road authorities to have access to low-cost individual travel times at a road network level, and many BT traffic information

collection systems and applications have been developed and used worldwide, for example, the BT sensors of the INRIX, TrafficCast BlueTOAD, and BlipTrack systems [13].

Apart from the cost advantage of BT traffic monitoring system, deriving BT TT estimates from the time-stamped MAC address data of a BT link is straightforward and can be done by a matching process: if a MAC address is recorded at both the upstream and the downstream BMS of a road link, the time difference between the two time-stamps yields the TT estimate of that MAC address. The BT TT estimate and speed estimate of a BT link AB can be written as

$$TT_{AB} = \text{Timestamp}_B - \text{Timestamp}_A, \quad (1)$$

$$V_{AB} = \frac{L_{AB}}{TT_{AB}}, \quad (2)$$

where Timestamp_A and Timestamp_B are the timestamps of a MAC address recorded at upstream BMS A and downstream BMS B in a time period; TT_{AB} is the travel time of a MAC address over Bluetooth road link AB; V_{AB} is the corresponding travel speed; and L_{AB} is the length between two perpendicularly projected points of BMS installation locations on the central line of a road. The associated location information of a timestamp cannot be directly measured and provided because Bluetooth technology is a zone to zone technology [3]. Furthermore, in travel speed calculations, the travelling distance L_{AB} is fixed, but TT_{AB} depends on which timestamp is chosen at A and B when there are multiple detections at BMS A and B. This multiple detection problem is one that we address in this work.

Although BT technology has been recognised as a reliable and accurate source of travel time data for freeways [14, 15], it is still unclear whether accurate TT information can be derived from BT time-stamped address data in urban traffic contexts, especially for short arterial road links [3, 6, 11, 16–18]. This is mainly because of the technical characteristics of BT technology (see section 2.2.1 and 2.2.2) and the characteristics of complex urban traffic environments (see section 2.2.3). Therefore, this empirical study aims to systematically evaluate the accuracy of BT travel time in an urban arterial context. Two major hurdles to deriving accurate BT estimates for arterial roads are the multiple detection problem and the noise in BT estimates [19]; however, they have neither been fully investigated nor addressed, and this study aims to fulfil that gap.

According to the classification of Bhaskar and Chung [12], there are four noise sources in BT TT estimates:

- (i) Nonvehicular modes, such as pedestrians and cyclists [3, 6, 16, 17, 20–22]
- (ii) Lack of information outside the detection zone, for example, when a vehicle uses an alternative route or stops along the route [20, 22]
- (iii) Multiple matches, for example, matching two detections of a MAC address at an upstream BMS with its single detection at the downstream BMS can generate two TT estimates (in this example, the two

upstream detections are generated because the vehicle may have driven in, out, and then back into the detection zone)

- (iv) Missing observations, for example, a discoverable BT device may have completed two trips, i.e., back and forth between two consecutive BMSs, but was only captured at the upstream BMS in the first trip and at the downstream BMS in the second trip, leading to an overestimated TT

To reduce the impact of TT estimate noise on deriving accurate average TT information, outlier filtering techniques have been developed, such as the Kalman filter [7], moving median filter [3], box-and-whisker filter [9], and a four-step offline filtering algorithm developed by Haghani et al. [15]. As discussed above, the multiple detection problem refers to the choice of detections that should be used to calculate TT estimates when a discoverable BT device is recorded several times by a BMS as it travels through the detection zone [11]. Clearly, a better understanding of factors causing TT estimate noise and multiple detection problem—and how to resolve them—will give us a better understanding about which detections should be used for the matching process.

Current empirical studies focus primarily on the direct matching of BT detections at different BMS [12], and there are very few studies that systematically investigated the sources of noise in BT TT estimates and the accuracy of the derived average TT information [23]. This study aims to fulfil this gap by

- (1) Identifying factors of BT TT estimate accuracy
- (2) Developing a framework for deriving accurate TT estimates from BT time-stamped MAC addresses and assessing their accuracy
- (3) Evaluating the accuracy of the derived BT average TTs or speeds through different matching methods

In this study of an arterial road in Perth, Western Australia, historical TT data (details in Section 3.1), derived from the crowdsourced GPS data from TomTom company, are used as the ground truth to evaluate the accuracy of BT average TT. To investigate the impact of the multiple detection problem on BT average speeds, five different matching methods have been implemented, and they are first-to-last (F-L, it means using the first detection and last detection at the upstream and the downstream BMS of a BT segment, respectively), first-to-first (F-F), last-to-first (L-F), last-to-last (L-L), and average-to-average (A-A).

The main contribution of this study lies in its comprehensive analysis using five different matching methods and a very large historical BT dataset collected from an urban arterial environment to investigate and quantify the impact of the multiple detection problem and the noise in BT estimates on the accuracy of average BT travel times or speeds. The results of this study will help researchers and road operators to better understand BT technology for TT analysis and consequently to optimise the deployment location and configuration of BT MAC address scanners.

2. Literature Review

The review of literature focuses on two aspects: introducing the current state of matching methods and the multiple detection problem, and investigating factors affecting the accuracy of BT TT estimate. The first aspect helps to identify the research gap, and the second enables the evaluation of accuracy to be systematic.

2.1. Matching Methods for Multiple Detections. To derive TT information from BT time-stamped MAC address data, various matching methods have been implemented on both arterial roads and freeways. Quayle et al. [17] chose the first-to-first method (matching the first detection from both the upstream and downstream BMS) to calculate the TT of a 2.5-mile signalised arterial segment for validating BT technology. Vo [22] also chose first-to-first detections to calculate TT for a 1-mile arterial road segment and suggested that the impact of other matching methods on improving TT accuracy should be investigated, such as the last-to-last method. In addition, in the study of Moghaddam and Hellinga [24], the first detections at consecutive BMSs were used to derive travel time estimates for analysing detection errors. Different from them, Tsubota et al. [9] chose the last-to-last method to calculate TT estimates and used the duration information (the time interval between the first detection and the last detection) to analyse the traffic congestion at signalised intersections. In these studies, which have different objectives than ours, only one matching method was consistently used to derive TT estimates.

Saeedi et al. [11] argued that the inaccuracies of signalised arterial average TT measures depended on the matching method used, and the nearest detection to the BMS should be used to minimise the location ambiguity. Therefore, they chose a detection method that had the strongest received signal strength for calculating the TT of a signalised highway. According to their results, this method gave the most accurate average TT compared with the ground truth average TT collected from GPS technology, following by last-to-last, average-to-average, and first-to-first. However, lower layer information such as received signal strength information (RSSI) may not be provided by or collected from other BT traffic monitoring systems, and Díaz et al. [19] pointed out that the RSSI is dependent on the class of BT devices, for example, two BT devices with two different transmitting power because of their different class types can still generate two distinct RSSI values on a BMS when they are at the exact same location. It is noticeable that the data in the study of Saeedi et al. [11] were collected from a controlled experiment, and in each run, only two estimates were collected from two mobile phones in the same vehicle.

By contrast, Bhaskar and Chung [12] developed a multilayer simulation model to systematically analyse and model the accuracy and reliability of TT estimates from three different segmentation methods: entrance-to-entrance section, stop-to-stop section, and exit-to-exit section. These three methods correspond to first-to-first, middle-to-middle, and last-to-last matching methods, respectively. Based

on the results from their simulation data, they suggested exit-to-exit should be used to develop intelligent traffic system (ITS) applications, such as traffic signal optimisation, because entrance-to-entrance only includes a proportion of delay observed at the upstream signalised intersection.

By contrast with these studies, this research uses five different matching methods and realistic data collected from an arterial road to investigate the impact of the multiple detection problem and noise in TT estimates on the accuracy of BT TT or speed information.

2.2. Accuracy Factors of BT TT Estimates. The total staying time in a detecting zone determines the total number of detections of a discoverable BT device: the longer a vehicle stays in a BMS detection zone, the more detections of its devices will be recorded. Various causes of multiple detections have been identified in previous research. For example, Araghi et al. [25] implemented a field experiment on a section of a freeway for investigating the impact of factors on the detection probability of a passing unique MAC address and exploring the spatial distribution of recorded detections. They summarised factors influencing multiple detections based on the study of Quayle et al. [17], including the strength and speed of a transmitting device, inquiry procedure, the ping cycle of BT sensors (0.1 s), the proximity of the BMS, the size and shape of the detection zone, and the staying time of a MAC address in the detection zone (the travelling time). It should be noted that the staying time in the detection zone of a BMS installed at arterial signalised intersection is not equivalent to the travelling time. The staying time should be the combination of the travelling time in the detection zone, the waiting time for the traffic signal, and the staying time on business premises.

Different from the previous summary, we classify the factors affecting BT TT estimates into the following three groups to emphasise the differences between groups, benefit the inaccuracy diagnosis in the following analysis, and highlight factors that should be considered in an urban arterial context (Factor Group 3).

2.2.1. Bluetooth Inquiry Process-Related Factors—Factor Group 1. The first group consists of factors related to the inquiry procedure of BT technology, including the strength and speed of a transmitting device, the proximity of the roadside BT sensor, the ping cycle of BT sensors (0.1 s) [17], and background noise [25]. The inquiry procedure aims to scan discoverable BT devices and obtain their MAC addresses and internal clock values. The frequency-hopping spread spectrum and frequency trains of the inquiry procedure aim to avoid the radio frequency interference for BT devices to communicate with each other in the unlicensed narrow radio band, from 2.4 to 2.485 GHz, and more explanation about them can be found in Franssens [26] and Bhaskar and Chung [12]. Theoretically, a single inquiry phase of detecting a device may take up to 10.24 seconds to finish, and most devices can be detected in 6 seconds [25, 26]. Malinovskiy et al. [27] stated that the frequency-hopping protocol could introduce a random error of up to

10.24 seconds in device inquiry time, which could cause variable location error depending on the speed of a vehicle. For an onboard discoverable BT device travelling at 50 km/h through 150 meters in the detecting zone of a BMS installed at a signalised intersection, without experiencing traffic light, the total travelling time is 9 seconds ($3.6 * 150/60$); therefore, it is very likely for this device to be detected more than once, but there is still a chance that it may be missed by the BMS because the total staying time is shorter than the detecting period (10.24 s) of the inquiry procedure.

For the BT monitoring system in this study, the interval between two consecutive inquiry procedures lasts around 17 seconds, and this might be caused by adding the time of storing the detected data from the BMS to the BT record tables of the database of the BT traffic intelligent system, which runs every 8-9 seconds, onto the time of a detecting procedure [28]. The main concern of this long interval is if a BT device is missed out in one inquiry procedure, it may be captured 17 seconds later. This could introduce significant location error because the device may have moved from one side of the detection zone to another side, whereas L_{AB} in equation (1) is fixed.

