Identifying Appropriate Sampling Interval for Travel Time Studies Using Bluetooth Probe Data

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ABSTRACT

Accurate, reliable, and timely travel time is critical to monitor transportation system performance and assist motorists with trip-making decisions. Travel time is estimated using the data from various sources like cellular technology, automatic vehicle identification (AVI) systems. Irrespective of sources, data have characteristics in terms of accuracy and reliability shaped by the sampling rate along with other factors. As a probe based AVI technology, Bluetooth data is not immune to the sampling issue that directly affects the accuracy and reliability of the information it provides. The sampling rate can be affected by the stochastic nature of traffic state varying by time of day. A single outlier may sharply affect the travel time. This paper brings attention to several crucial issues - intervals with no sample, minimum sample size and stochastic property of travel time, that play pivotal role on the accuracy and reliability of information along with its time coverage. It also demonstrates noble approaches and thus, represents a guideline for researchers and practitioner to select an appropriate interval for sample accumulation flexibly by set up the threshold guided by the nature of individual researches' problems and preferences.

INTRODUCTION

Travel time is an important component of Advanced Traveler Information Systems (ATIS), as it is a key factor for travelers who are faced with unexpected traffic delays (*1*). Aside from measuring transportation system performance, travel time has been used to predict future travel time and traffic state, which help the traffic operations room in versatile ways. In ATIS, fixed point traffic sensors, cellular geo-location technologies (*2*), and automatic vehicle identification (AVI) systems (e.g. Bluetooth readers, electronic toll collection tags, license plate readers, and signature re-identification based on detector or magnetometer measurement) are used to estimate instantaneous travel time (*3*). Amongst all available techniques, Bluetooth has emerged as one of the fastest growing data collection technologies whose market share is continuing to rise, mainly due to its cost effectiveness. Bluetooth is a probe based (*4*) AVI technique (*5*) for collecting travel time data. Each Bluetooth device contains a unique electronic identifier known as a Media Access Control (MAC) address. By mounting a simple antenna adjacent to the roadway, MAC addresses of other devices in range can be logged. When a logged MAC address matches at two consecutive stations, the difference in logging timestamps is used to estimate the travel time and speed (*6*).

The variation of travel time on a route with the same origin and destination can be defined as the travel time variability. According to Arup et al. (*7*), there are two distinguished components of travel time variability- incident related variability and day-to-day variability. The former one is random, whereas the latter one is predictable as it is demand and capacity related variability. Travel time variability is reciprocal to the reliability of travel time. According to Carrion, the higher the variability, the lower the reliability, and hence, the unreliability can be defined as the measure of spread of the travel time probability distribution (*8*). Although unreliable i.e. highly oscillating travel time is undesirable to travelers due to its cost in daily activities, the oscillation is a universal property of travel time, which should be preserved to perceive the travel time accurately.

For Bluetooth data, sample size is determined by the penetration rate of detectable Bluetooth signals in the traffic stream and the total number of vehicles per unit time. Generally speaking, higher sample size usually represents the population better than a lower sample size. The dilemma is that real-time information requires the travel time to be updated on a frequent basis, which may contradict with the desire for a large sample size collected over a long period given a low penetration rate. Another problem regarding sample size involves the penetration rate that varies over time. Provided that a valid sample size is determined, the time-varying penetration rate results in a changing time interval for updating the travel time: higher penetration rate requires a shorter time interval for travel time than lower penetration rate and vice versa. Dynamic time interval for travel time update creates confusion to travelers as information should be updated neither too frequent nor too slow. Another undesirable feature is the computation complexity added by constantly finding the proper time period that contains target samples. A few studies have been conducted to address the low sampling challenge of travel time estimation using Bluetooth data, hardly any of these has even mentioned sampling interval.

Bluetooth data is not immune to the sampling issue that directly affects the accuracy and reliability of the information it provides. Its sampling rate is very low and depends on many aspects including configuration, installation, location etc. Despite of having some limitations, Bluetooth Technology (BT) has become popular due to various reasons including low cost. Due to the low sampling rate and sampling error, data may not be available in every minute and a single outlier may affect the travel time sharply. Accumulation of data in several minutes would help to overcome these limitations. However, accumulation is a trade-off between the real time sensitivity and accuracy of the travel time. Since the longer the aggregation time period is, the more real time essence of travel time is compromised, it is imperative to know about the loss of stochasticity, a predominant property of travel time. FIGURE 1 delineates the loss of this predominant property among different aggregation intervals of travel time:

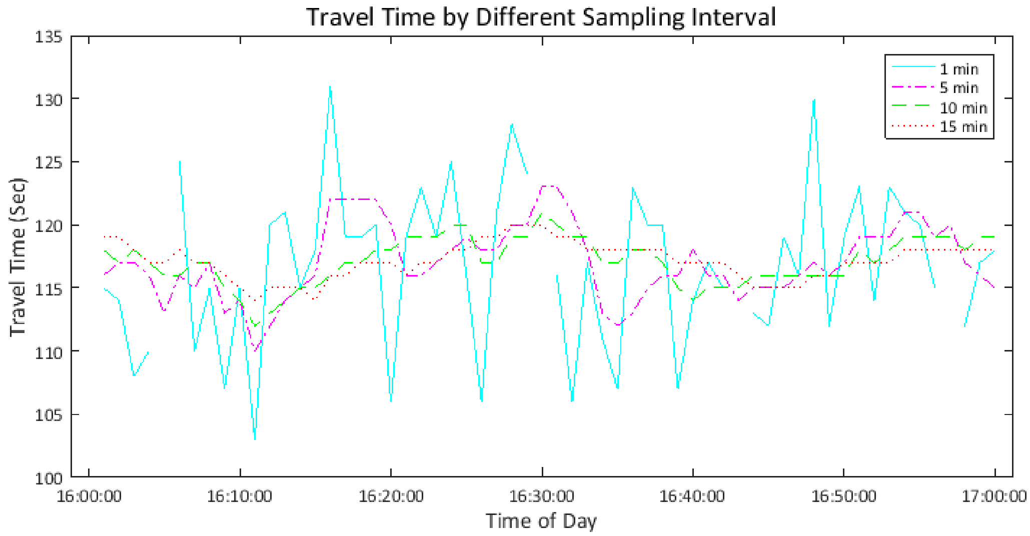

FIGURE 1 Variation in travel time stochasticity.

According to FIGURE 1, travel time variability decreases and coverage of intervals with no-sample increases in higher aggregation intervals e.g. 1-min, 5-min, 10-min and 15-min. The 1-min sampling interval yields excessive instability in travel time. The main objective of this study is to identify and recommend appropriate time interval for sampling Bluetooth data that balance the need for accurate, reliable, and timely update of the travel time on freeways. Rather than determining a fixed sample size that leads to varying time interval for travel time update, a simple method has been proposed considering a balance between real time sensitivity and reliability of the travel time estimation. A two-step framework has been developed to quantify the effect of aggregation on intervals in terms of high confidence sample rate, sample penetration rate and measure of succession.

LITERATURE REVIEW

More studies found that the information collected using Bluetooth technologies could be subject to errors due to low penetration rate, communication range, location placement and installation, and some studies offered solutions. A study based on a 24 hours empirical data set on I-65 in Indianapolis has found that the MAC address is discoverable for 7.4% of the vehicles within 30′ and 6.6% of the vehicles between 102′ and 114′ (*9*). The freeway market penetration rate usually varies within a certain range, for instance, 5-11% (*10*) or 6.25% (*11*) of total volume based on 24 hours counts. Communication range of Bluetooth devices is up to 300 feet, which can be affected by power rating, antenna quality, and obstructions between units etc. (*6; 11*). For instance, vertically polarized antennas with gains between 9dBi and 12dBi are the best antennas for travel time data collection (*12*). Limitations associated with MAC address scanners such as scanning frequency and maximum number of ID capturing in the same time frame can play a vital role during data collection (*13*). Moreover, the optimal number and location of Bluetooth sensors in a network for the reliability of data (*14*) were thoroughly investigated and recommendations were made.

Malinovskiy et al. considered several types of Bluetooth detector antenna, detector placement locations and Bluetooth device configurations (e.g. lane-length covered, antenna direction, opposite tandem, strength etc.) to estimate Bluetooth based travel time error on a short corridor for a 15-min window (*15*). Detection zone, device mounting location, antenna direction and even, combination of mounting locations and antennas have a significant impact on the accuracy of travel time estimation. Bluetooth data quality related error can be generally classified into - spatial, temporal and sampling error (*15; 16*). Spatial error indicates the lack of information about exact position of the vehicle at the time of detection. Temporal error includes multiple detections or no detection at all within the time range of up to 10.24 seconds after it enters the detection zone. Spatial and temporal error lead to the measurement error. Sampling error refers to the low sampling rate unable to represent the population. In addition, Malinovskiy et al. (*15*) considered sampling bias as a type of sampling error. Sampling bias includes an error due to fast moving cyclists and bus passengers' Bluetooth devices, multiple Bluetooth devices in a single vehicle, vehicles with planned en route stops.

Sample size not only varies with the techniques of data collection but also varies with the types of studies or application. In a typical travel time study, sample size could be fixed by the researcher prior to data collection. In contrast, continuous samples are necessary for a real time application like travel time prediction. Bluetooth technology has the advantage of collecting data continuously and anonymously (*17*). Different studies reflect researchers' efforts to find sampling requirement, more specifically, sample size for probe vehicles (*18-20*) which is applicable for controlled study design, but not for uncontrolled system like Bluetooth or Cellular probe. Chen and Chien estimated the minimum sample size using statistical method and applied heuristic approach using CORSIM simulation to find the minimum number of required probe vehicle with a desired statistical accuracy (*19*). Their study suggests that 3-12 probe vehicles are required for each 5-min interval depending on traffic flow rate from low or high to moderate. Similar method based approaches have also been applied to define the minimum sample size considering cost, measurement error, true error and confident interval (*21*). Li et al. utilized Chris's probe vehicle sampling size model combining capacity constraints of wireless communication system (*20*). The Chris's model (*22*) utilizes the information of traffic density, average link length and fraction of vehicles sampled to get the coverage. Ygnace and Drane studied cellular phones as probe vehicles to find the probe vehicle size to estimate travel time with 5% accuracy (*22*). In addition, Jiang et al. studied the impact of probe vehicle sample size and sampling interval and concluded that the time interval had little effect for same sample size. They also demonstrated that the estimation error of average link travel time varied steadily when the sample size reached a certain threshold (*23*). Therefore, the accumulation of several minute samples are capable to provide reasonably reliable travel time regardless of population size. In a study, Click and Lloyd concluded that the intervals with sample size 8 or more possess higher confidence in Bluetooth data on rural freeways (*11*). More accuracy can be ensured by applying appropriate methods of estimation. Araghi et al. estimated travel time in four different approaches- min, max, median and average travel time within two different sample intervals (15 and 30 mins) and found the min and median travel time were more robust in the presence of outliers (*24*).

