2016

Investigation of the Use of Bluetooth Sensors for Travel Time Studies under Indian Conditions

Jijo K. Mathew
Purdue University

V. Lelitha Devi
Indian Institute of Technology Madras

Darcy M. Bullock
Purdue University

See next page for additional authors

Investigation of the Use of Bluetooth Sensors for Travel Time Studies under Indian Conditions

Abstract

Travel time and its reliability are becoming increasingly important for a variety of real time applications such as Advanced Traveller Information Systems (ATIS), Route Guidance Systems (RGS) etc. which are a part of the Intelligent Transport Systems (ITS). They assist the road users in making timely decisions regarding their trip such as departure time, mode choice, route choice etc. There are various sensors which capture and monitor the travel time across a study corridor. However, their performance under Indian conditions is a major concern due to the vast heterogeneity in vehicle classes and the lack of lane discipline. Data from the GPS units equipped in the public transport buses are the current source of reliable travel time information. But these buses account for only 1% of the total traffic and have an inherent modal bias. One such technology which can capture data from across the vehicle classes and from any roadway of interest is the Bluetooth sensor. This study reports on the use of a Bluetooth based sensor to capture the travel time data and evaluate the reliability along two alternate routes in Chennai, India. Results from the cumulative frequency diagrams (CFD's) which are used to evaluate the reliability are also compared against the various reliability index measures.

Keywords

Travel Time, Reliability, Bluetooth, Raspberry Pi

Disciplines

Civil and Environmental Engineering | Transportation Engineering

Comments

This article is published as Mathew, Jijo K., V. Lelitha Devi, Darcy M. Bullock, and Anuj Sharma. "Investigation of the Use of Bluetooth Sensors for Travel Time Studies under Indian Conditions." Transportation Research Procedia 17 (2016): 213-222. 10.1016/j.trpro.2016.11.077. Posted with permission.

Authors

Jijo K. Mathew, V. Lelitha Devi, Darcy M. Bullock, and Anuj Sharma

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 17 (2016) 213 – 222

Transportation Research Procedia

www.elsevier.com/locate/procedia

11th Transportation Planning and Implementation Methodologies for Developing Countries, TPMDC 2014, 10-12 December 2014, Mumbai, India

Investigation of the Use of Bluetooth Sensors for travel Time Studies under Indian Conditions

Jijo K. Mathew[a], Lelitha Devi V.[b]*, Darcy M. Bullock[c] and Anuj Sharma[d]

[a]*Graduate Student, Purdue University, West Lafayette,IN-47907, USA*
[b]*Associate Professor, Indian Institue of Technology madras, Chennai-600036, India*
[c]*Professor, Purdue University, West Lafayette, IN-47907, USA*
[d]*Associate Professor, Iowa State University, Ames, IA-50010, USA*

Abstract

Travel time and its reliability are becoming increasingly important for a variety of real time applications such as Advanced Traveller Information Systems (ATIS), Route Guidance Systems (RGS) etc. which are a part of the Intelligent Transport Systems (ITS). They assist the road users in making timely decisions regarding their trip such as departure time, mode choice, route choice etc. There are various sensors which capture and monitor the travel time across a study corridor. However, their performance under Indian conditions is a major concern due to the vast heterogeneity in vehicle classes and the lack of lane discipline. Data from the GPS units equipped in the public transport buses are the current source of reliable travel time information. But these buses account for only 1% of the total traffic and have an inherent modal bias. One such technology which can capture data from across the vehicle classes and from any roadway of interest is the Bluetooth sensor. This study reports on the use of a Bluetooth based sensor to capture the travel time data and evaluate the reliability along two alternate routes in Chennai, India. Results from the cumulative frequency diagrams (CFD's) which are used to evaluate the reliability are also compared against the various reliability index measures.

Peer-review under responsibility of the Department of Civil Engineering, Indian Institute of Technology Bombay

Keywords: Travel time; Reliability; Bluetooth; Raspberry Pi

* Lelitha Devi V., Associate Professor, Indian Institute of Technology Madras Tel.: +91-944-437-6898; fax: 044-2257-4252.
E-mail address: lelitha@iitm.ac.in

Peer-review under responsibility of the Department of Civil Engineering, Indian Institute of Technology Bombay
doi:10.1016/j.trpro.2016.11.077

1. Introduction

With the advent of Intelligent Transportation Systems (ITS) deployments, there has been a rapid shift in the methods of assessing and reporting traffic characteristics. Travel time, average speed, average headway and delays are important performance measures for monitoring the transportation system. Travel time is one of the most popular indicators of the corridor performance as this can be easily understood by general public.

There are various sensors which capture and monitor the travel time across a study corridor, such as automatic license plate readers (ALPR), electronic tag identifiers, probe vehicles and other image processing sensors. However, under the Indian traffic conditions, where there is a lack of lane discipline and vast heterogeneity among the vehicle classes, the performance of majority of these sensors becomes a concern. Currently, GPS units deployed in the public transport buses are the only sources of reliable travel time information under Indian scenario. However, the buses account for only 1% of the total traffic, have an inherent modal bias, and travel along only selected routes. Hence, there is a need for a sensor which is capable of collecting data across all vehicle modes and roads of interest. One such sensor is the Bluetooth sensor.