2.2.2. Bluetooth Zone-Related Factors—Factor Group 2. The second group consists of factors related to the BMS detection zone, such as size, shape, and the length of a road that could be covered by the zone. According to the BT core specification mandates, typical Class 1 radios have a range of up to 100 meters. However, there is no upper limit on the actual detecting range of a BMS. BT device manufacturers can tune the range according to the needs of their customers. The impact of the BMS detecting zone on the accuracy of TT estimates and multiple detections has been investigated by several researchers. Malinovskiy et al. [27] found that vehicles travelling at a high speed were more likely to be undetected in a detection zone, leading to an overestimated average TT. A larger detecting zone may prevent this problem. Tsubota et al. [9] and Van Boxel et al. [29] argued that large BMS detection zone is a main cause of inaccurate TT estimates on arterial roads because a large zone means a long staying time, which leads to multiple detections. Although short-range antenna could provide a more accurate TT estimate because discoverable MAC addresses are captured in a location closer to a BMS, a smaller detection zone can cause a lower penetration rate, leading to a decrease of the accuracy of TT estimates [25]; they argued that there should be a trade-off between the size of the detection zone of a BMS and its penetration rate for configuration and coverage of the antennas.

2.2.3. Arterial Road-Specific Factors—Factor Group 3. The third group aims to highlight the multiple detections and noise caused by the arterial road-specific factors, including traffic lights, business premises, intersection layout, and vehicle-moving behaviours (for example, driving in and out of a BT detection zone). Arterial roads have many traffic signals, which may interrupt continuous travel of vehicles and force some vehicles to stay longer in a BT detection zone.

Saeedi et al. [11] stated that the number of detections could increase rapidly while waiting for the traffic signal to change, and under this circumstance, first-to-first and last-to-last matching methods may result in large TT errors. Compared with the waiting time for the traffic light to change, the waiting time on business premises may be up to several minutes or even longer, and a significant number of detections could occur. Some facilities, such as rest areas, gas stations, and toll plazas, between two sensors may also contribute some TT estimate noise [15], which belong to the noise source of no information outside the detection zone. Nonthrough vehicles could also cause TT noise because of the long distance of turning movements caused by the special layout of the intersection and the location of a BMS therefore, Bhaskar and Chung [12] and Tsubota et al. [9] only utilised TT estimates from through vehicles in their studies.

3. Research Data

3.1. Three Traffic Data Sources. In this study, three different traffic data sources, BT time-stamped MAC address data, traffic counts data, and TomTom historical TT data, were provided by Main Roads Western Australia (MRWA) for the systematic evaluation. The study area is Canning Highway (Hwy), Perth, Western Australia, a main urban and high-volume arterial road that runs west to east (see Figure 1).

The BT data were extracted from its installed BT traffic monitoring system, which aims to provide real-time road traffic information from in-vehicle discoverable BT devices detected by BMSs. Canning Hwy has 19 BMSs, which are installed in the traffic signal control cabinet of 19 signalised intersections, because the available power supply and access to Ethernet port significantly reduce the difficulty and cost of installation. However, this could cause a low capture rate of discoverable BT devices because the installation location and antenna characteristics of a BMS have significant impact on the capture of BT-enabled devices [30]. The lengths of BT road links along Canning Hwy vary from 133 m to 2.14 km, which enables the investigation of the accuracy of BT TT on both short and long arterial signalised road links. The data covered twenty weekdays from September 04 to 28, 2017. The study period during a day was defined to be from 06:00 to 20:00, which has 56 time sets of a 15-minute duration.

The traffic count information was obtained from the Sydney Coordinated Adaptive Traffic System (SCATS), which is an intelligent transportation system used to manage the real-time timing of signal phases at signalised intersections. The total counts of a signalised intersection can be obtained by summing the counts of each lane and is used to evaluate the penetration rate of vehicles having BT-enabled devices captured by the BMS.

TomTom is a Dutch manufacturer of automotive navigation systems, and its historical traffic database has trillions of anonymous GPS measurements collected from all its devices, with 11 billion new records being added on an average day. TomTom historical TT information has been adopted by MRWA to replace its own TT collection method (floating car survey) on limited roads in Perth Metropolitan

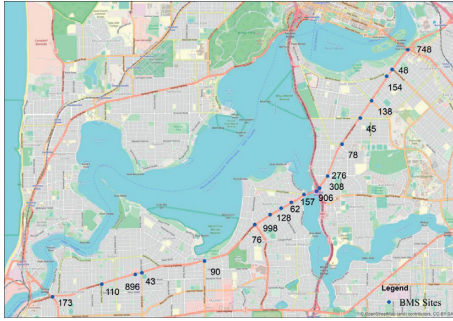


FIGURE 1: Canning Highway.

Area (PMA), including the Canning Hwy, because of its superiority of coverage, data abundance (i.e., accurate TT), and low cost. Therefore, the TomTom data were chosen as the ground truth to evaluate the accuracy of BT TT information. In each time set, the TomTom data can provide the aggregated average TT from 20 selected weekdays of each segment and the average sample size of all segments (the average sample size of each TomTom road segment in each time set cannot be derived from the TomTom historical portal website). The eastbound of the Canning Hwy has 301 TomTom segments ranging from 5.43 m to 293.91 m, and the westbound has 296 TomTom segments ranging from 5.01 m to 291.90 m. Because the spatial scale of TomTom road links are much finer than the spatial scale of BT road links, the TomTom TT of BT road links can be aggregated from corresponding split and matched multiple TomTom segments' TT.

3.2. Characteristics of the Collected BT Time-stamped MAC Address Data. This section aims to introduce the forms of multiple detection problem in the collected BT data. Table 1 shows a sample of the collected BT time-stamped MAC address data, in which each row is one record. The *ProbeId* field contains the MAC addresses encrypted as integers according to the sequence in which they are captured by the system [28]. A MAC address is a 48-bit address that has 6 pairs of two hexadecimal digits, for example, 50 : B4 : 21 : H8 : 9U : J4. The first three pairs identify the device manufacturer according to an identification code allocated by the Institute of Electrical and Electronics Engineers, and the last three pairs are set by the manufacturer [26]. However, collected MAC addresses were encrypted as integers to ensure privacy.

LogTime and *FirstSeenAt* fields store the two captured timestamps of a MAC address, and they are the last detection and first detection that specific MAC address being captured at a BMS, respectively. Any other detections between the *LogTime* and *FirstSeenAt* are discarded to reduce the number of detections and save storage space. The *Duration* field is the time difference between the *LogTime* and *FirstSeenAt*, which presents the time that the BT device stays in the detection area of a BMS. This duration information can be used for analysing traffic congestion [9] and measuring intersection performance [31]. The *SiteId* field stores the unique IDs of BMSs, which are named by the site ID of its corresponding signalled intersection.

The *Adjacent_TimeDiff* provides the time difference of two time-adjacent records, which is the difference between the *FirstSeenAt* of one record and the *LogTime* of its previous record. This added field gives clues about how multiple detections be classified and stored into different records of the BT record table of the BT traffic monitoring system. In the *Adjacent_TimeDiff* field, there are no values smaller than 30 seconds, and a reasonable guess is if a MAC address failed to be captured in its two consecutive inquiry phases, its previous detections and later detections will be treated as two different groups of detections, in which the first and last detection of a group be stored as *FirstSeenAt* and *LogTime* of a record in the BT record table in the database. There is one storing process (8 s or 9 s) between two inquiry procedures ($2 * 10.24$ s), so the minimum time difference between two records of a MAC address is ~29–30 seconds. NA means this information is not applicable for MAC addresses that have only one unique record or for the first record of a group records of a MAC address.

In this sample shown in Table 1, records belonging to one BT device were grouped and then sorted by time, and MAC addresses were deliberately picked out to show the following BT data characteristics:

- (1) A MAC address could have multiple identical records (duplicates, Group 1)
- (2) A single MAC address has multiple records (Groups 2, 3, and 4)
- (3) The number of records differs for different MAC addresses in a time period
- (4) The duration differs for different records, ranging from 0 seconds to several days

These characteristics are related to the multiple detection problem, in which each detection of a MAC address generates a timestamp. For the collected BT MAC address data, in one time set, the multiple detection problem has three forms:

- (1) A MAC address has one record with only one detection (*LogTime* and *FirstSeenAt* are the same timestamp)
- (2) A MAC address has one record with two different detections being saved (*LogTime* and *FirstSeenAt*)
- (3) A MAC address has multiple records, for which selecting appropriate detections from the collected MAC address data refers to which record should be chosen from a group of records of a MAC address and which timestamp should be used from the selected record, i.e., *LogTime* or *FirstSeenAt*

The following example illustrates that the accuracy of TT estimates is heavily affected by the choosing of a matching method. In Table 1, an encrypted MAC ID address 18134 has two records at sites 128 and 62, having four detections available at both sites. Because all the four detections of 128 are occurred earlier than the four detections of 62, the possibility that these four records represent two trips finished by this MAC address can be excluded. Obviously, for

TABLE 1: A sample of collected BT time-stamped MAC address data.

Group	ID	LogTime	SiteId	ProbeId	FirstSeenAt	Duration	Adjacent_TimeDiff
Group 1	1	2017-09-01 07:30:05	173	8798	2017-09-01 07:30:05	0 Day 00:00:00	NA
	2	2017-09-01 07:30:05	173	8798	2017-09-01 07:30:05	0 Day 00:00:00	NA
Group 2	1	2017-09-01 07:36:11	173	15696	2017-09-01 07:36:11	0 Day 00:00:00	NA
	2	2017-09-01 07:36:11	173	15696	2017-09-01 07:36:11	0 Day 00:00:00	NA
	3	2017-09-01 07:36:44	173	15696	2017-09-01 07:36:44	0 Day 00:00:00	00:00:33
	4	2017-09-01 07:36:44	173	15696	2017-09-01 07:36:44	0 Day 00:00:00	NA
Group 3	1	2017-09-04 07:31:54	128	33	2017-09-04 07:22:25	0 Day 00:09:29	NA
	2	2017-09-04 07:33:16	128	33	2017-09-04 07:32:35	0 Day 00:00:41	00:00:41
	3	2017-09-04 07:34:06	128	33	2017-09-04 07:33:47	0 Day 00:00:19	00:00:31
	4	2017-09-04 07:35:06	128	33	2017-09-04 07:35:06	0 Day 00:00:00	00:01:00
	5	2017-09-04 07:36:23	128	33	2017-09-04 07:36:23	0 Day 00:00:00	00:01:17
	6	2017-09-04 07:38:19	128	33	2017-09-04 07:37:41	0 Day 00:00:38	00:01:18
	7	2017-09-04 07:39:24	128	33	2017-09-04 07:39:05	0 Day 00:00:19	00:00:46
Group 4	1	2017-09-10 08:54:54	76	14810	2017-09-06 09:19:20	3 Day 23:35:34	NA
	2	2017-09-10 09:45:23	76	14810	2017-09-10 08:55:28	0 Day 00:49:55	00:00:34
	3	2017-09-10 10:41:10	76	14810	2017-09-10 09:45:55	0 Day 00:55:15	00:00:32
	4	2017-09-10 13:54:55	76	14810	2017-09-10 10:41:42	0 Day 03:13:13	00:00:32
	5	2017-09-10 15:48:03	76	14810	2017-09-10 13:55:29	0 Day 01:52:34	00:00:34
	6	2017-09-10 16:28:13	76	14810	2017-09-10 15:48:34	0 Day 00:39:39	00:00:31
Group 5	1	2017-09-04 07:33:29	128	18134	2017-09-04 07:33:29	0 Day 00:00:00	NA
	2	2017-09-04 07:35:19	128	18134	2017-09-04 07:34:03	0 Day 00:01:16	00:00:34
	3	2017-09-04 07:36:12	62	18134	2017-09-04 07:35:54	0 Day 00:00:18	NA
	4	2017-09-04 07:36:44	62	18134	2017-09-04 07:36:44	0 Day 00:00:00	00:00:32

this MAC address, the choice on selecting upstream detection and downstream detection can introduce huge TT difference; for example, using the *LogTime* of record 2 and the *FirstSeenAt* of record 3 can generate a TT of 35 seconds, corresponding to a travel speed of 41.14 km/h (the length of link 128-62 is 402 meters) in the morning peak; if the *LogTime* of record 2 and record 4 is selected, the TT and speed is 85 seconds and 16.9 km/h, respectively.