Although, studies regarding the impact of sampling interval and sample size are unavailable about Bluetooth data, studies related to probe vehicle explicitly exhibit that the sampling interval and sample size are interrelated. Low sampling rate affects the minute-by-minute data availability. Nevertheless, accumulation of several minute data would increase number of samples within a certain time interval without affecting the penetration rate. Since accumulation of data is a trade-off between the real time sensitivity and accuracy of the travel time, fixing the accumulation time window i.e. sampling interval is excessively challenging.

DATA PREPARATION AND REDUCTION

The selected study area consists of a 62.8-mile long route, or approximately 47.5 miles on I-90 and the remaining on the Beltline Highway in Madison, Wisconsin. The route is equipped with 41 unequally spaced Bluetooth stations, resulting in 40 links. The first 21 links are on I-90, the 22nd link is on both corridors, and the remaining links are on the Beltline. The spacing varies from 1.3-3.4 miles on I-90 and 0.4-1.3 miles on the Beltline Highway. Forty-seven days' worth of data (11/16/2015-01/01/2016) containing more than 100 million records was collected from traffic in both directions. Half of the records were from outside the study-area. However, a large portion (approx. three-fourths) of the data are either corrupted or contaminated due to multiple detections and unsuccessful detections (i.e. not detected in two consecutive stations).

Bluetooth data contains three variables: MAC ID of the detector and detected devices, and the detection timestamp. For a logged MAC ID, recorded timestamps at two consecutive stations are processed to estimate travel time and the corresponding traffic speed. A brief description of the complete process of data processing is shown in FIGURE 2 and briefly discussed.

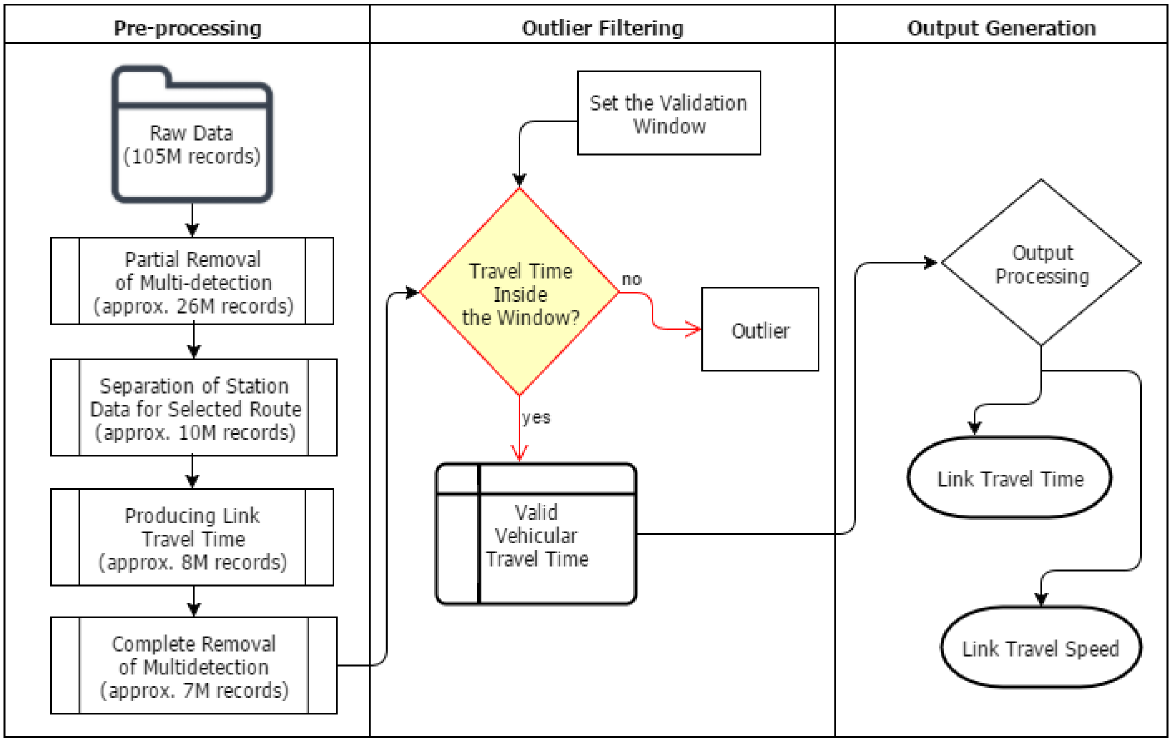

FIGURE 2 Data processing procedures.

