Data Collection of Freeway Travel Time Ground Truth with Bluetooth Sensors

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Accurate travel time information is essential to the effective management of traffic conditions. Traditionally, floating car data have been used as the primary source of ground truth for measuring the quality of real-time travel time provided by traffic surveillance systems. This paper introduces Bluetooth sensors as a new and effective means of data collection of freeway ground truth travel time. The concept of vehicle identification using Bluetooth signatures for travel time estimation along a section of freeway is explained. Issues related to error analysis, filtering of raw matched data, and accuracy of the resulting ground truth compared with floating car are discussed. Data from loop detectors on several freeway segments are used to approximate and report the average sampling rate of Bluetooth sensors. Results show that the new technology is a promising method for collecting high-quality travel time data that can be used as ground truth for evaluating other sources of travel time and other intelligent transportation system applications.

Traffic congestion and associated impacts such as air pollution pose major concerns to the public. Congestion has increased dramatically during the past 20 years in the 85 largest U.S. cities. During this time, the number of hours lost each year by an average driver to congestion has increased by 300%. In the 13 largest cities, drivers now spend the equivalent of almost 8 workdays each year stuck in traffic (*1, 2*). Increasing the capacity of the roadways is expensive, yet this is not even an option in some areas where land is scarce. Improving the efficiency of the current transportation system through the implementation of advanced technologies may not only alleviate traffic congestion but also decrease the fatality rate associated with vehicle-related crashes.

Accurate travel time information is essential in the effective management of traffic conditions, yet reliable methods for travel time surveillance are slow in coming. Until recently, inductive loop detectors were the most common traffic data collection method for most urban freeways and some city streets even though they are not always reliable and are expensive to maintain. Recently, vehicle probe data collection technologies, such as toll tags, license plate matching, cellular phones, and automated vehicle identification units have been developed and some are successfully deployed. The deployed toll tag programs include TransGuide in San Antonio, Texas, (*3*), TransStar in Houston, Texas (*4*), and the New York/New Jersey TRANSMIT System (*5*).

Meanwhile, efforts have been undertaken to evaluate the quality of various travel time data sources (*6–8*). For this purpose, many different methods are introduced and currently are in use. Recently, Haghani et al. (*6, 7*) evaluated real-time speed data from cellphone-based and Global Positioning System (GPS)–based technologies. Kothuri et al. (*8*) evaluated errors in detector-based real-time travel time estimates in Portland, Oregon. They outlined their solutions for reducing the estimation errors. In all of these studies, probe vehicle runs were used as the source for ground truth.

This paper introduces the Bluetooth sensors as an effective means of freeway ground truth travel time data collection. Authors have used the Bluetooth sensors for evaluating the quality of the real-time travel time data provided to the I-95 Corridor Coalition Vehicle Probe Project (VPP) by a third party. The VPP involves public and private sectors as well as academia to collect and evaluate real-time travel time and speed data for approximately 1,500 mi of freeways and 1,000 mi of arterials in New Jersey, Pennsylvania, Delaware, Maryland, Virginia, and North Carolina. The basic concept of using Bluetooth technology for collecting ground truth travel time, data processing algorithm, challenges, and lessons learned are discussed.

BLUETOOTH SENSORS

Technology

Bluetooth is a telecommunications industry specification that defines the manner in which mobile phones, computers, personal digital assistants, car radios, and other digital devices can be easily interconnected using short-range wireless communications. One example of the use of this technology is the interconnection of a mobile phone with a wireless earpiece to permit hands-free operation. Bluetooth-enabled devices can communicate with other Bluetooth-enabled devices anywhere from 1 m to about 100 m (300 ft). This variability in the communications capability depends on the power rating of the Bluetooth sub-systems in the devices. The Bluetooth protocol uses a 48-bit electronic identifier, or tag, in each device called a Machine Access Control (MAC) address.