For evaluating which TT estimate of the example is more accurate or which method is more appropriate, it is important to know what the factors of multiple detection are, and to understand different matching methods' captured factors, and the level of their impact.

4. Method

To derive accurate arterial road TT estimates from BT time-stamped MAC address, it is suggested to (1) use timestamps from vehicular mode, (2) avoid using timestamps from BMSs having clock drift phenomenon (see Figure 2) or an inaccurate internal clock, and (3) select an appropriate detection from multiple detections for the matching process.

Because only the integer-encrypted MAC address information was available in this study, selecting vehicular mode by using the first three pairs of a MAC address cannot be implemented. Nevertheless, this study shows that using a data filtering algorithm could mitigate the impact of noise data from nonvehicular modes. For the second suggestion, it is a prerequisite of analysing the impact of different matching methods on TT accuracy and has been ensured by selecting appropriate studying periods. At last, the realisation of the last suggestion has been ensured by the following

means. The real scenario that a vehicle can experience on arterial roads has been classified into three classes according to their dominant factor groups. These three scenarios also correspond to the three different forms of time-stamped MAC address data or BT records in the BT record table of the database. Through identifying the degree of the impact of these three factor groups on TT estimate accuracy, corresponding matching methods can be suggested.

Figure 3 shows the offline framework of deriving and evaluating BT TT information. The framework was implemented in the R language statistical environment [32]. In the framework, because the collected MAC addresses are integers, the first step is selecting studying periods and BMSs without clock drift phenomenon by using any matching method to generate TT estimates and then visualise them via TT scatterplots (see Figure 2). And then, the MAC-to-volume ratio (MtVR), a measure resembling the BT penetration rate, is calculated by using BT data and SCATS data because it is critical for evaluating the applicability of BT MAC address data [33]. Then, MAC addresses that have only one record at a BMS in a time set will be selected for the next step, which is calculating TT estimates by using those five proposed matching methods. Before calculating average TT and speed, and accuracy indices of arterial segments, TT estimates must be filtered by the adopted Kalman filtering algorithm to remove some extreme values (mainly large outliers). Finally, the accuracy indices and the MAC-to-volume ratio will be organised and visualised as a dashboard in Tableau, a business intelligent platform. Detailed descriptions of the core components of the proposed framework are listed below, and Sections 4.1, 4.2, and 4.3 aim to introduce the method of handling multiple detection problem in different scenarios.

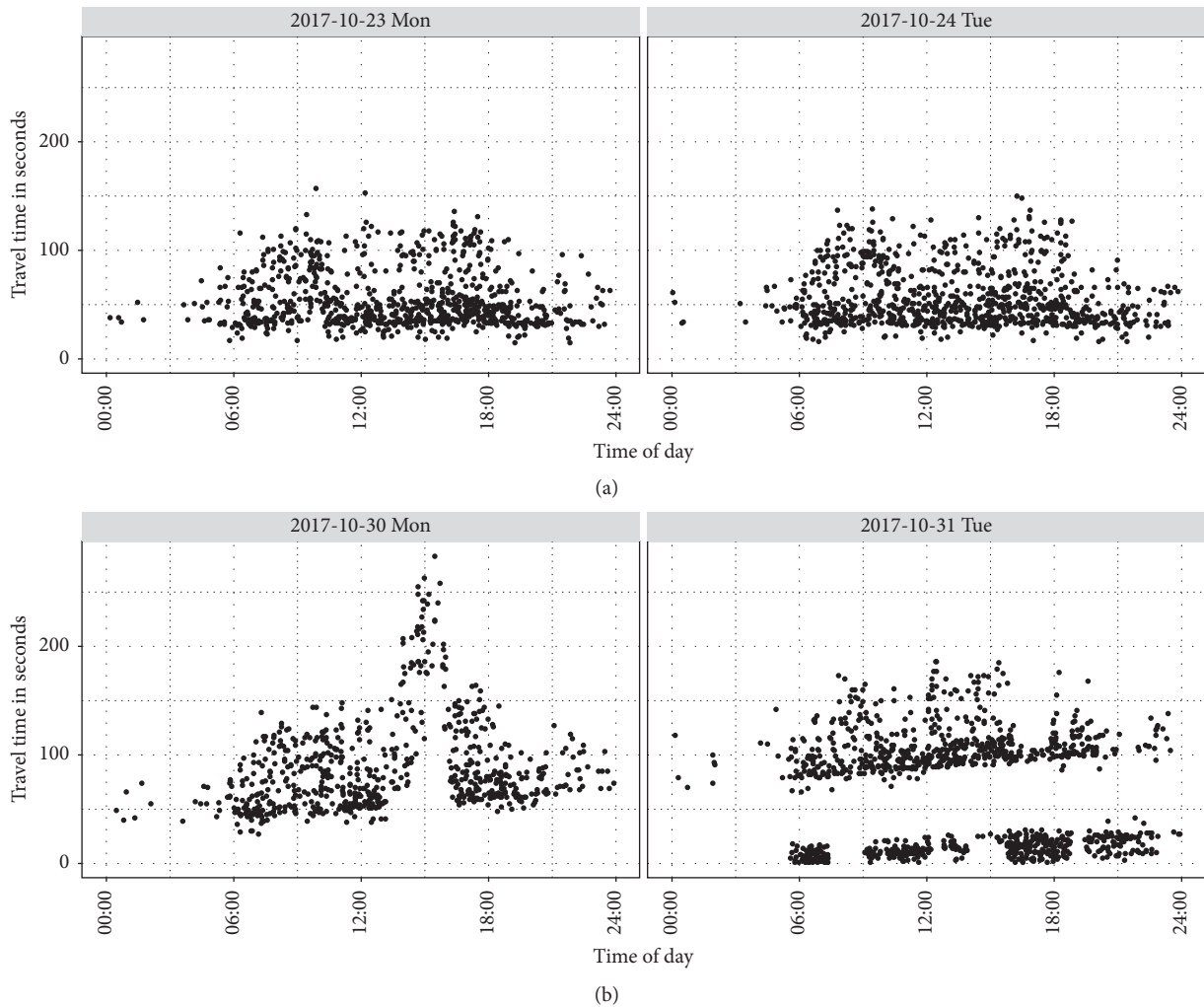


FIGURE 2: The clock drift phenomenon of link 998-76. (a) Although the top two subgraphs are normal, (b) the bottom two show the clock drift; in the bottom right subgraph, the TT estimates below the blank gap are from the opposite direction, link 76-998.

4.1. Scenario One-One Detection and One Record at a BMS.

In the simplest scenario that only one detection exists in a single record, TT error can still be introduced because this detection could be captured at any time in the 10.24 s of a detection procedure [3, 12]. This could introduce some location errors depending on the speed of a vehicle, causing TT errors, especially for shorter links [25]. In Figure 4, for example, the vehicle travelling through the detecting zone of BMS A and B can be captured anywhere from location 1 to location 3 for A and anywhere from location 3 to location 5 for B, respectively. If a BT device in this vehicle is detected once at location 2 of BMS A and location 4 of BMS B, the TT could be the most accurate. But the worst scenario can be that the detection by both BMS A and B occurred at location 3. This will cause zero-second TT; if the sample size is small, a single zero-second observation could introduce significant TT error to the average TT, leading to an overestimated average TT. This condition is typically experienced by vehicles on the freeway, and through vehicles on the arterial road that are under the free-flow conditions and not interrupted by traffic lights. For this scenario, different

matching methods generate the same result, and the TT error is introduced by the inquiry process. However, the TT errors of estimates caused by the inquiry process can be neutralised because the inquiry process caused error follows the generalised Gaussian distribution, leading to a more accurate average TT than individual TT estimates [12].

4.2. Scenario Two-Multiple Detections and One Record at a BMS.

In this scenario, a MAC address can be detected multiple times in the detection zone of a BMS, and only the first and last detections are stored in the *FirstSeenAt* and *LogTime* field of a record, respectively. Scenario two incorporates the impact of all three factor groups in Section 2.2, in which BT zone-related factors and arterial road-specific factors are the dominant factors. The duration depicts the total staying time in a BMS detection zone, and its value reflects the degree of combined impacts from three factor groups. Specifically, high duration values from several minutes up to hours, and even days, are more likely to indicate MAC addresses from nonvehicular modes,

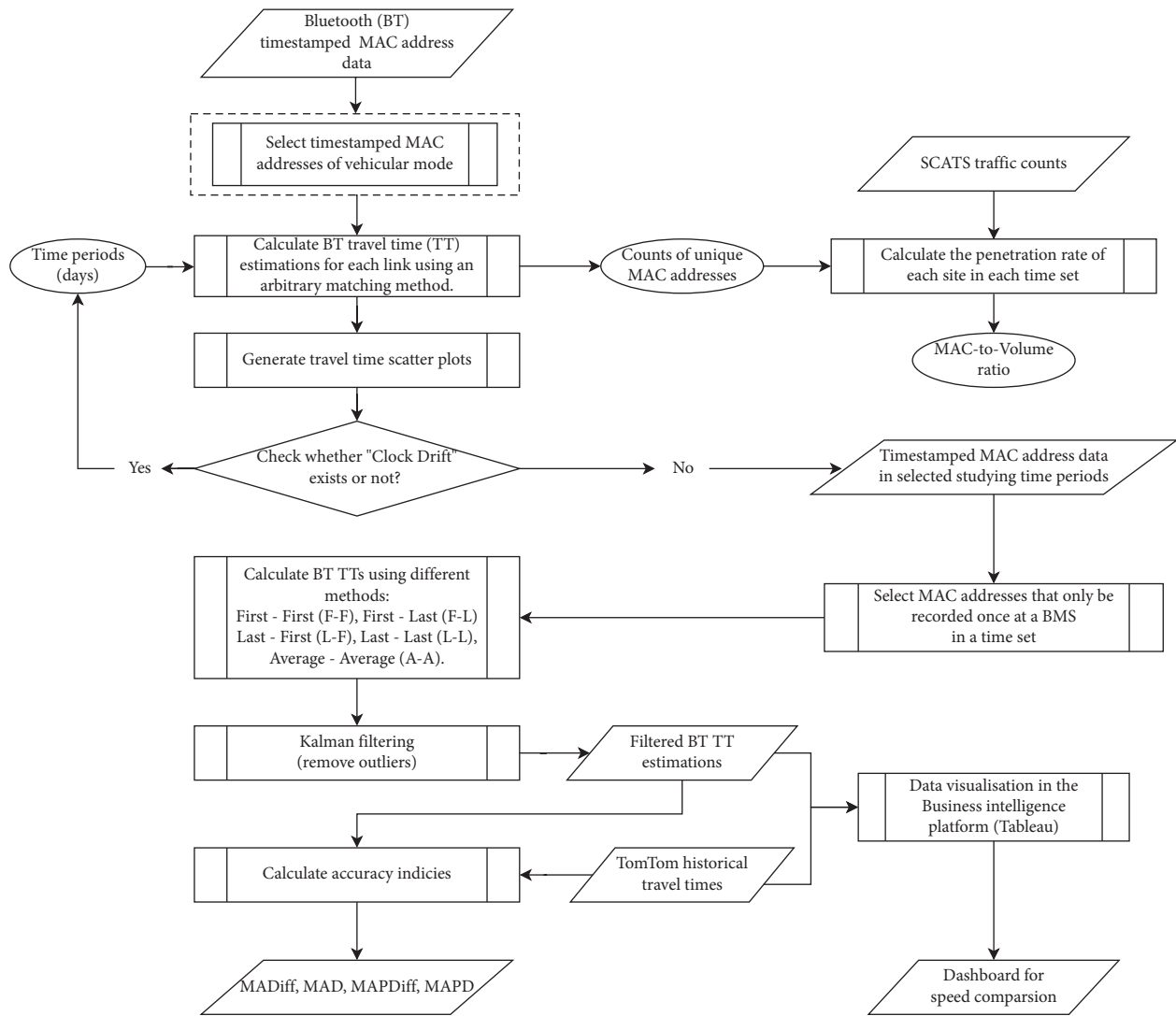


FIGURE 3: Offline framework of evaluating BT TT accuracy (the step in dash line box was skipped in this study).