A Bluetooth station usually detects a Bluetooth device in its range more than once. The number of such detections can increase significantly due to planned or unplanned stopping of vehicles. A general inspection of the dataset revealed that such detections usually vary two to four times. Oracle queries helped clean up the multi-detection, resulting in the total number of records decreasing from 105 million to 26 million. The data was then separated by each station for the selected routes, further reducing the records to 10 million. Unsuccessful detections were automatically ignored due to the vehicle's detection timestamps from two adjacent stations. Travel times were calculated. Next, the reduced dataset of 8 million samples was processed through a robust Java-based pre-processing module that investigated each record individually and cleaned all unnecessary records. The dataset ended up at 7 million records, which was further processed to filter outliers. Finally, a Java-based programming module produced the travel time data using the outlier filtered data.

METHODOLOGY

The methodology section details the process of estimating travel time by aggregating samples from several minutes and the method for selecting sampling interval.

Travel Time Aggregation Method

Estimating travel time in one-minute interval is straightforward, like taking the average of available samples. For an interval of more than one minute, two types of aggregation can be considered: a) simple average and b) moving average. The basic difference between these two estimation procedure is that the former one gives a single travel time for the aggregation interval which means same travel time for every minute within the interval while the latter one updates travel time at each min regardless of interval size. The estimation process is shown in TABLE 1.

TABLE 1 Travel Time Aggregation Process

Time of Day	09:01	09:02	09:03	09:04	09:05	09:06	09:07	09:08	09:09	09:10
Travel Times of Samples	t_{11}, t_{12}	t_{21}	t_{31}, t_{32}	t_{41}	t_{51}	t_{61}, t_{62}, t_{63}		t_{81}	t_{91}	t_{101}
Simple Average	N/A					$\frac{t_{11}+t_{12}+t_{21}+t_{31}+t_{32}+t_{41}+t_{51}}{7}$				
Moving Average	N/A	N/A	N/A	N/A	N/A	$T_{09:06}$	$T_{09:07}$	$T_{09:08}$	$T_{09:09}$	$T_{09:10}$
$T_{09:06} = \frac{t_{11}+t_{12}+t_{21}+t_{31}+t_{32}+t_{41}+t_{51}}{7}$, $T_{09:07} = \frac{t_{21}+t_{31}+t_{32}+t_{41}+t_{51}+t_{61}+t_{62}+t_{63}}{8}$, $T_{09:08} = \frac{t_{31}+t_{32}+\ldots+t_{63}}{7}$, $T_{09:09} = \frac{t_{41}+t_{51}+\ldots+t_{81}}{8}$, $T_{09:10} = \frac{t_{51}+t_{61}+\ldots+t_{91}}{7}$										

Sampling Interval Selection

Selection of sampling interval is a two-step process: In the first step, the high confidence sample rate for all the sampling intervals will be determined. The high confidence sample rate refers to the percentage of intervals that contain sample sizes equal or more than a predefined required sample size. Then, the sample penetration rate will also be estimated for all the sampling intervals. The sample penetration rate refers to the percentage of intervals that contain at least one sample. Based on the high confidence sample rate and the sample penetration rate, a minimum sampling interval selection would be determined. In the second step, a sampling interval from a bunch of candidate intervals (e.g. 5-min, 10-min etc.) would be selected based on the measure of succession. The candidate intervals must be equal or higher than the selected minimum interval. To measure the succession, a simple but effective method based on travel time reliability measure has been applied.

High Confidence Sample Rate

The high confidence sample rate (R_{HC}) is the percentage of intervals that contain samples more than a predefined threshold. R_{HC} for a route can be expressed by,

$$R_{HC} = \frac{\sum_n N_{HC.i}}{nN} \tag{1}$$

where $N_{HC.i}$= total number of high confidence sample interval in a link i, n = number of links and N = total number of intervals within the analysis period.

Total number of high confidence intervals (N_{HC}) for a link can be estimated by,

$$N_{HC} = \sum_N I_{j(m/r)} \tag{2}$$

where $I_{j(m/r)}$ is a Boolean function to determine whether the j^{th} interval with m samples has high or low confidence given required minimum sample size, r.

The Boolean function,

$$I_{j(m/r)} = \begin{cases} 1, & m \geq r \\ 0, & otherwise \end{cases} \quad (3)$$

where m represents number of samples in j^{th} interval and r is the required minimum samples.

Sample Penetration Rate

Since the sample penetration rate refers to the percentage of intervals that contain at least one sample, it can be estimated by following the same method of estimating high confidence sample rate using r=0.

Measure of Succession

In general, succession refers to the action or process of inheriting a property. Therefore, the measure of succession indicates the measure of inheriting a foremost property. Within the travel time dataset, succession should be the measure of travel time variability or stochasticity inheritance since variability is a foremost property of travel time. Therefore, the inheritance i.e. the conveyance of variability with aggregation should be evaluated before selecting an appropriate time interval. The conveyance of travel time variability refers to the degree of variability conveyed to the candidate intervals after aggregation from the benchmark interval. Travel time variability, also referred as travel time reliability, is a measure of spread to the travel time distribution (*8*) which can be quantified by mean and standard deviation of travel times (*25*). Therefore, conveyance of travel time variability into the aggregated travel time can be estimated by travel time reliability test based on these statistical properties (mean and standard deviation).