Bluetooth transceivers transmit their MAC ID for the purpose of identifying a device with which to communicate. This “inquiry mode” is used to establish a link with the “responding devices.” Inquiries are made by a Bluetooth transceiver, even while it is already engaged in communication with another device. The continuous nature of this process facilitates the identification of passing vehicles containing Bluetooth devices, since all equipped and activated

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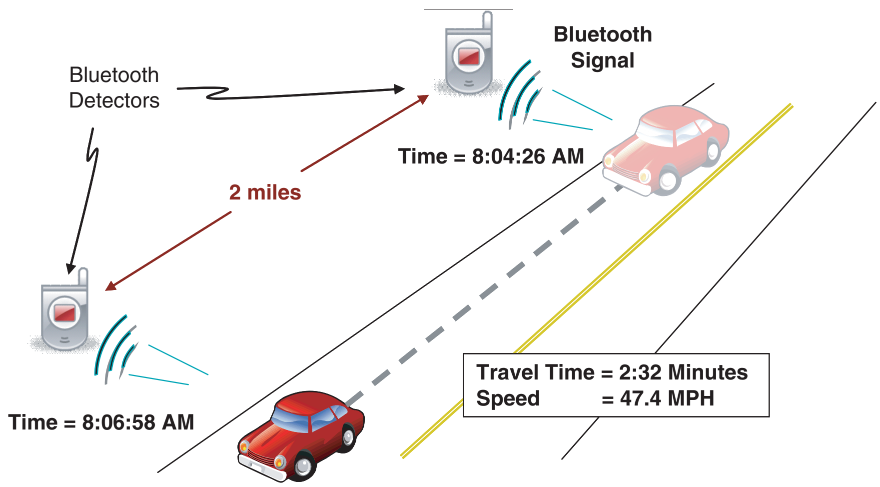

FIGURE 1 Bluetooth traffic monitoring operation concept.

devices will be transmitting inquiries as long as they have their discovery mode enabled.

In principle, the Bluetooth traffic monitoring system calculates travel times by matching public Bluetooth wireless network IDs at successive detection stations. The time difference of the ID matches provides a measure of travel time and space mean speed based on the distance between the successive stations as demonstrated in Figure 1.

Sampling Error Analysis

As it was explained, the Bluetooth receiver can pick up signals anywhere within a 300-ft radius around the sensor. Having two sensors at both ends of a freeway segment implies that in the resulting travel time samples obtained using this technology, one might expect to see errors caused by a maximum of 600-ft error in the length traveled (L). It can be shown that the maximum error in the speed estimates resulting from local inaccuracies in readings at each sensor is a function of the coverage radius of the sensor (R), the average speed of the traffic (S), error in travel time estimate ($\Delta T_{\min}$), and the actual travel time between a pair of sensors (T).

$$L = S \times T \tag{1}$$

$$L + \Delta L = (S + \Delta S) \times (T + \Delta T) \tag{2}$$

$$\Delta L = S \times \Delta T + \Delta S \times T + \Delta S \times \Delta T \tag{3}$$

Equations 1 and 2 show the relationship between the traveled length and the average speed and travel time when accurate and inaccurate values for each of these parameters are used, respectively. Equation 3 is derived by subtracting Equation 1 from Equation 2.

Equation 3 can be rearranged to obtain the statement for error in speed estimate shown in Equation 4.

$$\Delta S = \frac{\Delta L - S \times \Delta T}{T + \Delta T} \tag{4}$$

With the distance error set at its maximum possible level ($\Delta L_{\max} = 2R = 600$ ft) and with the smallest possible time error equal to the scan period of the sensor ($\Delta T_{\min} = 5$ sec), an upper bound for the error in speed estimate can be obtained. Equations 5 and 6 can be directly used to estimate the maximum error in speed estimate.

$$\Delta S \leq \frac{\Delta L_{\max} - S \times \Delta T_{\min}}{T + \Delta T_{\min}} \tag{5}$$

$$\Delta S[\text{mph}] \leq \left[\frac{600 - (1.47)(5)S[\text{mph}]}{(3{,}600)\dfrac{L[\text{mile}]}{S[\text{mph}]} + 5} \right] \div 1.47 \tag{6}$$

Figures 2 and 3 show the changes in maximum possible errors in speed estimates at different speeds and over segments from 0.5 mi to 3 mi long. It can be observed from both figures that in general the maximum error in speed estimate will be less on longer segments. In a 1-mi segment the error will be less than 2.5 mph in all different speed levels. Hence, using Bluetooth sensors on freeway segments less than 1 mi may deteriorate the quality of travel time estimates. Also, it should be noted that in Figure 2 at every given length the maximum possible error first increases with speed from 15 to 45 mph and then it starts to decrease as speed goes beyond the 45-mph threshold as shown in Figure 3. This in fact is the result of the nonlinear relationship between the maximum possible error in speed measurements and the actual speed of the observed vehicles as described by Equation 6. Therefore, in Figures 2 and 3 the curves representing the maximum possible speed errors at speed ranges below and over 45 mph are separated from each other.