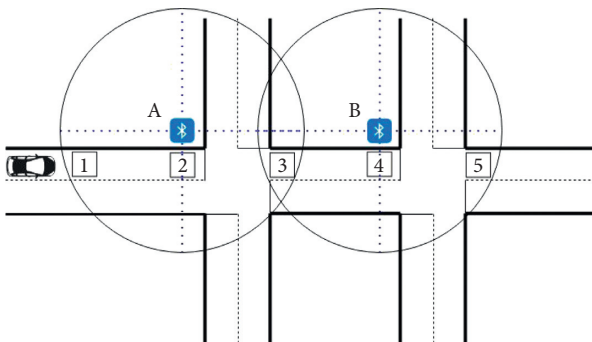


FIGURE 4: Illustration of Scenario one of a through vehicle on a signalised arterial link.

staying time on business premises, or stationary discoverable BT devices. Medium duration values up to several traffic signal cycles could indicate BT devices that may be heavily affected by traffic signals or traffic congestion. Short duration values within one signal cycle could indicate those

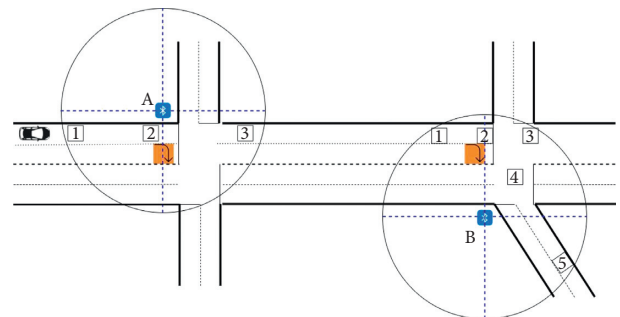


FIGURE 5: Illustration of scenario two of a vehicle on a signalised arterial link.

MAC addresses that are slightly affected by traffic signals or traffic congestion, the impact of vehicles' turning behaviour, the impact of the intersection layout, or the location of the BMS. These impacts caused the travelling time of a MAC address to be long enough for itself to be detected in several consecutive inquiry procedures of a BMS.

For scenario two, different matching methods have very different meanings. Theoretically, the F-L matching method can capture all three factor groups' combined impact in both the upstream and the downstream detection zone. For example, Figure 5 shows detection A1 and detection B3 of a through MAC address, or detection A1 and detection B5 of a nonthrough MAC address. Similarly, whereas the L-L (A3 and B3, or A3 and B5) can capture the combined impact in the downstream detection zone, the F-L (A1 and B1) can capture the combined impact in the upstream detection zone. Meanwhile, the A-A (A2 and B2, or A2 and B4) could partially capture the combined impact in the upstream and the downstream detection zone; however, the degree and elements of the partial capture are hard to be determined and quantified. The L-F method (A3 and B1) is likely to ignore the combined impact in the upstream and the downstream detection zone. Noticeably, the statement that a method can capture the combined impact does not indicate the full capture of all impacts, for example, the length of a segment affected by a traffic signal may be much longer than the part covered by the BMS.

The average detection is simply the average of the last detection and the first detection. Noticeably, the average detection is not always nearer to a BMS than the first detection and last detection; for example, when the first and last detection is A2 and A3, respectively, the nearest detection is still the first detection, A2. This is also influenced by factors of BT TT accuracy; for example, for a directional antenna, the nearest detection will always occur at the near end of the BMS detecting zone.

4.3. Scenario Three-Multiple Detections and Multiple Records at a BMS. In scenario 3, see Table 2, the multiple detection problem has two forms: multiple records from a single trip and multiple records from multiple trips. The difficulty of choosing the most appropriate detection does not lie in which record should be chosen but in which detection should be chosen from the selected record, the first detection or the last detection, because under this scenario, the duration of the selected record can be up to several minutes or even longer (for example, the staying time on business premises). First, the last detection of the last record of a MAC address at the upstream BMS and the first record of this MAC address at the downstream BMS should be used. Then, if the duration of the downstream selected record is longer than a threshold, which indicates the staying time on premises, the first detection of the first record at downstream BMS should be used; if not, the last detection should be used. The threshold depends on factors such as the travelling speed and the traffic signal settings.

Factors that could increase the chance of a BT device being undetected in two consecutive inquiry procedures are the strength and speed of the transmitting device, the proximity of the BMS, vehicle moving behaviours (in and out of the detection zone), and the length of the total staying time. Those discoverable BT devices that have a weak transmitting strength signal and a low transmitting speed, and that are located at the peripheral of a detection

zone, are more likely to be undetected by a BMS. Multiple records caused by vehicle moving behaviours and long total staying time are more common cases in an arterial road context.

In this study, records belonging to scenario 3 were excluded from TT calculation because the implemented experimental test on a link gave zero matches. This could be the result of the narrow 15-min time interval, arbitrary time sets, and the relatively low proportion of back-and-forth vehicles. Considering the complexity in handling this scenario and the small benefit, only records belonging to the scenario one and two were considered.

4.4. The MAC-To-Volume Ratio of Bluetooth Data. BT penetration rate, the percentage of vehicles having discoverable BT devices, is difficult to determine because of the one-to-many relationship of a vehicle and its onboard BT devices [33]. However, the capture rate, the ratio of the unique MAC addresses to the traffic counts in a time set at a signalised intersection, can be easily calculated because traffic count data can be supplied by traditional inductive loop detectors such as SCATS. The following equation (3) was used to calculate the MtVR on a 15-minute interval for 24 hours of a day over 20 weekdays, from September 04 to 28, 2017

$$\text{MtVR}_i^j = \frac{N_{\text{BT}}^{ij}}{N_{\text{SCATS}}^{ij}}, \quad (3)$$

where N_{BT}^{ij} is the number of unique BT MAC addresses at site j in time set i and N_{SCATS}^{ij} is the SCATS traffic counts at site j in time set i .

4.5. Kalman Filter. Removing outliers is an essential step for obtaining accurate TT. Apart from the outliers from non-vehicular traffic modes, such as pedestrians and cyclists, vehicles stopping on a business premises or using alternative routes could also cause high TT estimates. In this study, the Kalman filtering algorithm proposed by Barceló et al. [7] was implemented in R because of its applicability, and a time window of 3 minutes was used because it gave the best results after trials. Figure 6 shows the filtering results of two selected links on different days. It is clear that the majority of large TT outliers (especially extreme large outliers) have been well identified. However, some generally large TT estimates are still suspicious because they are far from other TT estimates in the approximate time window; for example, the estimate with a value of 160 seconds occurred at 19:46:57 in Figure 6(a). At last, although very limited small estimates were identified as outliers, some small estimates may be missed from treating as outliers; for example, the estimate with a value of 89 seconds occurred at 11:48:54 in Figure 6(b).

4.6. Accuracy Indices. The travel time differences between BT and TomTom average TTs in 56 time sets of a typical weekday are time series data. The median absolute difference (MADiff, km/h) of the space-mean speeds of a link in 56 time sets was chosen to overall evaluate the accuracy of BT

TABLE 2: An example of multiple records of a MAC address at a BMS.

ID	FirstSeenAt	LogTime	SiteId	ProbelId	Duration	Adjacent_diff	Position	Trip	From/to
1	2017-09-05 08:30:05	2017-09-05 08:30:10	128	5467	0 Day 00:00:05	NA	Upstream	1	From
2	2017-09-05 08:30:45	2017-09-05 08:34:45	128	5467	0 Day 00:04:00	00:00:35	Upstream	1	From
3	2017-09-05 08:36:20	2017-09-05 08:36:26	128	5467	0 Day 00:00:06	00:01:35	Upstream	1	From
4	2017-09-05 08:37:29	2017-09-05 08:37:55	62	5467	0 Day 00:00:26	00:01:03	Downstream	1	To
5	2017-09-05 08:38:27	2017-09-05 08:42:43	62	5467	0 Day 00:04:16	00:00:32	Downstream	1	To
6	2017-09-05 08:43:43	2017-09-05 08:43:43	62	5467	0 Day 00:00:00	00:01:00	Downstream	2	To
7	2017-09-05 08:44:15	2017-09-05 08:44:26	62	5467	0 Day 00:00:11	00:00:32	Downstream	2	From
8	2017-09-05 08:45:24	2017-09-05 08:45:59	128	5467	0 Day 00:00:35	00:00:58	Upstream	2	To
9	2017-09-05 08:46:30	2017-09-05 08:47:59	128	5467	0 Day 00:01:29	00:00:31	Upstream	2	To

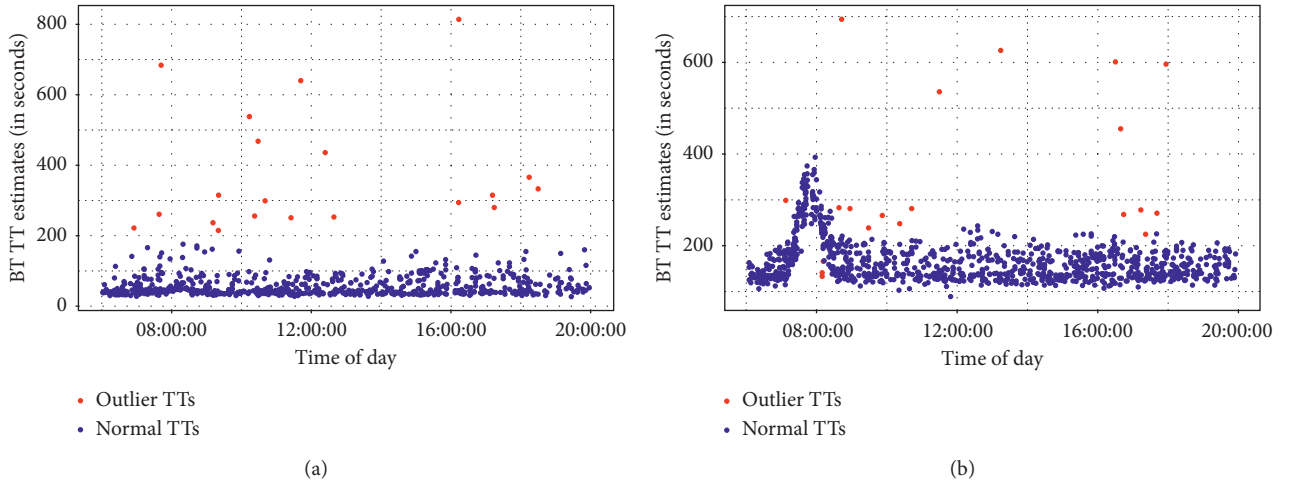


FIGURE 6: Two examples of running adopted Kalman filter. (a) Link 62-157 on Sep 04, 2017, and (b) Link 90-76 on Sep 12, 2017.