The Bluetooth wireless protocol has been extensively used by the consumer electronics industry in many portable devices such as smartphones, laptops and headsets. A substantial amount of these devices are Bluetooth enabled with a unique Media Access Control (MAC) address, allowing them to be detected by a Bluetooth sensor as they pass along the corridor. A MAC addresses matching algorithms can be developed to estimate the travel time and origin – destination matrices from the obtained MAC addresses. This Bluetooth based travel time estimation is gaining popularity due to its low cost, possibility of anonymity of the detections and flexibility in both installing and maintaining the sensors.

The MAC addresses are 48-bit electronic identifiers for each device in the form of “12:34:56:78:90:ab”. The first three octets “12:34:56” represent the Organizationally Unique Identifier (OUI) which gives information on the manufacturer and the last three “78:90:ab” are assigned by the manufacturer in order to give a unique address to the device. Bluetooth radios are classified into three groups based on their communication range: Class 3 has a range of up to 1 metre, Class 2 up to 10 metres, and Class 1 up to 100 metres. However, only a minimum range is mandated by the Bluetooth specification and manufacturers can tune their devices for the required ranges. The Bluetooth transceivers transmit their MAC addresses for the purpose of identifying other devices. This inquiry mode is used to establish a link with responding devices. Inquiries can be made to a device even when it is engaged in communication to another device. When a device communicates with another, it responds to the inquiry scan with its MAC address and clock information. This facilitates the identification of Bluetooth enabled devices in vehicles, provided the discovery of the device is enabled. If the same address is detected at two different locations, the time difference between the two detections can give the time taken to travel that stretch. Also, the journey speed can be computed, given the distance between the two sites is known. Aggregating results from multiple devices can be used to estimate the average travel time and space mean speed along the corridor.

This paper reports on the development of a Raspberry Pi based Bluetooth sensor to capture the MAC addresses and estimate the travel time along two alternate routes in Chennai, India. Apart from the type of devices detected, the study also determines the penetration and match rates along the corridor. The cumulative frequency diagrams (CFDs) are used to assess the travel time reliability on the study corridor. This data is also used to generate the commonly used performance measures such as mean, standard deviation and travel time index. These measures were used to compare the different sections. In short, the study examines the ability of Bluetooth sensor to capture travel time and monitor the traffic conditions along the study stretch.

2. Literature review

Traditional travel time collection techniques include direct measurement techniques and indirect techniques. Direct measurement includes automatic license plate readers (ALPR) (Kennedy et al. 2004), automatic vehicle location (AVL) (Hunter et al. 2006), floating car techniques (Robertson 1994) and data from global positioning system (GPS) (Quiroga and Bullock, 1998) etc. Indirect estimation of travel time is achieved through various models which vary from the application of simple to complex algorithms for the estimation of stream travel time from other known parameters. All the aforementioned sensors have inherent disadvantages such as high capital, operating and maintenance costs, privacy issues, can work only with homogeneous traffic, less sample size and inability to provide travel times in real time. These limitations lead to the search for innovative sensors for travel time and one such technology, which can address the above problems, which is highly non-invasive and cost-effective, is the Bluetooth sensor.

Bluetooth technology was shown to be a possible part of in-car communication and navigation system from 2000 (Nusser and Pelz, 2000). Murphy et al. (2002) verified and confirmed that Bluetooth enabled devices can be discovered in moving vehicles. In 2007, researchers from University of Maryland developed a portable Bluetooth monitoring unit which consisted of various sensors and a processing unit (Young, 2008). Tarnoff et al. (2009) showed that Bluetooth based travel time estimation as one of the most cost effective methods. Wang et al. (2011) demonstrated that the travel time estimated from Bluetooth sensors and loop detectors are roughly similar. Malinovskiy et al. (2010) compared the travel time from ALPR with Bluetooth data and found that average travel times were 4-7% higher than that from ALPR. Other studies using Bluetooth technology include freeway travel time variability (Bullock et al. 2011), speed limit compliance in work zones (Wasson et al. 2011), estimating route choice (Hainen et al., 2011), Origin – Destination estimation (Barceló et al. 2012) and security checkpoint waiting times in airport (Remias et al. 2013).

Reliability is commonly used in reference to the level of consistency in transportation service for a mode, trip, route or corridor (Lomax et al., 2003). Lyman and Bertini (2008) defines travel time reliability as the measure of the amount of congestion that the users experience during a particular period of time. The various performance measures to indicate the reliability can be broadly classified into three categories: (a) statistical range – uses the standard deviation and coefficient of variation to estimate the range of transportation conditions experienced by the users, (b) buffer time measures – indicates the extra amount of time required to complete the trip during irregular traffic conditions and (c) tardy trip indicators – showing how often a traveler will be unacceptably late. Saberi and Bertini (2010) used some of the buffer time measures like the buffer time index, planning time index and travel time index to study the reliability of various links within the study corridor. They found that the buffer index and coefficient of variation have a higher consistency among the other measures. Remias et al. (2013) used the cumulative frequency diagrams to study the travel time reliability of various links within the study corridor and showed that they are very efficient in quantifying the reliability. Some of these relevant measures will be used in this study to check the reliability of travel time collected using Bluetooth.