These errors are the maximum for a single Bluetooth device. In practice, data from multiple Bluetooth detections are statistically combined (as described herein) to obtain highly accurate estimates of ground truth travel time. As these errors are independent and identically distributed, statistical averages tend to cancel the errors. As the segment length grows shorter, the dispersion about the mean becomes greater as a result of the errors contributions described above. It must be noted that a MAC address could be detected multiple times by each sensor in a short time period.

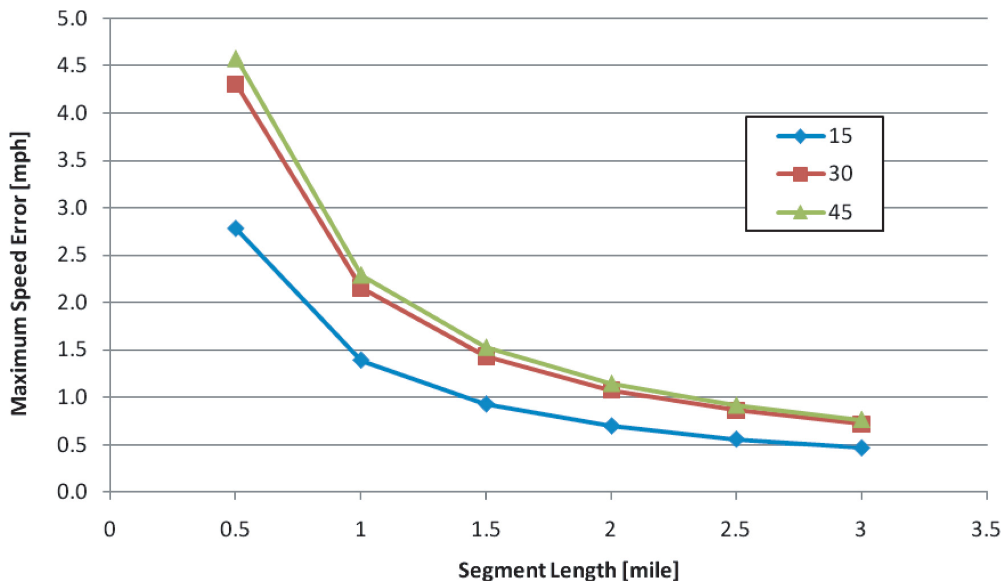

FIGURE 2 Maximum possible speed error at speeds below 45 mph and different segment lengths.

In this case only the first detection by each sensor is selected and used in matching.

Privacy Concerns

The anonymous nature of this technique is due to the use of MAC addresses as identifiers. MAC addresses are not directly associated with any specific user account (as is the case with cell phone geolocation techniques) or any specific vehicle (as is the case with deriving travel time from automated toll tags). The MAC address of a cell phone, camera, or other electronic devices, though unique, is not linked to a specific person through any type of central database, thus minimizing privacy concerns. Additionally, users concerned with privacy can set options in their device (referred to as "Discovery Mode" or "Visibility") so that the device is not detectable.

Data Collection and Filtering

Portable Bluetooth sensors, developed at the Center for Advanced Transportation Technology at the University of Maryland, have been used for data collection in this study. The portable units run on rechargeable batteries and are deployed on freeways in proximity to the roadway at the base of a sign post or guard rail post. These units are the size of a large briefcase or small carry-on and when charged