Travel time reliability, a key performance indicator, is related to the properties of the day-to-day travel time distribution. The reliability measures include 90th or 95th percentile travel time, buffer index, planning time index, frequency that congestion exceeds some expected threshold, and several statistical measures of variability such as standard deviation and coefficient of variation (*26*). It also includes some probabilistic approaches, tardy trip measures or misery index, and some other modern approaches (*27-29*). Objective and quantitative criteria are keys to selecting the appropriate measure for travel time reliability. In this study, coefficient of variation (CV) was applied to estimate the conveyance of travel time uncertainty. For each link i, CV is estimated by following equation,

$$cv_i = {}^{\sigma_i}/_{\mu_i} \tag{4}$$

The difference between the measure of uncertainty between an aggregated interval (k-min) and the benchmark interval is the measure of its conveyance. Therefore, travel time uncertainty/unreliability conveyance of link i is measured by,

$$d_{ik} = |cv_{ib} - cv_{ik}| \tag{5}$$

where cv_{ib} and cv_{ik} are the measure of reliability for the benchmark and an aggregated interval (k-min) respectively in link i. Assuming $d_{1k}, d_{2k}, \dots d_{nk}$ are the change in travel time uncertainty/unreliability of the links $1, 2, \dots i \dots n$ for any aggregated interval of k-min. Let, the mean and standard deviation of these changes in uncertainties are μ_k and σ_k (where suffix k denotes the aggregation time interval).

Smaller μ_k corresponds to smaller average difference in CV for the entire route, which means higher conveyance of travel time reliability/variability. Smaller σ_k corresponds to smaller variations among the differences in travel time reliability/variability over the entire route, which means conveyance of travel time reliability/variability is consistent or somewhat similar in the network i.e. among all the links. However, larger σ_k refers to the situation where some links have higher loss in travel time reliability and some have lower. Therefore, conveyance of travel time reliability/variability is inconsistent within the network.

RESULTS & DISCUSSION

A study (*11*) shows that 8 samples per 15-min are sufficient to provide a reliable and accurate travel time or speed estimation using Bluetooth data collected on rural freeways. The penetration rate of that study data was around 5-6%, which is a general penetration rate of Bluetooth data. Since 8 samples are sufficient for a 15-min interval, it will also be sufficient for the intervals lower than 15-min. Therefore, to estimate the high confidence sample rate, the value of the required minimum sample size (r) parameter was set to 8 samples per interval. The high confidence sample rate and the sample penetration rate were estimated for 1-min to 15-min intervals.

FIGURE 3 represents that both the high confidence sample rate and the sample penetration rate increase with the increment of sampling interval while the increasing rate gradually decreases. It shows that the increasing rate of sample penetration rate becomes significantly low after 5-min aggregation. However, increasing rate of the high confidence sample rate decreases after 8min aggregation that transforms 54% of total intervals to high confidence intervals. Generally, the traffic flow rate is significantly low resulting free-flow before 6:00AM in the morning and after 9:00PM at night. Within this period, it would be extremely difficult to get 8 samples for a 15-min interval. Hence, a general expectation is that the 15 hours or 62.5% time of a day should be under high confidence surveillance to provide reasonably reliable and accurate information to the control rooms as well as travelers. Therefore, 10-min aggregation providing around 62% intervals of high confidence sample would be a great choice of minimum aggregation interval. This interval will also ensure 93% sample penetration rate which is higher than 88% (for 5-min interval).