3. Field implementation and data collection

Saidapet and SRP Tools in Chennai, connected by two alternate routes, were selected as the common origin and destination points respectively for the present study. The first one via Velachery and Taramani Link Road had a total length of 9.5 km, whereas, the second route via the Sardar Patel Road and Rajiv Gandhi Salai was 6.1 km long. The Velachery – Taramani road is a 4 lane road with 2 lanes in each direction. The road section passes through a commercial area with multi-storeyed buildings and residential developments on either side of the road. There are 4 major signal controlled intersections along the route.

The Sardar Patel Road and Rajiv Gandhi Salai are 6 – lane roadways, with 3 lanes in each direction and each having a width of 3.5m/lane. Major part of the traffic from Sardar Patel Road takes a right turn at the signal controlled T-shaped Madhya Kailash intersection and enters into the Rajiv Gandhi Salai. A part of the flow enters as the free left turn traffic coming from the opposite direction. This roadway is also known as ‘IT corridor’ since Information Technology industries occupy most of the area. The study site also houses a number of automated sensors, the data from which were used to estimate the daily traffic. This route has two major signal controlled intersections – Madhya Kailash intersection and the Tidel Park intersection. SRP Tools, the destination point, is also a T intersection like the Madhya Kailash intersection, where both the routes meet. Figure 1 shows a Google maps image of the study site along the two alternate routes.

The Bluetooth sensors were deployed at four points along the study site – one each at the common origin (Saidapet) and destination (SRP Tools), one along the IT Corridor route at the First Foot Over Bridge (FOB) and one along the Velachery – Taramani route at the Blue Cross. The sensors were placed at a height of 1.8m on lamp posts and bridge columns. Three of the four monitoring stations were equipped with power backup which allowed the sensors to run throughout the study period. Saidapet was the only location where raw power was not available and hence the sensors were operated using batteries which lasted for 4 days.

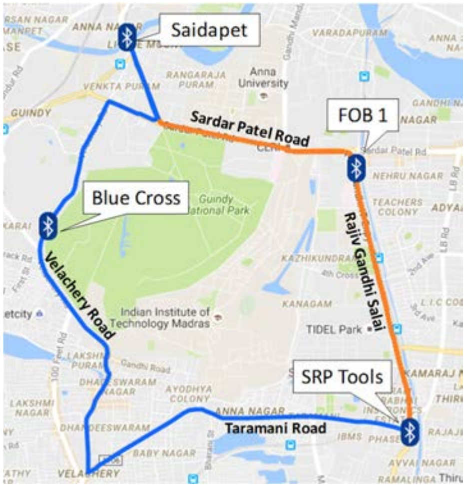


Fig. 1. Google Maps image showing the study site.

Data collection was carried out during the month of April, from 03 to 29 April 2014 at all the locations except Saidapet. Due to the unavailability of power at Saidapet, data collection was performed using a 12V 28AH battery from 26 to 29 April 2014.

4. Data analysis

4.1. Total observations

Table 1 shows the unique MAC addresses captured at each BMS with their respective duration during the study period. Data filtering with a 30-minute time period was performed to remove the duplicate MAC addresses. The 30-minute time gap also ensured that the same vehicle making another trip via the same BMS location is counted rather than being neglected as a duplicate.

SRP Tools has the highest detection rate which is probably due to its proximity to an intersection. Blue Cross captured less data although it ran only for 3 weeks. There was a loss of data for 1 week at this location due to an intermittent sensor failure. Another reason may be that the number of vehicles with Bluetooth enabled devices operating on this road is less compared to the other road that mainly caters to the IT companies. This is confirmed by the penetration rate discussed in the next section. Table 1 also provides the average hits per day at each of the locations, which gives a better approximation of the number of devices detected.

Table 1. Unique MAC addresses at the various Bluetooth Monitoring Stations (BMS)

BMS	Saidapet	FOB I	Blue Cross	SRP Tools
Duration	26 – 29 Apr	03 – 29 Apr	03 – 19 Apr 25 – 29 Apr	03 – 29 Apr
	4 days (battery power)	4 weeks	3 weeks	4 weeks
Unique MAC Hits	48,121	1,61,929	1,12,807	1,98,567
Average hits per day	13,121	8,829	5,950	13,160

4.2. Penetration and match rate

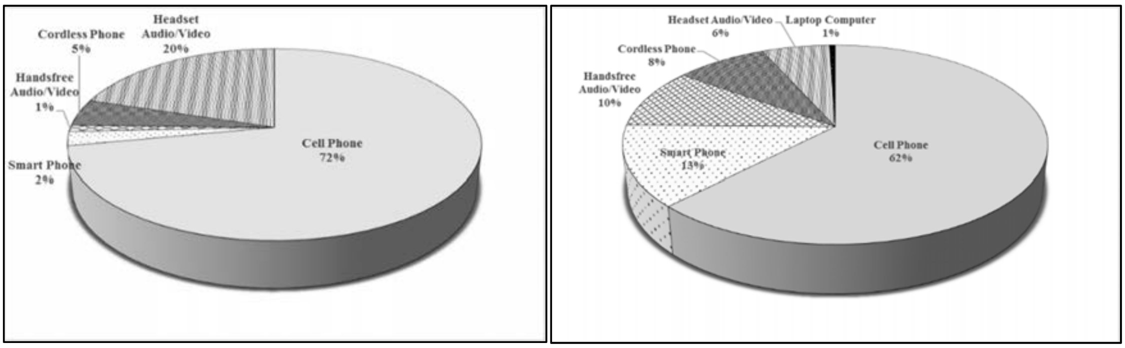
A penetration rate analysis was carried out to find out the percentage of vehicles being identified using this sensor. The total volume count in southbound and northbound direction was obtained from an automated sensor. The penetration rate is then expressed as a percentage of the total number of Bluetooth devices detected to the total number of vehicles that passed the particular section. IT Corridor had a penetration rate of around 10.04%, whereas along the Velachery - Taramani Road, it was found to be around 7.11%.