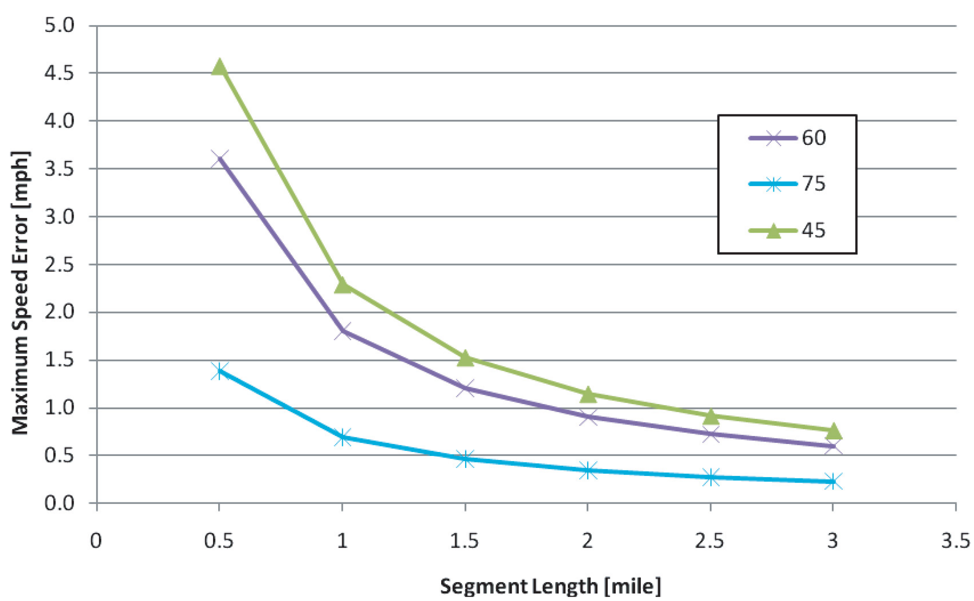

FIGURE 3 Maximum possible speed error at speeds above 45 mph and different segment lengths.

can collect data for approximately 10 to 14 days. The sensors store the MAC ID of the detected Bluetooth devices along with their detection time in a removable memory card. The collected data are downloaded to a server for processing at the end of each deployment. The MAC addresses for all devices that are detected between two consecutive sensors are matched to develop a sample of travel time for that particular segment of the roadway. Figure 4 shows data from a segment of Interstate I-95 between Washington, D.C., and Baltimore, Maryland, on July 23, 2008, between 10:00 a.m. and 12:05 p.m. Each data point represents the speed from a matched detection at each end of the segment. The figure depicts the impact on travel time as a result of an incident that began around 10:45 a.m. and was cleared at approximately 11:30 a.m. Traffic returned to normal flow around 12:00 p.m.

The reader is reminded that travel time and speed are inversely related and throughout this paper they have been used interchangeably. It should be noted that the conversion to speed is based on the measured distance between sensor locations. To establish the ground truth for travel time, individual observations must be aggregated in specified time intervals, which in this paper are assumed to be equal to 5 min. It must also be noted that the detection time of the second sensor is used as the time label for the individual observations.

It can be seen in Figure 4 that some data points obtained in the matching stage are, in fact, unacceptable for several reasons. These include matches that have the following characteristics:

- Observations with unreasonably low speeds,
- Observations in a particular time interval that are far from the average of the rest of the speeds observed in the same time interval to avoid erratic variations, and
- Presence of a small number of observations in a time interval that are not enough to establish a reliable ground truth speed.

To address each of the mentioned potential problems, a cascade of four consecutive steps was designed and sequentially applied to the pool of unfiltered observations that result from the matching step. In particular, we designed and implemented an offline filtering algorithm that is discussed in the next section.

GROUND TRUTH ESTIMATION

A four-step offline filtering algorithm is designed to extract ground truth from the pool of Bluetooth observations. The first two steps are designed to identify and discard outliers among single observations in each time interval. The third and the fourth steps are designed to exclude time intervals during which we either do not have enough observations (proxy for low-volume traffic conditions) or when there are large variations among individual observations within the time interval even if there are a sufficient number of observations to consider.

Filtering Outlier Observations

Step 1

Abnormal travel times typically indicate a match between two observations at consecutive Bluetooth sensors in which the same MAC address has been registered during different vehicle trips