speeds through a typical weekday because the median is more robust to outliers in the data than the mean. The traffic condition varies from segment to segment and the range of average speed can be quite different among segments, causing the comparison of absolute speed difference among several segments to be meaningless. Therefore, the median absolute speed percentage difference (MAPDiff, %) of speeds was used for accuracy comparison among different links. MADiff and MAPDiff are defined as

$$\begin{aligned} \text{MADiff} &= \text{Median}\left(|V_{\text{BT}}(t) - V_{\text{Tom}}(t)|\right)_{t=[T_{\text{start}}, T_{\text{End}}]}, \\ \text{MAPDiff} &= \text{Median}\left(\frac{|V_{\text{BT}}(t) - V_{\text{Tom}}(t)|}{V_{\text{Tom}}(t)}\right)_{t=[T_{\text{start}}, T_{\text{End}}]}, \end{aligned} \quad (4)$$

where $V_{\text{BT}}(t)$ and $V_{\text{Tom}}(t)$ is the space (harmonic) mean speed from BT and TomTom, respectively, and T_{start} and T_{End} is the start time set (06:00–06:15) and end time set (19:45–20:00), respectively.

According to the Federal Highway Administration (FHWA)'s guidance, the maximum error (speed percentage error, or the MAPDiff in this study) of a reliable TT (speed) source should not exceed ± 20 percent, and ideally it should be ± 10 percent [3]. Therefore, 20 percent and 10 percent were used as the thresholds to classify route segments into

three groups in terms of travel speed accuracy, which are inaccurate ($\text{MAPDiff} > 20\%$), acceptable ($10\% \leq \text{MAPDiff} \leq 20\%$), and accurate ($\text{MAPDiff} < 10\%$) travel speed group, respectively.

In addition, to evaluate the spread of the travel speed differences of 56 time sets, median absolute deviation (MAD, km/h) and median absolute percentage deviation (MAPD, %) were selected as the robust measures:

$$\begin{aligned} \text{MAD} &= \text{Median}\left(\left\{|V_{\text{BT}}(t) - V_{\text{Tom}}(t)| - \text{MADiff}\right\}\right)_{t=[T_{\text{start}}, T_{\text{End}}]}, \\ \text{MAPD} &= \text{Median}\left(\left\{\left|\frac{|V_{\text{BT}}(t) - V_{\text{Tom}}(t)|}{V_{\text{Tom}}(t)} - \text{MAPDiff}\right|\right\}\right)_{t=[T_{\text{start}}, T_{\text{End}}]}. \end{aligned} \quad (5)$$

5. Results

5.1. Result of MAC-To-Volume Ratio. Investigating the MtVR pattern of 24 hours can provide insights about the applicability of using BT traffic system to monitor the traffic. The box-and-whisker plot of Figure 7 shows the distribution pattern of MtVR at Site 90 in a typical average weekday, and the same pattern occurred at the other 18 BT sites. First of all, the time period from 06:00 to 20:00 was the most reliable period in terms of the characteristics of the MtVR

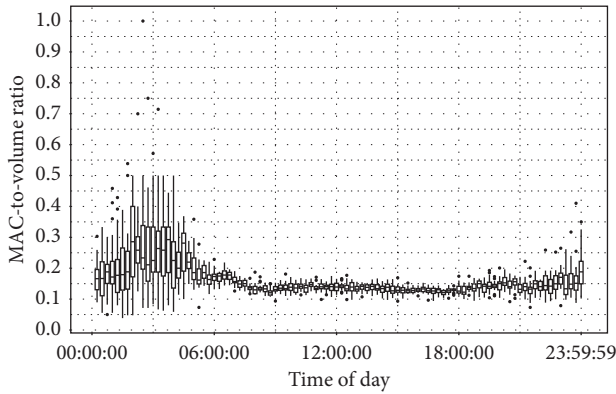


FIGURE 7: The box-plot of MAC-to-volume ratio of BMS 90.

distribution. During this period, the range, median, and outliers of the MtVR distribution were usually smaller than the counterparts of other time sets. In addition, a typical 4 phase can be identified from these 96 time sets; phase1, roughly from 23:00–06:00, when the traffic volume was quite low, the MtVR was subject to the penetration rate, stationary MAC addresses, traffic signal settings, and multiple BT devices of a vehicle; phase 2, from 06:00–08:00, although the traffic volume was significantly increasing, the MtVR decreased because the stationary MAC addresses’ impact was weakening and the proportion of discoverable BT devices that have not been captured was increasing; phase 3, from 08:00–18:00, the MtVR fluctuated in a narrow range, indicating the fluctuation of traffic volume and the reach of the capacity of a BMS; and phase 4, from 18:00–23:00, the traffic volume was decreasing, causing the MtVR decreases. Therefore, from 6 AM to 8 PM, the BT system is believed to be more applicable to supply reliable traffic information.

Significant differences between MtVRs of several adjacent BMSs can help to identify those BMSs that may have poor installation locations. Figure 8, a box-and-whisker plot, shows the distribution of MtVR values of selected 56 time sets of a day among 20 weekdays for all the 19 BMS sites. The median MtVR of 19 BT sites ranges from 4.8% to 16%, and the MtVR of half of the sites is more than 10%. Overall, through the investigation of the location of each site and the layout of the signalised intersection via satellite image, a MtVR of around 5% indicates a poor location of the installed BMS. Additionally, the BMS at Site 748 was installed near a main transfer bus station, and this was believed to be the reason of the high MtVR of BMS 748 because of the many BT devices carried by passengers.

5.2. MAPDiff–Median Absolute Percentage Difference (Percentage Travel Speed Error). Five different matching methods were implemented to derive BT TT estimates of each link from 6:00 am to 8:00 pm on a 15-minute time interval. Table 3 shows the median absolute percentage difference (percentage travel speed error) of BT and Tom-Tom space-mean speeds, and the records in the table are classified into four groups, in which the records are sorted by the length of segments. The eastbound and westbound

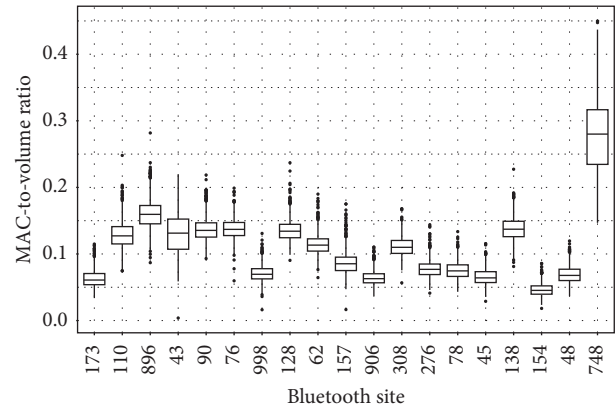


FIGURE 8: The box-plot of MAC-to-volume ratio of 19 BMSs along Canning Hwy.

Canning Hwy together has 36 different lengths of route segments, and 1 km was chosen to be the threshold of long and short route segments; Group 1 is long segment, and other three groups are short segments. In addition, *BT_counts* field gives the number of matched BT TT estimates of a link using the last-to-last method, and other methods’ corresponding counts are not provided because of minor difference among different methods and the size limit of the table; *S_counts* field gives the traffic counts of the downstream SCATS loop detectors (*Y_ID*) of a link, and *Ratio* field is the ratio of *BT_counts* and *S_counts*; the *Diff* field shows the difference between the MAPDiff of the best method and worst method.

Table 4 shows the ranking and scoring scheme to evaluate the overall performance of different matching methods across BT links. The smaller the value of the MAPDiff, the more accurate the BT travel speed is; therefore, in Table 4, for one BT link, the MAPDiffs of five different matching methods are ranked in an ascending order as 1st, 2nd, 3rd, 4th, and 5th, in which each rank gains a score of 2, 1, 0, -1, -2, respectively. The total score that a method gained in a group can be derived from the counts of different ranks it has and each rank’s unit score; for example, the best method for the Group 1 is A-A with the highest score of 15, which equals to $4 \times 2 + 5 \times 1 + 0 \times (-1) + 0 \times (-2)$.

For the 12 long route segments (length ≥ 1 km) of Group 1 in Table 3, it is noticeable that some of these long segments have quite a small sample size of TT estimates, such as link 173-110 (2 or 3 TT estimates per time set), 110-173 (5 to 8 estimates per time set), and link 78-45 (2 to 8 estimates per time set). According to the study of Lyons [34]; a general rule of thumb is three TT estimates every 15 minutes is an acceptable size of supplying TT information. Furthermore, the MAPDiff value ranges from 1.26% to 5.12%, indicating that the A-A matching method can provide accurate travel speed information for segments longer than 1 km. The *Diff* field varies from 3.56% to 12.96%, which means even for long segments, the matching method used can significantly influence the accuracy of the derived space-mean speed.

Overall, for the 24 short route segments (length < 1 km), the last-to-last method is superior to other methods (see

TABLE 3: The MAPDiff of all BT links of Canning Hwy.