The match rate is defined as the percentage of a successful pair of Bluetooth enabled vehicles among the total traffic volume matched at two or more stations along the road segment under a specific time period (KMJ Consulting Inc. 2010). In order to find the match rate, the difference in timestamps of all the matched pairs of MAC addresses between FOB 1 & SRP Tools (IT Corridor), and Blue Cross & SRP Tools (Velachery-Taramani) were determined. Those addresses, with a positive difference, indicate that the vehicle travelled towards south and vice versa. Only the addresses with positive differences were used to study the match rate. The match rate along the IT Corridor was found to be around 7.69%, while the same along Velachery – Taramani Road was only 3.93%. The low match rate along the second route is probably due to the lesser detections along this route as seen in the previous section.

4.3. Device classification

One of the major outputs from the Raspberry Pi was the type of device detected. This information was used to classify the devices according to their type. Figure 2 shows a pie chart with the different classes of devices detected along both the routes. We can observe a high percentage of cell phones along both the routes. However, the IT corridor has a higher percentage of smartphones (13%) compared to the Velachery route (2%). This might be due to the presence of IT professionals along this route who tend to use more smartphones. Also, we find a higher number of Headset devices along the Velachery route (20%) when compared to the IT Corridor (6%). A possible explanation for this could be due to more two-wheelers who tend to use the Bluetooth headsets more often. The Handsfree Audio/Video mainly includes the audio systems in cars and other heavy vehicles. High percentage of Handsfree devices along the IT corridor could suggest the presence of more cars and heavy vehicles along this route. However, these results can only be justified if suitable vehicle classification data is available from both routes.

The lesser number of smartphones along both the routes could be due the default visibility timeouts of 120 seconds present in them. Other devices detected include laptop computers and cordless phones.



(a) (b)

Fig. 2. Detected devices along (a) Velachery - Taramani route and (b) IT Corridor

4.4. Travel time analysis

Figure 3 represents the travel time graph for both the routes from the common origin (Saidapet) and destination (SRP Tools). The travel time was obtained by MAC address matching of those vehicles passing through Saidapet and SRP Tools. Data filtering and outlier removal using Median Absolute Deviation (MAD) was carried out for the 5 days data set. This data set containing the travel time of vehicles using both the routes, was then separated for each route. The dark dots in Figure 3 represent the IT corridor and light dots shows the alternate route. Travel times for all 5 days are shown, with some missing data for short intervals during one or two days. It can be observed from Figure 3 that the IT corridor (dark dots) route has a much lesser travel time when compared to the Velachery - Taramani Road, for majority of the time. However, during the peak hours both the routes experience more or less the same travel time. During peak hours, it takes around 25 minutes to travel using both the routes. Vehicles using the IT corridor take around 10 minutes to travel during non-peak hours whereas the other route takes around 20 minutes during the same time periods. The Velachery-Taramani Road covers more distance to reach the destination and comprises of more intersections when compared to the IT Corridor. Hence, the Velachery - Taramani Road is expected to take more time to reach the destination and the data from the Bluetooth sensors also reveal the same.