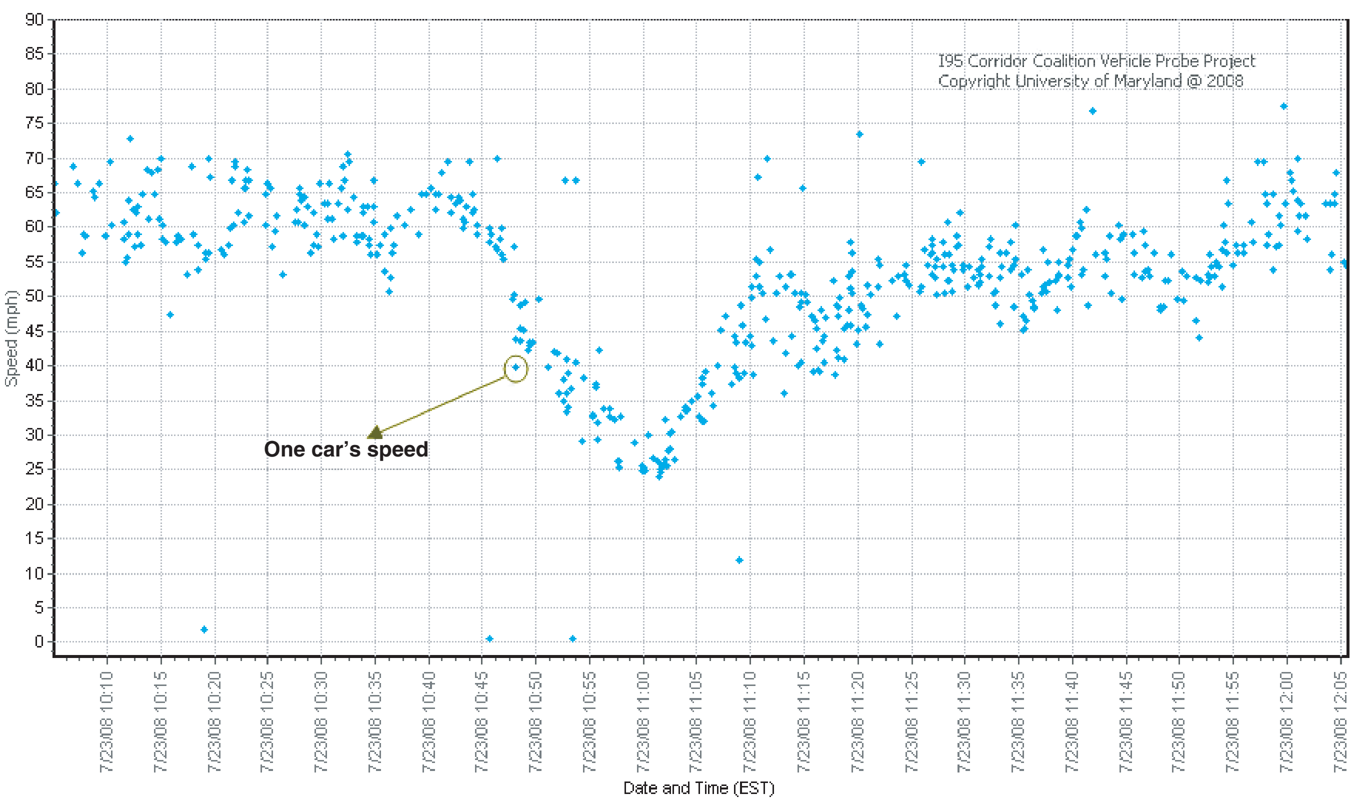

FIGURE 4 Sample Bluetooth data.

between these locations. This is mainly due to the sampling nature of the technology utilized to measure the ground truth. For example, consider the case of a multi-day travel time study in which a commuting vehicle gets detected by the first sensor on the first day, but is not detected by the second sensor. If on the second day the same vehicle is not detected by the first sensor, but is detected by the second sensor, the recorded MAC ID of Day 1 will be matched with the same MAC ID of Day 2, resulting in very large travel time. To filter out these obvious outliers, a method based on the assumption of the smooth transition of travel times is adopted. In this method, first the histogram of observed speeds in a past time window is formed. Then, a moving average of the speed frequencies is calculated which establishes the basis for identification of lower and upper cut-off points. Observations falling beyond these lower and upper limits are automatically flagged as outlier and therefore will not be part of the ensuing calculations.

Figure 5 shows the daily speed histogram for a 1.2-mi segment of I-95 near Richmond, Virginia, on November 18, 2008, for a 24-h period. This figure also shows the moving average of the speed distribution based on different window sizes. The horizontal axis shows the speed and the vertical axis shows the total number of Bluetooth observations in that speed category during the day. Equation 7 shows how the moving averages are calculated.

$$\mathrm{MA}(n) = \left\{ \frac{\sum_{i=s-(n-1)/2}^{i=s+(n-1)/2} F_i}{n} \right\} \qquad s = 1, 2, \ldots, \left\lceil \frac{S_{24\,\max} - S_{24\,\min}}{L} \right\rceil \tag{7}$$

where

$\mathrm{MA}(n)$ = moving average frequency estimate with radius $\frac{n-1}{2}$,
F_i = frequency of speed observations in speed interval i,
L = length of each speed interval in mph, and
$S_{24\,\max}$, $S_{24\,\min}$ = the maximum and the minimum speeds observed in the past 24 h, respectively.