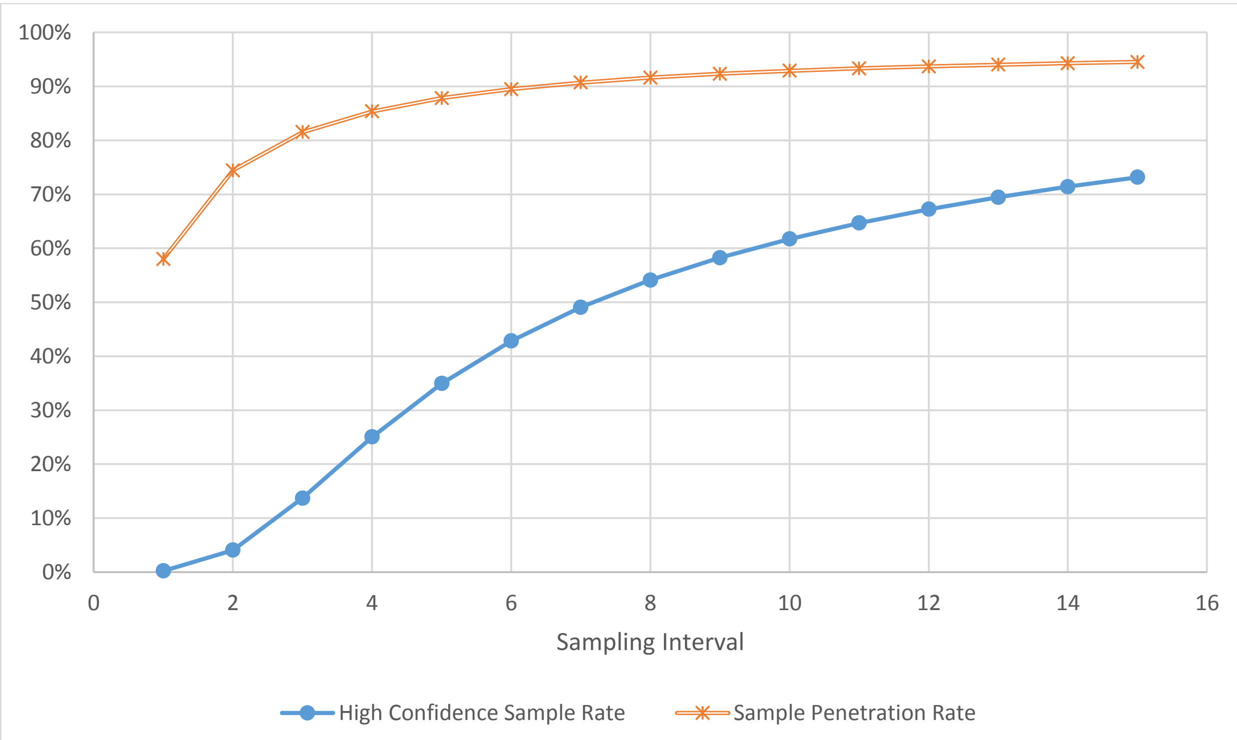

FIGURE 3 Change is sampling character for different intervals.

Benchmarked (1-min travel time) against 10-min and 15-min (multiplier of five minutes, as a general trend of travel time estimation interval) aggregations were examined for the travel time variability conveyance. Since two types of aggregation were considered, four sets of travel time data (10-min and 15-min simple and moving average) with the 1-min data as benchmark were evaluated by the reliability test. Since the study network is comprised of parts of two different corridors (I-90 and Beltline Highway, Madison, WI), the reliability test results of one corridor's links are significantly different from the scores of another corridor's, as shown in FIGURE 4. The results of 10-min and 15-min moving average are almost identical to the results of 10-min and 15-

min simple average, respectively. Therefore, 10-min and 15-min simple average has not been included to ensure better presentation/visualization of the graph.

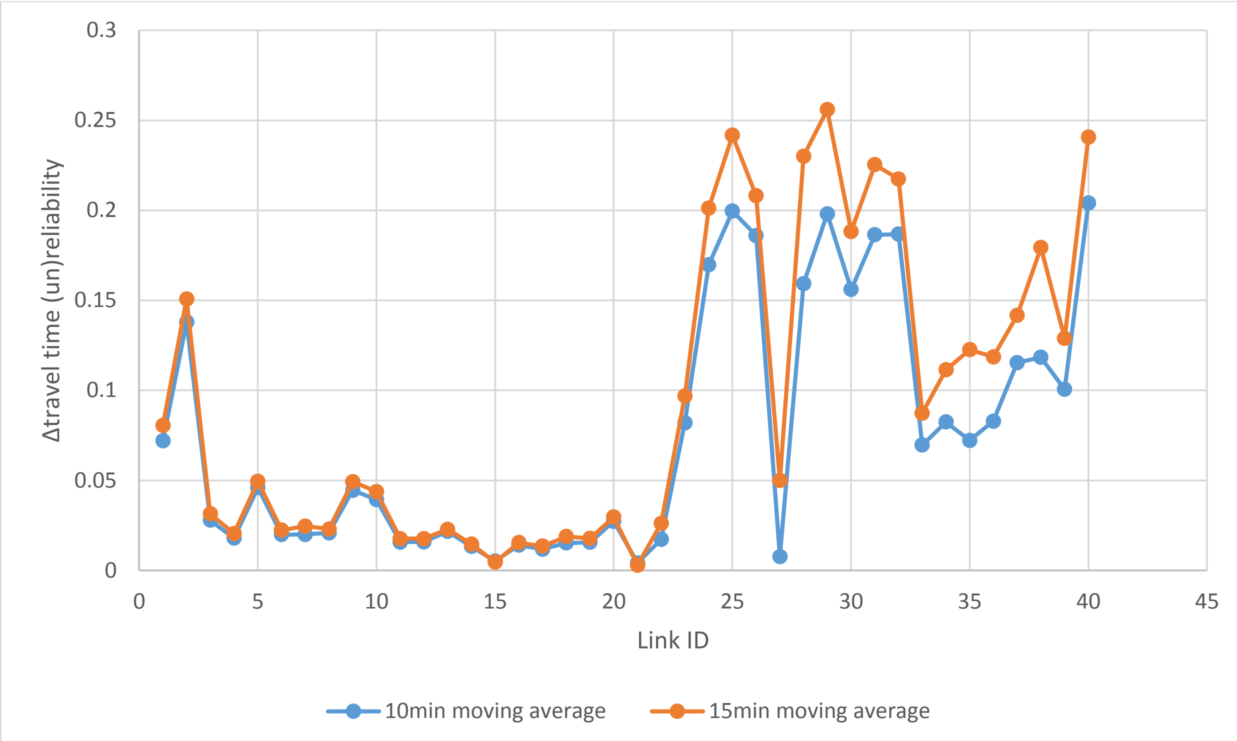

FIGURE 4 Results of reliability test in each link.