Group	Direction	BT_Link (X-Y)	MAPDif (%)						Length (meter)	BT_counts	Y_ID	S_counts	Ratio (%)
			F-F	F-L	L-F	L-L	A-A	Diff					
Group 1	EB	43-90	2.50	8.10	11.80	4.20	1.80	10.05	2139	12,115	90	879,331	1.38
	WB	76-90	1.90	7.00	12.90	2.00	1.20	11.64	2139	23,799	90	879,331	2.71
	WB	90-43	2.10	7.10	15.10	3.60	2.60	12.96	2137	13,689	43	635,721	2.15
	EB	90-76	1.90	7.90	11.70	1.50	1.30	10.48	2134	24,222	76	889,385	2.72
	WB	110-173	5.80	9.10	9.70	6.10	3.00	6.65	1723	8,058	173	916,968	0.88
	EB	173-110	4.30	3.90	7.40	4.30	4.40	3.56	1719	3,942	110	493,099	0.80
	EB	276-78	2.80	2.30	9.10	4.50	2.80	6.83	1179	9,827	78	793,522	1.24
	WB	78-276	2.20	3.40	8.30	5.30	2.40	6.17	1177	15,335	276	874,136	1.75
	EB	110-896	2.80	8.30	10.10	3.90	2.50	7.64	1166	15,569	896	490,929	3.17
	WB	896-110	5.70	2.00	10.40	3.50	5.10	8.42	1165	16,327	110	493,099	3.31
	EB	78-45	2.80	4.00	8.40	4.10	3.40	5.54	1061	6,831	45	757,245	0.90
WB	45-78	3.60	5.30	15.90	5.10	3.70	12.31	1060	10,672	78	793,522	1.34	
Group 2	EB	998-128	82.20	21.50	125.60	37.50	56.10	104.06	426	29,051	128	978,601	2.97
	WB	48-154	40.20	43.20	32.70	36.30	38.80	10.47	291	6,198	154	830,555	0.75
	WB	308-906	56.10	57.10	21.80	24.80	45.50	35.30	146	24,237	906	1,216,273	1.99
Group 3	WB	748-48	21.50	24.80	18.90	22.60	21.80	5.90	841	5,632	48	954,676	0.59
	WB	276-308	31.60	12.20	46.40	21.40	24.90	34.25	479	22,528	308	1,258,637	1.79
	EB	154-48	30.90	42.90	4.80	23.10	27.90	38.13	291	12,421	48	954,676	1.30
	WB	43-896	28.40	37.30	43.30	14.20	14.80	29.11	227	21,474	896	490,929	4.37
	EB	906-308	20.80	40.50	16.70	24.60	24.10	23.76	133	25,511	308	1,258,637	2.03
Group 4	WB	154-138	6.40	12.40	21.00	3.10	4.90	17.96	958	3,169	138	769,156	0.41
	EB	138-154	25.60	28.40	7.40	12.10	20.30	21.00	958	5,479	154	830,555	0.66
	EB	48-748	2.80	11.50	11.60	3.20	3.60	8.85	845	13,619	748	464,461	2.93
	WB	138-45	17.50	24.50	2.50	10.50	14.60	22.00	688	12,952	45	757,245	1.71
	EB	45-138	21.10	5.60	35.40	3.50	10.20	31.98	687	8,809	138	769,156	1.15
	EB	76-998	24.80	29.80	2.50	6.40	18.70	27.29	608	25,834	998	916,127	2.82
	WB	998-76	36.20	3.00	50.60	7.90	18.40	47.58	607	17,594	76	889,385	1.98
	EB	62-157	34.60	36.20	8.90	12.20	25.80	27.26	497	15,671	157	790,301	1.98
	WB	157-62	3.20	15.40	4.10	13.30	8.10	12.23	495	11,037	62	1,053,829	1.05
	EB	308-276	11.20	21.70	9.00	5.90	11.00	15.78	477	15,928	276	874,136	1.82
	WB	128-998	11.50	17.10	18.70	7.20	5.10	13.62	427	19,325	998	916,127	2.11
	EB	157-906	16.80	25.00	12.00	6.30	12.60	18.69	421	6,100	906	1,216,273	0.50
	WB	906-157	27.10	6.70	45.70	11.40	12.40	38.96	420	12,755	157	790,301	1.61
	WB	62-128	8.20	15.70	30.20	3.50	4.80	26.70	392	31,471	128	978,601	3.22
	EB	128-62	10.00	29.50	35.50	5.20	9.60	30.29	390	41,019	62	1,053,829	3.89
EB	896-43	24.70	13.50	60.30	6.50	11.80	53.75	224	18,120	43	635,721	2.85	

Table 4). In the Group 2 of Table 3, the smallest MAPDiffs of these three links are all greater than 20 percent, and their length are all shorter than 500 meters, whereas the first-to-last (F-L) method shows the best result, all five matching methods failed to provide acceptable travel speed data; for link 48-154, the average sample size of a time set is only 5.5 TT estimates.

In the Group 3 of Table 3, apart from link 43-896, only the smallest MAPDiffs of each link fall into the range of 20 percent and 10 percent, indicating that only when using the best matching method, the BT time-stamped MAC address information could provide acceptable level of TT or speed information for links in this group. Noticeably, while the length of link 748-48 is more than 800 meters, its sample size is quite small; on average, a time set has only five estimates.

In Table 3, overall, the last-to-last method is the best for Group 4. Using the best matching method for each link of Group 4, BT time-stamped MAC address data can provide accurate TT (speed) information. From the Diff field of this group, the difference between the biggest and smallest

MAPDiff ranges from 8.85% to 53.75%, indicating the importance of selecting appropriate matching method. Furthermore, nine segments of this group have a length shorter than 500 meters. Even links that having a small sample size still could provide accurate travel speed information under using an appropriate matching method, such as link 154-128, 138-154, and 157-906.

5.3. *MADiff, MAD, and MAPD*. Table 5 summarises the result of MADiff, MAD, and MAPD. For MADiff among different matching methods, it ranges from 1 km/h up to 25 km/h. However, the comparisons of MADiffs of speeds between links are meaningless because the length and the free-flow speed of links are different. The range of MAD of all matching methods is quite narrow, from 0.28 km/h to 4.34 km/h. And, although most MAPDs of all methods are also small, ranging from 1% to 9%, only 10% of MAPDs have a value higher than 5%. The most significant characteristics of this table include that the spread of speed difference is

TABLE 4: Ranking and scoring to evaluate the performance of different matching methods.

Group	Matching method	Rank/rank score					Total scores
		1st 2	2nd 1	3rd 0	4th -1	5th -2	
Group 1	A-A	5	5	2	0	0	15
	F-F	4	5	2	1	0	12
	L-L	0	4	6	2	0	2
	F-L	3	0	2	7	0	-1
	L-F	0	0	0	0	12	-24
	L-L	0	3	0	0	0	3
Group 2	L-F	2	0	0	0	1	2
	A-A	0	0	3	0	0	0
	F-L	1	0	0	0	2	-2
Counts	F-F	0	0	0	3	0	-3
	L-L	1	2	0	2	0	2
	L-F	3	0	0	0	2	2
	A-A	0	1	4	0	0	1
	F-F	0	2	1	2	0	0
Group 3	F-L	1	0	0	1	3	-5
	L-L	7	8	0	1	0	21
	A-A	1	4	11	0	0	6
	F-F	2	0	4	10	0	-6
	L-F	4	3	0	0	9	-7
	F-L	2	1	1	5	7	-14

quite small, and the speed difference is consistent, throughout different time sets, no matter which method is used, indicating the travel speed difference is a systematic error. This characteristic is more evident and visualised by using the line chart, in which the BT travel speeds and the TomTom travel speed are presented as individual lines, see the line graphs in section 5.4.

From a pragmatic point of view, the implication of that the travel speed difference is consistent or a systematic error is that the BT speed can be easily calibrated by using other travel speed sources, adding a certain speed value the BT speed of a problematic BT link can be accurate. For example, for the problematic average BT speed derived from A-A matching method of link 48-154, a positive speed value of 13.18 can be added on it, which is its MADiff in Table 5, to derive the calibrated BT speed, the dashed blue line in Figure 9. It is clear that the calibrated BT speed matches well with the TomTom speed (the solid pink line) in most of the time sets.

The main motivation of proposing this pragmatic method is that other methods that aim to identify and tackle all the error sources, like optimising BMS installation location, the antenna, and its settings, are much more resource intensive, which undermines the advantages of BT traffic system, for example, BMSs are cheap and easy to deploy. However, for critical road links, the resource-intensive method is still recommended as the benefits out from the costs can be worthy.

5.4. Problematic Road Links with High MAPDiff. Selecting an appropriate matching method and the adopted Kalman filtering algorithm could not eliminate the impact of noise on the derived BT average speed or the accuracy of TTs. Therefore, the analysis of problematic arterial road

segments' inaccurate space-mean travel speeds was mainly focused on the following aspects: noise of estimates, and whether the collected estimates could represent the whole traffic flow or not.

In Figure 10, for link 998-128, the BT average speed of five matching methods was all faster than the TomTom average speed, whereas lines represent BT and TomTom average speeds, whose values can be read from the left axis; white vertical bars represent the average sample size of L-L method in different time sets and their values can be read from the right axis. Because the finding of small TT estimates (<5 s or even 0 s), these small estimates were believed to be the causes of average speed errors of link 998-128, whose normal TT estimates should be around 25.56 seconds (the length is 426 m, and the speed limit is 60 km/h). The impact of these small TT estimates can be great when the sample size was relatively small, such as the time period of 06:00–07:15 AM and 19:00–20:00 PM, which had significant larger speed differences than other time periods, see Figure 10. To counteract the impact of these underestimated TT estimates (noise that might be caused of the overlapping of detection zones), longer total staying time should be captured, and the F-L method gave the best result.

For link 43-896 (westbound) and 896-43 (eastbound), the accuracy of average speeds were believed to be significantly affected by the traffic signal at site 43, the overlapping of detection zones, and the estimates from nonvehicular mode. First, differences in speed differences between five matching methods and the TomTom indicated that the traffic signal at site 43 have a larger impact on TT estimates (see Figures 11 and 12), causing more waiting time before a red light, which in line with the fact that the traffic signal at site 896 is for pedestrians cross the Canning Hwy. Furthermore, although the finding of zero-second TT estimates from link 896-43 implied the overlapping of two detection

TABLE 5: The MADiff, MAD, and MAPD of all BT links of Canning Hwy.