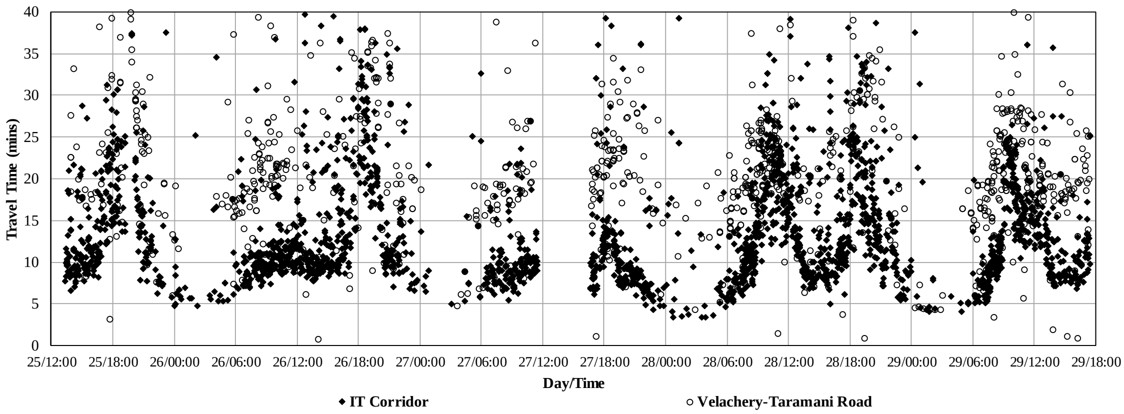


Fig. 3. Travel time analysis along both routes

4.5. Reliability studies using CFD

The cumulative frequency diagrams (CFD's) are plots with the cumulative frequency of travel times on the x-axis and their corresponding percentiles on the y-axis. In order to compare both the routes and their reliability, the CFD's were plotted for different time periods across four days from April 26 to April 29. Three sets of CFD's were plotted for a day with time periods ranging from 08:00 - 12:00, 12:00 - 16:00 and 16:00 - 20:00, in order to capture the variations during morning peak, afternoon off peak, and evening peak. Figure 4 shows the CFD's for both the routes during the three different time periods for all the days which consisted of a weekend and two working days.

It can be observed that the IT corridor is far more dependable than the Velachery - Taramani Road during all the three time periods on both weekdays and weekends. Both the routes have similar conditions during the morning peak and evening peak, with the morning peak experiencing a bit more travel time on working days. In the IT corridor, the median travel time is around 20 minutes during the first time period (08:00 - 12:00) while the same in the other route is more than 25 minutes on working days. But during weekends, the median travel times were lower on both the routes. During the next two time periods (12:00 to 16:00 and 16:00 to 20:00) the vehicles plying along the IT corridor took around 10 minutes to reach SRP Tools whereas almost double the time was taken along the other route. The "NO DATA" shown in the figure indicates the loss of data due to sensor failure.

Similarly, weekly assessment of reliability studies was also carried out. Since AC power was not available at the origin (Saidapet), it was decided to carry out the weekly assessment from Blue Cross along the Velachery Road to SRP Tools and from the First FOB along the IT corridor to SRP Tools. The data were collected for a month and the analysis was performed for the four weeks. The CFD's along both the routes were plotted. Figure 5 shows the CFD's for all the weeks except the fourth week, where considerable data loss occurred at Blue Cross.

The travel times were separated for both the routes and grouped under three time periods - 08:00 to 12:00, 12:00 to 16:00 and 16:00 to 20:00. It can be seen that the weekly patterns are quite similar to the daily pattern with the IT corridor route more reliable than the other route for all the three time periods. The median travel times for the morning and evening peak are around 10 minutes for the IT corridor. The morning peak for the Velachery route is nearly double, taking around 20 minutes but the evening peak was worse where the vehicles take more than 25 minutes to reach SRP Tools from Blue Cross.