The first 22 links of the selected route are from I-90, which shows lower sensitivity towards aggregation than the rest 18 links from the Beltline Highway. Beltline Highway suffers from recurrent congestion during peak period while I-90 highway doesn't. Therefore, one may argue that the speeds of vehicles in a congested situation can show significantly lower variation than speeds in free flow condition. The relatively high variation of travel time in a free flow condition is potentially affected by the drivers' flexibility to drive at different speeds. Since the variation is higher at free flow condition, data aggregation in a longer time period reduces the variation in travel time significantly for the links that mostly experience the free-flow condition. However, that may not be the case due to two potential reasons: a) total congested (or peak) period is much shorter than the total free flow (or off-peak) period and b) since the posted speed is lower and the link lengths are much shorter in the Beltline Highway, the relative variation in driving speed as well as travel time might be higher at free flow condition. Moreover, the much shorter (0.4-1.3 miles) links in Beltline Highway might contribute to the inclusion of spatial error in Bluetooth data. Since Bluetooth device has a detection zone covering a significant length, for instance, 300 feet (*11*). From the local perspective, 10-min interval is preferred than 15-min interval.

The performances of moving and simple average approaches are also compared. The two different corridors have significantly different sensitivity towards the conveyance of reliability, it is better to examine the global/overall conveyance. Table 2 compares the conveyance of travel time variability/(un)reliability of the corridors and the entire route.

TABLE 2 Conveyance of (un)Reliability Property (Global Perspective)

Sampling Interval		10-min		15-min	
Averaging Method		Moving	Simple	Moving	Simple
I-90 corridor	MEAN	0.0207	0.0203	0.0228	0.0188
	STD. DEV.	0.0282	0.0285	0.0309	0.0320
Beltline Highway Corridor	MEAN	0.1110	0.1205	0.1559	0.1328
	STD. DEV.	0.0565	0.0527	0.0609	0.0696
Overall Route	MEAN	0.0750	0.0760	0.0936	0.0966
	STD. DEV.	0.0682	0.0674	0.0840	0.0905

TABLE 2 shows that the simple average of 15-min interval has the least distinction with the benchmark in I-90 while with the maximum variation (the highest standard deviation) over the different links in the corridor. The moving average aggregation of 10-min interval shows the least distinction with the benchmark in the Beltline Highway and exhibits the moderate variation (second lowest standard deviation) over the different links in the corridor. However, the moving average aggregation of 10-min interval also represents minimum deviation from the benchmark over the entire study route (two corridors). In addition, it shows the second lowest variation (slightly higher than the lowest) over the route. The global indicators (mean and standard deviation) of moving and simple aggregations in 10-min interval are off by a negligible value (0.001) and one shows the most conveyance and another shows the least variation in conveyance over different links on the entire route. Therefore, 10-min moving or simple aggregation can be selected considering the patterns of update: former one will provide new/updated travel time at each minute and latter one will provide updated travel time at the end of each 10^{th} minute.

CONCLUSION

In general, sample size is considered as the accurate sampling criteria which is extremely easy to apply in a controlled system or study. In an uncontrolled system (e.g. Bluetooth or Cellular probe), sample size based sampling unit would yield a variable sampling interval which will create complexity in advanced tasks (e.g. prediction of future travel time). This study introduced an empirical method to avoid the complexity by following the aforementioned quantitative approach. It demonstrated the varying nature of properties over the aggregation by different time intervals. The properties include the reliability of travel time which is affected by the sample size, the availability of travel time which is affected by the availability of sample, and the stochasticity of travel time which is an inherit property. The major advantage of this study is the scope of applying engineering judgement at some points.

This study proposed a framework for an excessively challenging task of selecting a sampling interval ensuring accuracy, reliability and preserving the primary property within a tangible proximity. This framework is applicable in any process, especially, uncontrolled process that requires sampling interval instead of sample size. Computation process of the high confidence sample rate and sample penetration rate would be directly applicable to other studies while in some cases a little alteration would be inevitable in computing the succession i.e. the inheritance of a foremost property.

REFERENCES

[1] Khattak, A., A. Polydoropoulou, and M. Ben-Akiva. Modeling revealed and stated pretrip travel response to advanced traveler information systems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1537, 1996, pp. 46-54.

[2] Sussman, J. M., V. Pearce, B. Hicks, M. Carter, J. E. Lappin, R. F. Casey, J. E. Orban, M. McGurrin, and A. J. DeBlasio. What Have We Learned About Intelligent Transportation Systems?In, 2000.

[3] Xiao, Y., S. Qom, M. Hadi, and H. Al-Deek. Use of Data from Point Detectors and Automatic Vehicle Identification to Compare Instantaneous and Experienced Travel Times. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2470, 2014, pp. 95-104.

[4] Puckett, D. D., and M. J. Vickich. Bluetooth®-based travel time/speed measuring systems development.In, 2010.

[5] Day, C. M., T. M. Brennan, A. M. Hainen, S. M. Remias, and D. M. Bullock. Roadway system assessment using Bluetooth-based automatic vehicle identification travel time data. 2012.