Group	Link	MADiff (km/h)					MAD (km/h)					MAPD (%)				
		F-F	F-L	L-F	L-L	A-A	F-F	F-L	L-F	L-L	A-A	F-F	F-L	L-F	L-L	A-A
Group 1	43-90	1.12	3.99	5.86	2.02	0.84	0.75	1.08	0.64	0.88	0.46	2.00	2.00	2.00	2.00	1.00
	76-90	0.97	6.39	3.52	0.98	0.61	0.55	0.59	0.61	0.37	0.39	1.00	1.00	1.00	1.00	1.00
	90-43	0.96	6.90	3.30	1.69	1.25	0.52	0.75	0.81	0.85	0.75	1.00	2.00	2.00	2.00	2.00
	90-76	0.94	3.94	5.67	0.73	0.63	0.44	0.61	0.48	0.34	0.28	1.00	1.00	1.00	1.00	1.00
	110-173	2.13	3.20	3.08	2.11	1.00	1.30	1.12	1.04	1.08	0.64	4.00	4.00	2.00	3.00	2.00
	173-110	1.71	1.48	2.92	1.72	1.72	1.03	1.09	1.58	0.90	0.88	2.00	3.00	4.00	3.00	2.00
	276-78	1.10	1.00	3.69	1.78	1.15	0.57	0.59	0.87	0.86	0.53	1.00	1.00	2.00	2.00	1.00
	78-276	0.83	3.04	1.29	1.84	0.89	0.52	0.63	0.68	0.64	0.51	1.00	2.00	2.00	2.00	1.00
	110-896	1.32	3.88	4.81	1.85	1.19	0.89	1.37	1.17	0.87	0.67	2.00	3.00	3.00	2.00	1.00
	896-110	2.83	4.98	0.94	1.68	2.43	1.11	1.00	0.58	0.93	1.10	2.00	2.00	1.00	2.00	2.00
	78-45	1.16	1.68	3.49	1.71	1.40	0.74	0.97	1.20	0.84	0.68	2.00	2.00	3.00	2.00	2.00
45-78	1.31	6.07	2.03	1.94	1.41	0.66	0.93	0.98	0.90	0.76	2.00	3.00	2.00	3.00	2.00	
Group 2	998-128	25.05	6.27	37.92	11.67	16.64	3.65	1.55	4.34	1.40	2.05	8.00	4.00	9.00	4.00	6.00
	48-154	14.21	11.10	15.22	12.23	13.18	1.32	1.68	1.19	1.54	1.57	3.00	5.00	3.00	4.00	3.00
	308-906	20.03	7.95	20.49	8.83	16.60	2.27	2.53	1.90	2.42	1.92	5.00	6.00	4.00	6.00	5.00
Group 3	748-48	8.87	7.49	10.18	8.95	8.85	1.34	1.28	1.52	1.45	1.26	3.00	3.00	3.00	2.00	2.00
	276-308	7.78	11.04	2.91	5.02	6.13	1.39	1.96	0.76	1.17	1.22	3.00	7.00	3.00	4.00	3.00
	154-48	9.52	13.06	1.36	6.94	8.46	2.32	2.28	0.92	1.71	1.91	5.00	3.00	4.00	4.00	4.00
	43-896	10.68	16.58	14.15	5.26	5.56	2.09	1.72	1.76	2.25	1.54	4.00	5.00	4.00	6.00	4.00
	906-308	3.18	6.15	2.58	3.88	3.69	0.48	0.91	0.62	0.66	0.62	2.00	3.00	4.00	3.00	3.00
Group 4	154-138	2.60	8.56	4.90	1.26	1.87	1.67	2.52	2.20	0.92	1.44	4.00	8.00	5.00	2.00	4.00
	138-154	10.45	11.74	3.12	5.10	7.81	1.51	1.60	1.54	1.54	1.32	2.00	2.00	3.00	3.00	2.00
	48-748	1.42	5.85	5.83	1.64	1.86	1.09	1.54	1.03	1.15	1.27	2.00	3.00	2.00	2.00	3.00
	138-45	6.05	0.84	8.39	3.57	4.81	1.01	0.50	1.04	0.92	0.70	2.00	1.00	2.00	2.00	1.00
	45-138	8.74	2.14	14.80	1.44	4.22	2.65	1.37	1.73	0.79	1.25	7.00	3.00	6.00	2.00	4.00
	76-998	9.75	11.78	0.90	2.48	7.22	1.20	1.22	0.52	0.98	0.83	3.00	3.00	1.00	2.00	2.00
	998-76	13.86	18.57	1.08	3.19	6.91	1.49	1.44	0.63	0.86	1.00	3.00	4.00	1.00	3.00	3.00
	62-157	12.87	13.64	3.10	4.46	9.49	1.63	1.80	1.05	1.06	1.62	3.00	3.00	3.00	3.00	2.00
	157-62	0.98	1.22	4.91	4.25	2.74	0.70	0.68	1.13	1.24	1.10	2.00	2.00	3.00	4.00	3.00
	308-276	4.34	8.41	3.06	2.11	4.38	1.85	1.69	0.88	1.40	1.22	4.00	4.00	3.00	4.00	3.00
	128-998	5.20	8.33	7.66	3.33	2.25	1.03	1.16	0.79	1.17	0.88	3.00	3.00	2.00	3.00	2.00
	157-906	4.87	7.03	3.34	1.80	3.41	1.99	1.85	1.29	0.73	1.64	5.00	5.00	5.00	2.00	5.00
	906-157	10.66	17.81	2.55	4.30	4.76	2.19	3.51	1.50	2.28	1.95	6.00	7.00	3.00	6.00	4.00
	62-128	3.09	11.89	6.01	1.23	1.95	1.53	1.91	1.63	0.74	0.75	5.00	8.00	3.00	2.00	2.00
128-62	3.20	9.35	11.40	1.72	3.11	1.19	0.69	1.13	1.01	0.76	3.00	3.00	4.00	3.00	3.00	
896-43	5.57	2.97	13.37	1.50	2.60	1.55	0.86	1.90	0.81	0.82	7.00	3.00	10.00	4.00	5.00	

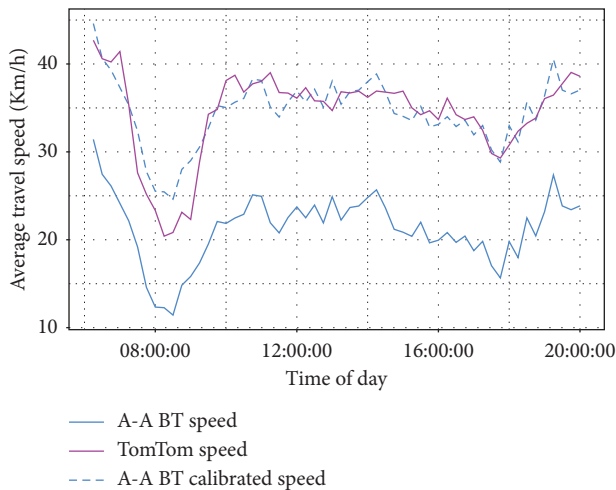


FIGURE 9: An example of calibrating the average BT speed. A-A BT speed represents the average speed deriving by A-A matching method.

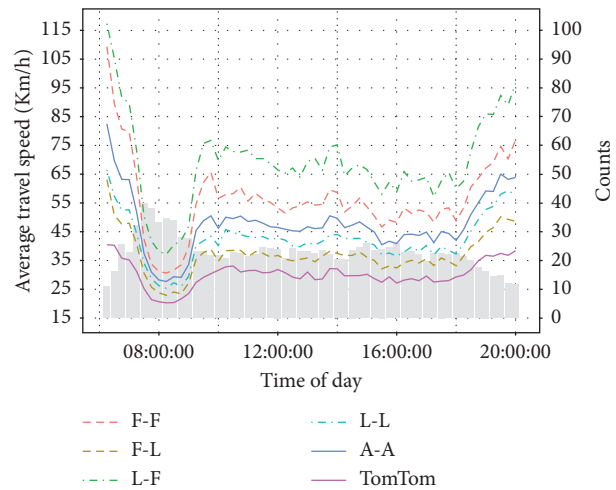


FIGURE 10: The comparison of five BT average speeds and TomTom average speed of link 998-128.

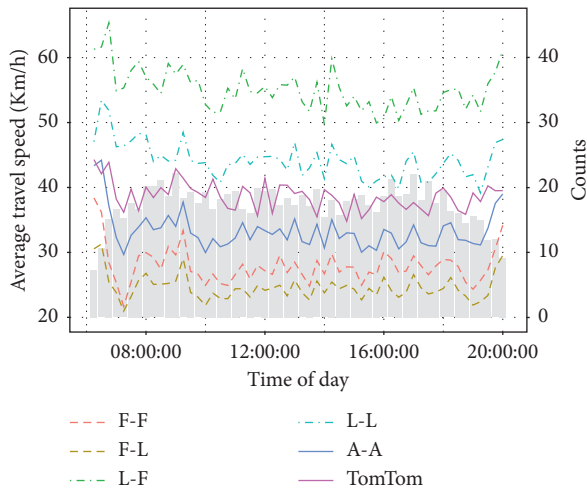


FIGURE 11: The comparison of five BT average speeds and TomTom average speed of link 43-896.

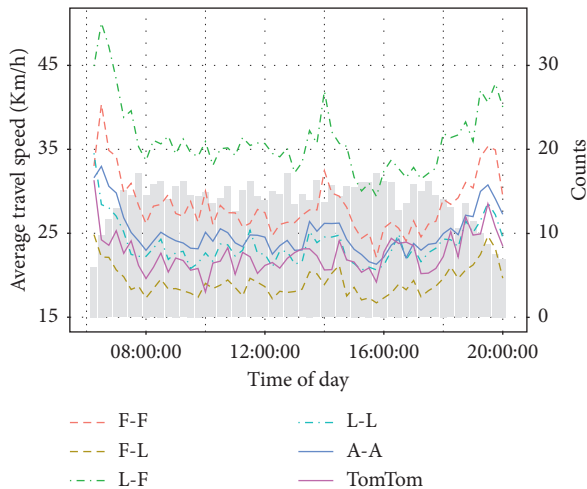


FIGURE 12: The comparison of five BT average speeds and TomTom average speed of link 896-43.

zones on eastbound of Canning Hwy, the short length of these two links, and surrounding shopping centres and other business premises indicated that some large estimates were inevitably from nonvehicular modes, such as pedestrians and cyclists. For link 896-43, except F-L method, speeds of all other four methods were faster than TomTom speeds, see Figure 12, which implied that the overlapping of detection zones was the dominant noise source because the adopted Kalman filter could not eliminate small TT estimates (include zero second). The situation for the westbound (43-896) was slightly different, whereas estimates around several seconds were found, there were no zero-second TT estimates, which indicated the impact of small estimates was less severe than link 896-43; L-L method gave the best result, see Figure 11, which could be the reason that the staying time captured by the L-L method at the detection zone of site 896 was the most appropriate amount to counteract the impact of small and large estimates, which were from nonvehicular modes.

For link 154-48 (EB) and link 48-154 (WB), the existence of alternative routes and the poor location of BMS 154 were believed to be the reasons causing high MADiff; the number of BT records at BMS 48 was nearly twice of the number at BMS 154. Specifically, BMS 154 was located far from the centre of the intersection and adjacent buildings hinder the spread of the signal. Therefore, vehicles on Way Rd were more likely to be captured by the BMS, compared with vehicles on Canning Hwy. Furthermore, vehicles on Canning Hwy eastbound were more likely to be detected compared with vehicles on the westbound, which can be supported by the evidence that the BT counts of eastbound was twice of westbound. However, a proportion of estimates might come from the alternative routes (for example, the orange section S_{BGHIJ} in Figure 13) instead of Canning Hwy (the blue section S_{BE}); if this proportion exceeds a threshold, the average speed will represent the speed of the alternative route. Therefore, for link 48-154, all methods generated a much slower average travel speed, see Figure 14. For link 154-48, although other methods produced a much slower average travel speed, the last-to-first method generated the most accurate average travel speed, see Figure 15. This could be the counteract effect of TT estimates from Canning Hwy (travelling distance shorter than the S_{BE}), and TT estimates from alternative route (travelling distance longer than the blue line, for example, S_{BGHIJ}), or simply the proportion of estimates from the alternative route was too small to affect the average speed of Canning Hwy.

For link 748-48 (westbound), the inaccurate or slow average travel speed of link 748-48 was because the sample size was small, and all the estimates (2 or 3 observations of a time set) were from slow travelling vehicles. Because of the height difference between the overpass (connecting Canning Hwy and Great Eastern Hwy) and the BMS 748, only slowly moving vehicles on the overpass were likely to be captured by the BMS. Therefore, for this link, no matter which matching method was used, they all generated a much slower average speed compared with the TomTom average speed (see Figure 16).

Link 906-308 and 308-906 are the two directions of the Canning Bridge, and two noise sources were identified. The existence of multiple traffic mode facilities, such as a bus station, a train station, and bicycle shelters, indicates the possibility that some estimates were from nonvehicular mode. Zero-second estimates were found from the sample of link 906-308, which indicated the overlapping of two adjacent BMSs' detecting zone. Apart from these noise sources, the derived average speed of different matching methods can be significantly affected by the quite long traffic signal cycle at these two signalised intersections, where the traffic flow on Canning Hwy drive in and out of the most heavily used road—Kwinana Freeway; this was reflected from the evidence that the last-to-first method gave the smallest speed difference and was the only one speed that faster than TomTom average speed (see Figure 17) because this method cannot capture the total staying time in upstream and downstream detection zone. For the link 308-906, no zero-second TT estimates have been found in TT estimates, and the results of

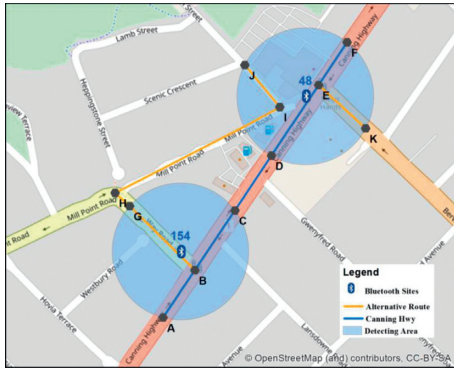


FIGURE 13: An alternative route of link 48-154 and 154-48.