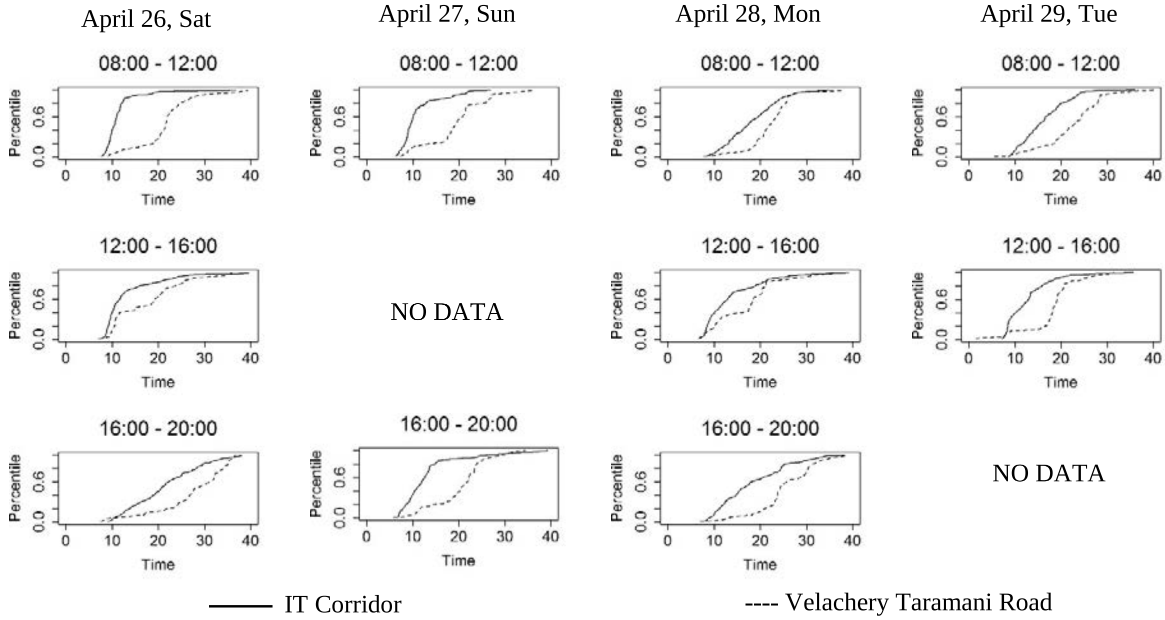


Fig. 4. Daily assessment of travel time reliability along both the routes

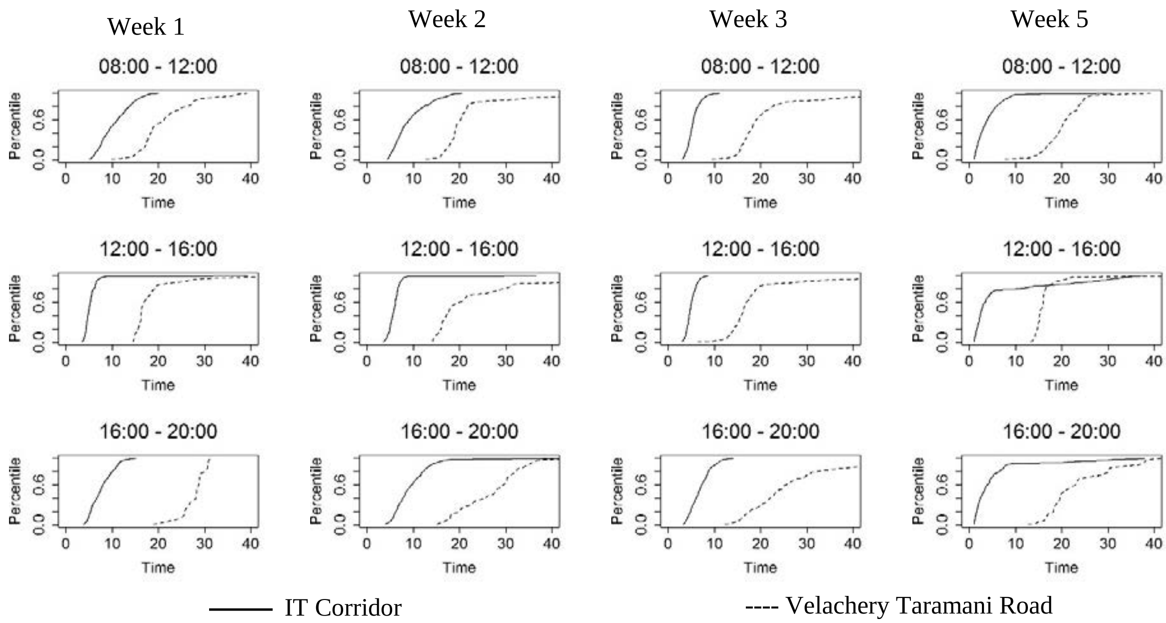


Fig. 5. Weekly assessment of travel time reliability along both the routes

Apart from the daily and weekly assessment of the reliability between the two routes, an in-depth study was conducted to analyse those time frames where both the routes yielded the same amount of reliability. Analysis was carried out on all the four days for every 30 minutes interval to determine the reliability of the two routes. The time periods from 08:00 - 11:00, 12:00 - 15:00 and 18:00 - 21:00 were split in to intervals of 30 minutes each to implement the analysis. The travel time of vehicles during these time periods were grouped together and separated for each route. The CFD's were then plotted to study the reliability of each of the route. Figure 6 represents a sample plot for Monday, 28 April 2014. It can be observed that, during the weekends the Velachery Road is better or as good as the IT corridor during selected time periods. During all the other periods, the IT corridor had lesser travel times. During the morning peak from 09:00 - 11:00 the CFD's for both the routes were very close to each other during certain days. During the morning peak, the number of vehicles operating on the roadway is more leading to more congestion and more travel time. As a result, both the routes experience nearly same travel time. It can be concluded that a vehicle opting either of the two routes from Saidapet during this time period on a working day would take more or less the same time to reach SRP Tools. Apart from the morning peak on a working day, it was found that the CFD's for both the routes resembled each other during the time period 12:30 to 13:00.

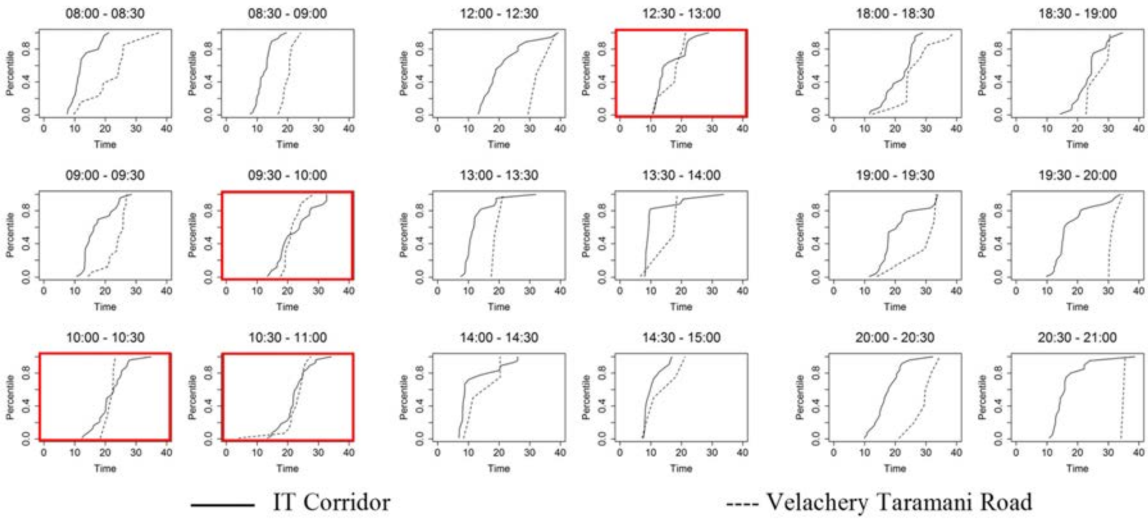


Fig. 6. 30 minutes comparison of both the routes

4.6. *Reliability studies using reliability measures*

Travel time reliability not only reflects the performance of an urban arterial but also as an index for quantifying the effects of congestion. Thus, it is important to measure travel time reliability in a suitable way and study its effect on route choice analysis. There are several measures for quantifying travel time reliability. Some of the important measures are analyzed in this paper and are listed below.