In Figure 5, the red line shows the moving average with a radius of one, while the green, blue, and purple lines show similar moving average with radii of two, three, and four respectively. The larger the radius, the smoother the moving average curves, but there is a tradeoff between the smoothness and the resolution of the fluctuations in the trend. The tests performed on various speed data sets show that a moving average with a radius of four produces the best results. After creating the histograms and calculating the moving average, the algorithm identifies the peak in the moving average and looks for the first speed category on either side that violates the expected downtrend, that is, has a larger smoothed frequency in comparison with the previously examined speed category that is closer to the one with maximum smoothed frequency. Figure 6 shows the outcome of the first step when applied to the multi-day speed data obtained for the same segment in central Virginia. The horizontal lines in this figure indicate the cut-off speeds beyond which data points will be considered as outlier.

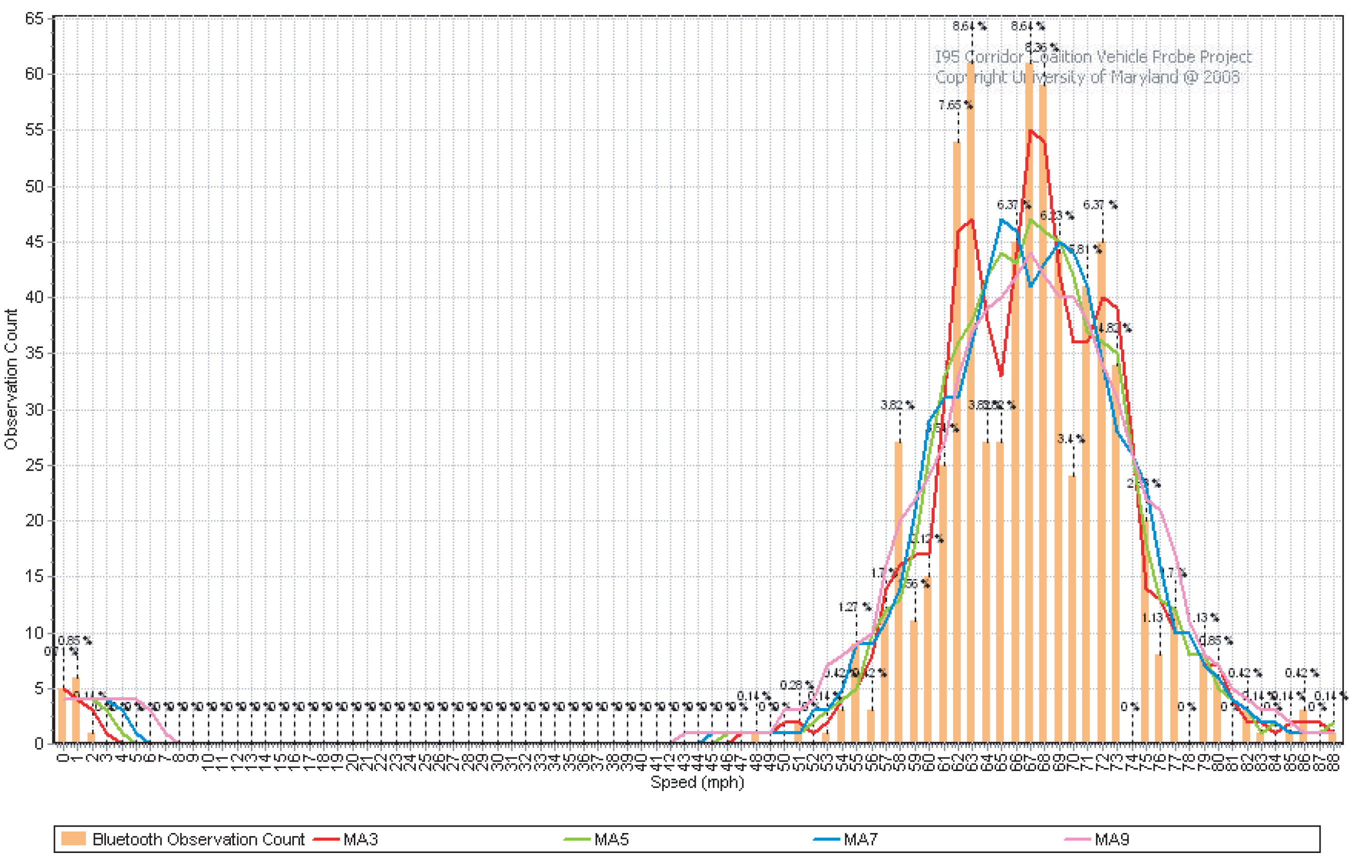

FIGURE 5 Speed histogram on southbound I-95, Exits 83 to 82, on November 18, 2008.