[6] Bachmann, C., B. Abdulhai, M. J. Roorda, and B. Moshiri. A comparative assessment of multi-sensor data fusion techniques for freeway traffic speed estimation using microsimulation modeling. *Transportation Research Part C: Emerging Technologies*, Vol. 26, 2013, pp. 33-48.

[7] Arup, O., J. Bates, J. Fearon, and I. Black. Frameworks for modelling the variability of journey times on the highway network.In, Report for Department of Transport, London, UK, 2004.

[8] Carrion, C., and D. Levinson. Value of travel time reliability: A review of current evidence. *Transportation research part A: policy and practice,* Vol. 46, No. 4, 2012, pp. 720-741.

[9] Brennan Jr, T. M., J. M. Ernst, C. M. Day, D. M. Bullock, J. V. Krogmeier, and M. Martchouk. Influence of vertical sensor placement on data collection efficiency from bluetooth MAC address collection devices. *Journal of Transportation Engineering*, Vol. 136, No. 12, 2010, pp. 1104-1109.

[10] Quayle, S., and P. Koonce. Arterial Performance Measures Using MAC Readers—Portland's Experience. *North American Travel Monitoring r_report. htm*, 2010.

[11] Click, S. M., and T. Lloyd. Applicability of bluetooth data collection methods for collecting traffic operations data on rural freeways.In *Transportation Research Board 91st Annual Meeting*, 2012.

[12] Porter, J. D., D. S. Kim, M. E. Magaña, P. Poocharoen, and C. A. G. Arriaga. Antenna characterization for Bluetooth-based travel time data collection. *Journal of Intelligent Transportation Systems,* Vol. 17, No. 2, 2013, pp. 142-151.

[13] Abedi, N., A. Bhaskar, and E. Chung. Bluetooth and Wi-Fi MAC address based crowd data collection and monitoring: benefits, challenges and enhancement. 2013.

[14] Asudegi, M. Optimal number and location of Bluetooth sensors for travel time data collection in networks.In, 2009.

[15] Malinovskiy, Y., U.-K. Lee, Y.-J. Wu, and Y. Wang. Investigation of Bluetooth-based travel time estimation error on a short corridor.In *Transportation Research Board 90th Annual Meeting*, 2011.

[16] Mei, Z., D. Wang, and J. Chen. Investigation with Bluetooth sensors of bicycle travel time estimation on a short corridor. *International Journal of Distributed Sensor Networks,* Vol. 2012, 2012.

[17] Moghaddam, S., and B. Hellinga. Real-time prediction of arterial roadway travel times using data collected by Bluetooth detectors. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2442, 2014, pp. 117-128.

[18] Turner, S. M., and D. J. Holdener. Probe vehicle sample sizes for real-time information: The Houston experience.In *Vehicle Navigation and Information Systems Conference, 1995. Proceedings. In conjunction with the Pacific Rim TransTech Conference. 6th International VNIS.'A Ride into the Future'*, IEEE, 1995. pp. 3-10.

[19] Chen, M., and S. Chien. Determining the number of probe vehicles for freeway travel time estimation by microscopic simulation. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1719, 2000, pp. 61-68.

[20] Li, W., W. Chuanjiu, S. Xiaorong, and F. Yuezu. Probe vehicle sampling for real-time traffic data collection.In *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE,* IEEE, 2005. pp. 222-224.

[21] Toppen, A., and K. Wunderlich. *Travel time data collection for measurement of advanced traveler information systems accuracy*. Mitretek Systems, 2003.

[22] Ygnace, J.-L., and C. Drane. Cellular telecommunication and transportation convergence: a case study of a research conducted in California and in France on cellular positioning techniques and transportation issues.In *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE*, IEEE, 2001. pp. 16-22.

[23] Jiang, G., L. Gang, and Z. Cai. Impact of probe vehicles sample size on link travel time estimation.In *Intelligent Transportation Systems Conference, 2006. ITSC'06. IEEE*, IEEE, 2006. pp. 505-509.

[24] Araghi, B. N., K. S. Pedersen, L. T. Christensen, R. Krishnan, and H. Lahrmann. Accuracy of travel time estimation using Bluetooth technology: Case study Limfjord tunnel Aalborg. *International Journal of Intelligent Transportation Systems Research*, Vol. 13, No. 3, 2015, pp. 166-191.

[25] Martchouk, M., F. L. Mannering, and L. Singh. Travel time reliability in Indiana. 2010.

[26] Reliability, T. T. Making It There on Time, All the Time. *Federal Highway Administration, USA*, 2006.

[27] Van Lint, J., H. J. Van Zuylen, and H. Tu. Travel time unreliability on freeways: Why measures based on variance tell only half the story. *Transportation research part A: policy and practice*, Vol. 42, No. 1, 2008, pp. 258-277.

[28] Clark, S., and D. Watling. Modelling network travel time reliability under stochastic demand. *Transportation Research Part B: Methodological*, Vol. 39, No. 2, 2005, pp. 119-140.

[29] Guo, F., H. Rakha, and S. Park. Multistate model for travel time reliability. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2188, 2010, pp. 46-54.