(1) *Mean*

(2) *Standard deviation*

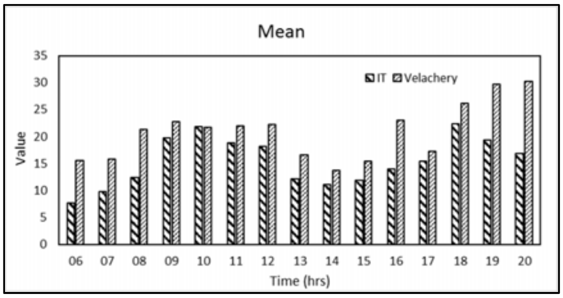
(3) *Travel time index*: Mean time taken to travel during peak hours compared to that at free flow conditions and can be computed as mean travel time divided by free flow travel time.

(4) *Buffer time index*: Buffer index of any link is used to account for the extra time that travellers should add to the mean travel time to ensure on time or earlier arrivals. It is computed as the difference between 95th percentile travel time and mean travel time, divided by mean travel time. Low buffer index value indicates high reliability.

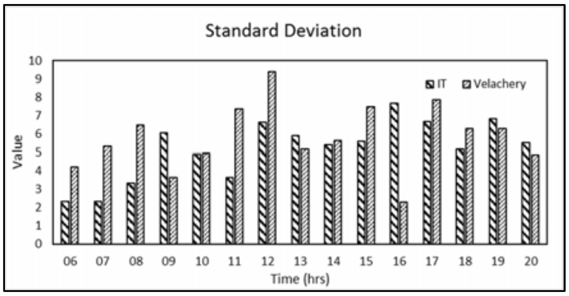
(5) *Planning time index*: Percentage of total travel time when an adequate buffer time is included. It is computed as 95th percentile travel time divided by assumed free-flow travel time. Higher planning time index leads to lower reliability.

Out of these, the planning time index is biased by congestion since it is based on the difference between the actual travel time and free flow travel time (Saberi and Bertini, 2010). Thus, the longer route will have higher free flow travel time bringing down the planning time index. Same is the case of Buffer time index. Hence, only the mean, standard deviation and travel time index were calculated in this study.

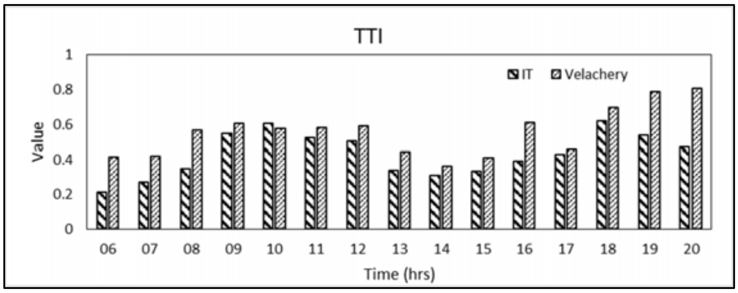
These reliability measures were calculated for every one- hour intervals from 06:00 to 21:00 for all the five days. The mean, standard deviation and the travel time index values were found to be more realistic than the buffer time index and planning index values, on comparing the reliability of both the routes. Figure 7 (a) compares the mean values across both the routes and, as expected, the shorter distance IT Corridor has lesser travel time compared to the Velachery route. However, during peak hours, the mean values across both the routes seem to be more or less the same. The standard deviation values for both the routes, especially the Velachery route, (Figure 7 (b)) seems to be very high, indicating the huge variation in travel time values recorded. The less number of data points could be one of the factors for this huge variation in the travel time. Figure 7 (c) shows the travel time index values for both the routes which complies with the actual situation. During off peak hours the IT Corridor is shown more reliable than the Velachery route whereas during peak hours both are unreliable.



(a)



(b)



(c)

Fig. 7. (a) Mean (b) Standard deviation and (c) Travel time index comparisons for both the routes on 28 April

5. Conclusions

Bluetooth technology for travel time data collection in India is gaining popularity over the past few years due to its cost-effectiveness and ease of installation. This paper examines the use of Bluetooth technology for estimating the travel time across two alternate routes and their reliability. Data collection was carried out for a period of 1 month where more than 5,00,000 unique MAC addresses were analysed. Penetration rates of around 10% and 7% were observed along the IT Corridor and Velachery – Taramani Road respectively. The device classification results showed that both the routes had a vast majority of cell phones with a higher percentage of Bluetooth headsets along the IT Corridor and Handsfree audio/video devices along the Velachery route. The travel time analysis revealed that the IT Corridor had better travel times throughout, except during the peak periods, where both the routes had similar travel times. To determine the travel time reliability of both the routes, reliability studies were performed using the CFD's and the reliability measures. Daily, weekly and 30-minute interval CFD studies revealed that the IT Corridor to be far more reliable than the Velachery route. The 30-minute interval study found both the routes to have the same reliability during the time period 09:00 – 11:00. The reliability study using the various measures in the literature showed the mean, standard deviation and travel time index values to predict the reliability accurately compared to other measures. The other measures yielded good results while comparing the reliability of various segments within a corridor. The studies show that Bluetooth technology has the potential to provide fairly accurate travel time estimations across urban arterials in India.