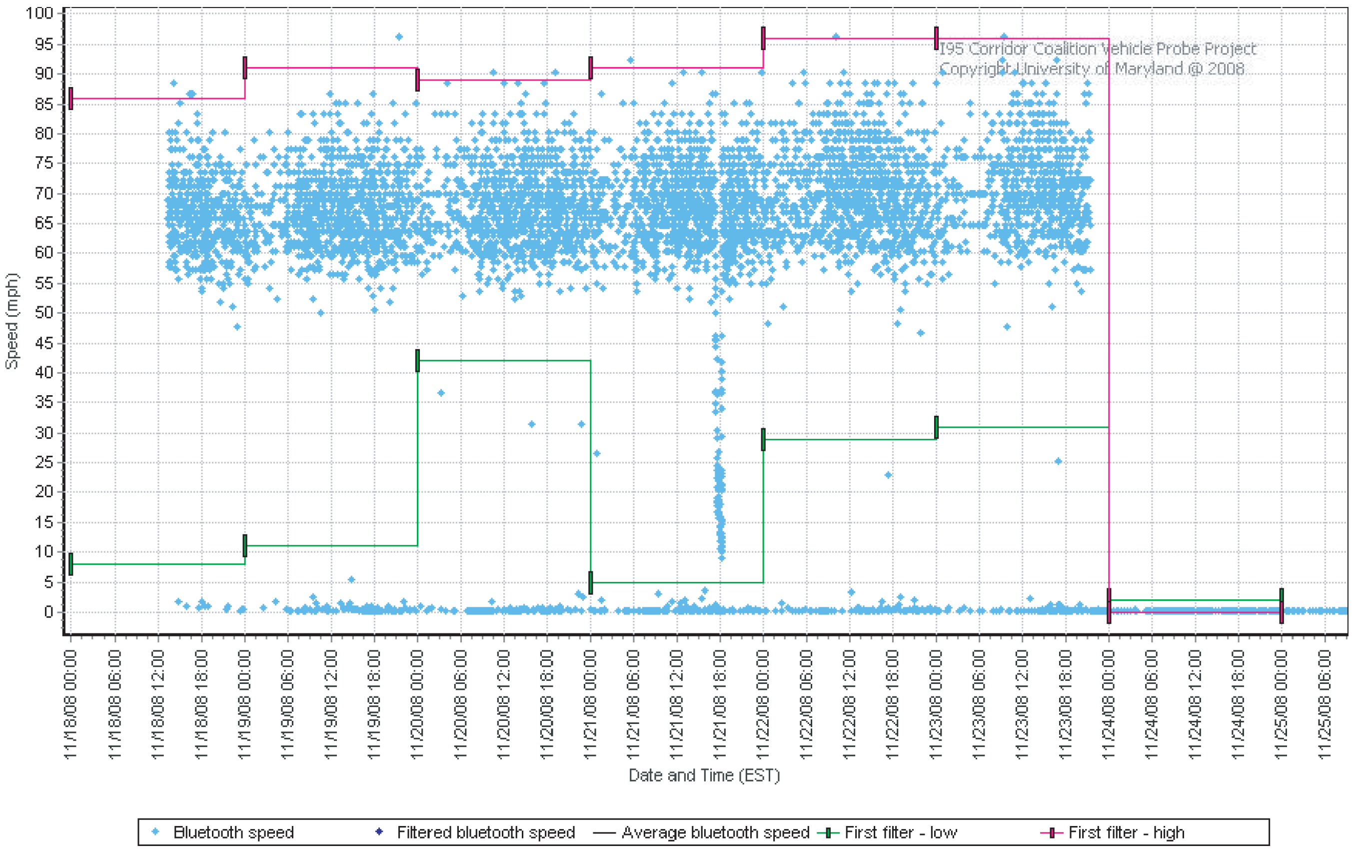

FIGURE 6 Suggested daily validity range for a sample traffic message channel.