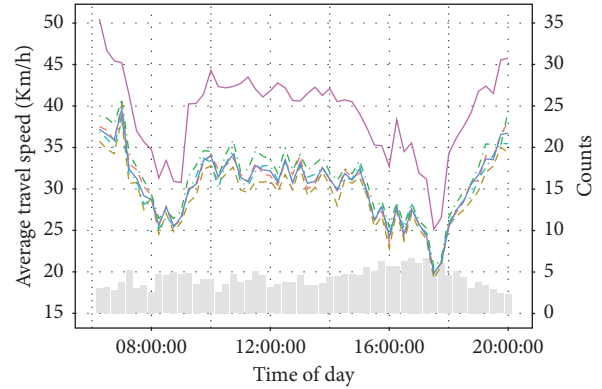


FIGURE 16: The comparison of five BT average speeds and TomTom average speed of link 748-48.

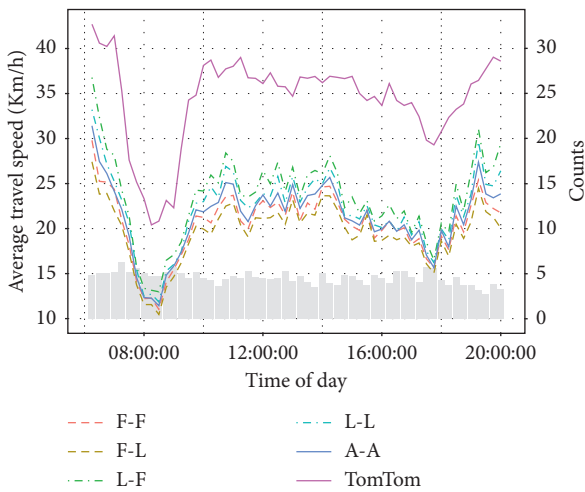


FIGURE 14: The comparison of five BT average speeds and TomTom average speed of link 48-154.

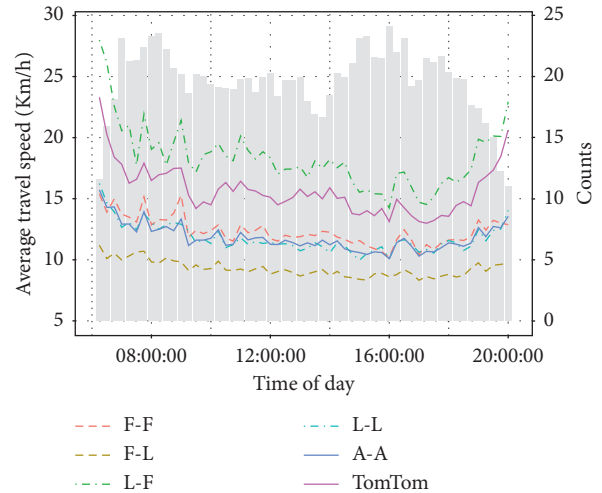


FIGURE 17: The comparison of five BT average speeds and TomTom average speed of link 906-308.

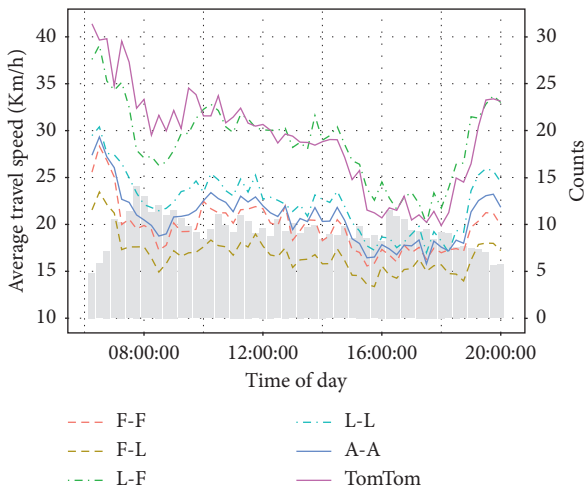


FIGURE 15: The comparison of five BT average speeds and TomTom average speed of link 154-48.

all methods gave a much slower average speed, compared with TomTom average speed, which could be caused by the large estimates from nonvehicular traffic modes.

6. Discussion and Conclusions

To evaluate the accuracy of BT travel time measures, this study investigated the following factors: the multiple detection problem and TT estimate noise. Through the development and implementation of the methods in a case study, the following three issues were identified.

6.1. Classification of Noise Sources of the BT TT Estimates. Based on the classification of Bhaskar and Chung [12], new four sources of BT TT estimate noise have been proposed,

and they are nonvehicular mode, no information out of the detection zone, missed observation, and the overlapping of upstream and downstream detecting zone. The multiple match source in the previous classification was replaced by the noise source of overlapping of upstream and downstream detecting zone because the multiple matches source can be handled by selecting an appropriate matching method.

Considering the overlapping of two BMSs' detecting zones as a noise source is necessary, especially for short arterial road links. If the detection zones of two BMSs are overlapped, the TT estimate from a discoverable BT device can be quite small or even to be zero second, such as link 998-128, 896-43, 43-896, and 906-308 illustrated in Section 5.4. This noise source can be the result of many factors, such as the size and shape of the detection zone and the BT inquiry procedure. Potential solutions to this noise source can be to optimise the configuration settings of an antenna or use a directional antenna instead of using an omnidirectional antenna. Additionally, Quayle et al. [17] suggested that instead of dealing with the problem from a hardware perspective, adding different weights to the data may be a good way to improve TT estimates.

Other three noise sources have also been found to cause errors of derived average travel time or speed. Two error sources, no information out of the detection zone and nonvehicular mode, are more likely to occur on arterial roads and caused by the factor group of arterial road-specific factors. The result shows that alternative routes and intermediate stops are the two examples of no information out of the detection zone factor, and they could cause overestimated TT estimates. Nonvehicular mode could also lead to overestimated TT estimates when BT facilities of other traffic modes present in and between detection zones. Apart from arterial roads, these two noise sources may occur on some sections of freeways, such as a frontage road, or a path for pedestrians and cyclists, or a service area. However, most of these noise can be easily handled by filtering algorithm due to high speed limits of freeways. Compared with these two noise sources, the missed observation could cause errors in estimating TT on both arterial roads and freeways; for example, a BT device with a slow transmitting speed but in a vehicle travelling in a high speed may not be detected.

It should be clarified that when the majority of TT estimates from a subset of vehicles that could not represent the whole traffic, these TT estimates cannot be considered as noise and cannot be identified by the filtering algorithm either. The derived average TT or speed information based on these TT estimates only reflect these vehicles' movement characteristics and cannot represent the real traffic performance. Typical example is a BMS that installed far from the road or at different height (Site 748) is more likely to capture those slowly moving vehicles on the closest lane, leading to an overestimated average speed measure.

6.2. Limitations of Filtering Algorithms. To handle the noise in BT TT estimates, various outlier filtering algorithms have been developed in the literature [3, 7, 9, 15]. However, these

algorithms could not identify and remove all kinds of noises. The adopted Kalman filtering algorithm cannot effectively identify those small estimates (including zero-second estimates) because the differences between these TT estimates and normal TT estimates usually are not large enough to trigger the algorithm. Meanwhile, the noise of large TT estimates can only be partially handled by the adopted filtering algorithm. Therefore, the noise of small TT estimates could counteract with the noise of remaining large TT estimates. However, the counteraction degree is hard to be determined. Because of the limitations of adopted filtering algorithm, comparing the performance of existing filtering algorithms, and developing a better filtering method are worthy research areas for future study.

6.3. Adapting Matching Methods to Travel Time Estimates.

Various noise exists in BT TT estimates. It varies from segment to segment because of different sample sizes, segment lengths, and traffic environments. However, an appropriate matching methods may be used to improve the accuracy of the average TT via smoothing out the remaining noise in filtered estimates. According to the result, long arterial road segments were believed to have a low level of TT estimate noise, and A-A method was the most appropriate matching method. For these long segments (Length ≥ 1 km, Speed limit = 60 km/h), apart from the noise source of no information out of zone, other three noise sources can produce very limited noise. Firstly, it is unlikely there was a large number of nonvehicular trips that can be finished on these long segments in this 15-minute window because the speed of pedestrians and cyclists is about 4–15 km/h, which takes them 4–15 minutes to travel through, and also the proportion of nonvehicular modes was low; however, these nonvehicular modes can take up a quite large proportion of the total traffic on some segments in some highly populated cities. Secondly, the overlapping of BMSs' detection zones was also unlikely to occur on these long segments because the typical detecting zone of Type 1 class BMS is 100m. At last, the missed observation noise source was also believed to have limited impact because of the low proportion of back-and-forth vehicles. Different from Saeedi et al. [11] result, $L-L > A-A > F-F$, the result of long arterial segments showed the performance of the following three methods was $A-A > F-F > L-L$ method. The cause of this difference was unknown; however, their sample data were collected from controlled field experiment without the aforementioned concerns, such as the estimate noise, the staying time on business premises, and nonthrough vehicles. Additionally, one kilometre may be recommended as the shortest length of a BT road segment for deriving accurate travel time information, instead of the one-mile length recommended in the previous study [15].

The BT estimate noise level of short arterial segments was high and varied significantly from segment to segment. Choosing an appropriate matching method could cause the accuracy of average TT or speed of a segment changing from unacceptable to accurate level because an appropriate amount of staying time can smooth out the impact of

remaining TT estimate noise. Overall, the L-L method was the best method for all short arterial segments.

Furthermore, from pragmatism perspective, the derived average TT or speed measures of problematic segments, such as those in Groups 2 and 3, can be calibrated by adding a certain value to improve its accuracy, which is a cost-effective and practical method. In addition, optimising BMSs' location and antenna configuration could improve the TT estimate accuracy, and a relatively low MtVR index could indicate problematic BMSs having poor installation location and antenna configuration settings.

Because the accuracy of BT average TT measure is determined by TT estimate noise, the adopted filtering algorithm, the matching method, and whether the collected sample estimates can represent the whole population, we conclude that the accurate space-mean BT travel speed of a signalised arterial route segment can be derived from BT time-stamped MAC address data of typical through vehicles that can represent the whole traffic flow, in which the TT estimates should be calculated by using an appropriate matching method to smooth out the remaining noise in the filtered estimates.

The output of this study may help road operators and researchers to have a better understanding of the characteristics of BT average TT and TT estimates along different signalised arterial road segments. Most importantly, although the previous literature showed that BT average TTs or speeds of short arterial segments were usually inaccurate [3, 11, 17, 22, 33], this study shows that accurate TT information on the majority of short arterial segments could still be derived from BT time-stamped MAC address data by using an appropriate matching method, and other short segments having inaccurate speeds or TTs can be improved by adding a calibration value because the error is found to be systematic.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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