Acknowledgments

The authors acknowledge the support provided by Indo-US Science and Technology Forum (IUSSTF), Government of India under the grant IUSSTF/JC-Intelligent Transportation Systems//95-2010/2011-12. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation.

References

Barceló, J., Montero, L., Bullejos, M., Serch, O., Carmona, C. 2012. A Kalman Filter Approach for the Estimation of Time Dependent OD Matrices Exploiting Bluetooth Traffic Data Collection. In: Transportation Research Board 91st Annual Meeting. Retrieved from http://trid.trb.org/view.aspx?id=1130522

Bullock, D., Martchouk, M., Mannering, F. 2011. Analysis of Freeway Travel Time Variability Using Bluetooth Detection. Journal of Transportation Engineering, 137(10), 697–704. doi:10.1061/(ASCE)TE.1943-5436.0000253.

Hainen, A. M., Wasson, J. S., Hubbard, S. M. L., Remias, S. M., Farnsworth, G. D., Bullock, D. M. 2011. Estimating Route Choice and Travel Time Reliability with Field Observations of Bluetooth Probe Vehicles. Transportation Research Record: Journal of the Transportation Research Board, 2256(-1), 43–50. doi:10.3141/2256-06

Lomax, T., Schrank, D., Turner, S., Margiotta, R. 2003. Selecting travel reliability measures. Texas Transportation Institute, (May 2003).

Lyman, K., & Bertini, R. L. (2008). Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations. Transportation Research Record: Journal of the Transportation Research Board, 2046(-1), 1–10. doi:10.3141/2046-01

Malinovskiy, Y., Wu, Y.-J., Wang, Y., Lee, U. K. 2010. Field Experiments on Bluetooth-Based Travel Time Data Collection. In Transportation Research Board 89th Annual Meeting. Retrieved from http://trid.trb.org/view.aspx?id=910907

Murphy, P., Welsh, E., Frantz, J. P. 2002. Using Bluetooth for short-term ad hoc connections between moving vehicles: a feasibility study. Vehicular Technology Conference. IEEE 55th Vehicular Technology Conference. VTC Spring 2002 (Cat. No.02CH37367), 1, 414–418. doi:10.1109/VTC.2002.1002746

Nusser, R., Pelz, R. M. 2000. Bluetooth-based wireless connectivity in an automotive environment. In Vehicular Technology Conference Fall 2000. IEEE VTS Fall VTC2000. 52nd Vehicular Technology Conference (Cat. No.00CH37152) (Vol. 4, pp. 1935–1942). IEEE. doi:10.1109/VETECF.2000.886152

Remias, S. M., Hainen, A. M., Bullock, D. M. 2013. Leveraging Probe Data to Assess Security Checkpoint Wait Times. Transportation Research Record: Journal of the Transportation Research Board, 2325(-1), 63–75. doi:10.3141/2325-07

Remias, S. M., Hainen, A. M., Day, C. M., Brennan, T. M., Li, H., Rivera-Hernandez, E., Bullock, D. M. 2013. Performance Characterization of Arterial Traffic Flow with Probe Vehicle Data. Transportation Research Record: Journal of the Transportation Research Board, 2380(1), 10–21. doi:10.3141/2380-02

Saberi, M., Bertini, R. 2010. Beyond Corridor Reliability Measures: Analysis of Freeway Travel Time Reliability at the Segment Level for Hot Spot Identification. Transportation Research Board 89th Annual Meeting,, 514 (July 2009), 1–13. Retrieved from http://trid.trb.org/view.aspx?id=910455

Tarnoff, P. J., Bullock, D. M., Young, S. E., Wasson, J., Ganig, N., Sturdevant, J. R. 2009. Continuing Evolution of Travel Time Data Information Collection and Processing. In Transportation Research Board 88th Annual Meeting. Retrieved from http://trid.trb.org/view.aspx?id=881513

Wang, Y., Vrancken, J. L. M., Seidel, P. 2011. Measure travel time by using Bluetooth detectors on freeway. In Proceedings of the ITS World Congress (pp. 1–5).

Wasson, J. S., Boruff, G. W., Hainen, A. M., Remias, S. M., Hulme, E. a., Farnsworth, G. D., Bullock, D. M. 2011. Evaluation of Spatial and Temporal Speed Limit Compliance in Highway Work Zones. Transportation Research Record: Journal of the Transportation Research Board, 2258(1), 1–15. doi:10.3141/2258-01

Young, S. 2008. Bluetooth Traffic Monitoring Technology: Concept of Operations and Guidelines. Retrieved September 17, 2013 from http://www.catt.umd.edu/documents/UMDBT-Brochure%20REV3.pdf