Step 2

In this step the variations in speed observations are considered to identify additional outlier speed observations. To that end, all observations corresponding to each of the time intervals for which we have Bluetooth observations are identified and the average and standard deviations of the speeds in those time intervals are calculated. Observations that correspond to speeds falling within ±1.5 times the standard deviation are kept and the rest are discarded. Assuming a normal distribution for the observations around the mean, this approach translates into keeping nearly 87% of the data. At this point the number of observations, the averages, and the standard deviations of the speed in all time intervals for which we have Bluetooth data are updated and kept ready for future use in the analysis.

Filtering Undersampled and Erratic Time Intervals

Step 3

This step is designed to exclude all time intervals with a small number of observations that will render ground truth estimation in those time intervals impossible. Similarly, this step can serve as a surrogate method for identification of time intervals with extremely low traffic volumes [typically fewer than 500 vehicles per hour (VPH)]. Generally speaking, this step is designed to ensure that the ground truth speed estimations are reliable under low sampling rate conditions. Equation 8 specifies the minimum number of required observations in each time interval.

$$n_{\min} = \frac{V_{\text{thresh}} \times T \times \text{PSR}}{60} \tag{8}$$

where

- $n_{\min}$ = minimum number of observations required per time interval,
- V_{thresh} = threshold hourly volume of traffic below which ground truth estimation with low sampling rate may not be reliable (VPH),
- T = length of time interval for which estimation is being performed (min), and
- PSR = percentage of sampling rate that can be reasonably sustained throughout the analysis period.

Various tests suggest that the sampling rate obtained by using Bluetooth sensors, in an AVI setting, will be between 2% and 5% of the traffic volume (*9*). Setting the sampling rate at its maximum, we can obtain the minimum expected number of observations that resembles a certain traffic flow in a given time interval. This is obviously a very conservative estimate of the minimum number of required observations in a given time interval. Therefore, according to the abovementioned default values for each parameter, every 5-min time interval that has fewer than three observations will be excluded from further consideration.

Step 4

Finally, to ensure that the variability among speed observations inside a given time interval is within a reasonable level, the coefficient of variations (COVs) of Bluetooth speed observations in each time interval that survive the previous three steps is estimated, then time intervals that have a COV greater than 1 are excluded, and their corresponding observations are discarded from further consideration in the ground truth estimation process. A sample graph illustrating the effect of applying these steps on Bluetooth sensor data for a traffic message channel (TMC) path is presented in Figure 7. TMC is an industry adopted standard for location referencing (*10*). In this graph, the light blue dots represent the Bluetooth observations that are kept in the analysis, the dark blue dots are those observations that are discarded, and the black line represents the harmonic mean of the Bluetooth speed observations in consecutive 5-min time intervals. A detailed comparison between the proposed filter and an alternative method by Dion and Rakha (*11*) can be found in Sadabadi et al. (*12*).

COMPARISON WITH FLOATING CAR DATA

To verify the accuracy of speed estimates obtained through the use of Bluetooth technology, we compared them with those obtained from data produced by floating car runs. In total, 9 days of drive testing were carried out in Maryland and Northern Virginia during morning and afternoon rush hours where Bluetooth sensors were simultaneously deployed. The actual drive tests were performed by Motion Maps, LLC, during which a second-by-second log of the vehicle locations was recorded using a GPS device that was carried in the vehicle. These drive tests were conducted with the primary intention of providing a basis for comparison with Bluetooth technology to ensure that the new technology is accurately providing the ground truth travel times and speeds. The resulting GPS logs were converted to a format readable by ArcGIS and were processed to extract the travel time on the target segments.

To add more insight to the analysis, four speed categories were defined: (1) speeds below 30 mph; (2) speeds between 30 and 45 mph; (3) speeds between 45 and 60 mph; and (4) speeds of 60 mph and above. We conducted a statistical hypothesis test (Equation 9) in each speed bin to understand whether the mean speeds obtained from the Bluetooth sensor data were significantly different from those obtained from floating car data. The null hypotheses in these statistical tests were that the Bluetooth mean speeds (μ_{BT}) are not significantly different from the floating car mean speeds (μ_{FC}) in each speed bin.

$$\begin{cases} H_0: \mu_{BT} = \mu_{FC} \\ H_1: \mu_{BT} \neq \mu_{FC} \end{cases} \tag{9}$$

The statistic that was used in this test is given as

$$Z = \frac{(\mu_{FC} - \mu_{BT}) - 0}{\sigma_{FC-BT}} \tag{10}$$

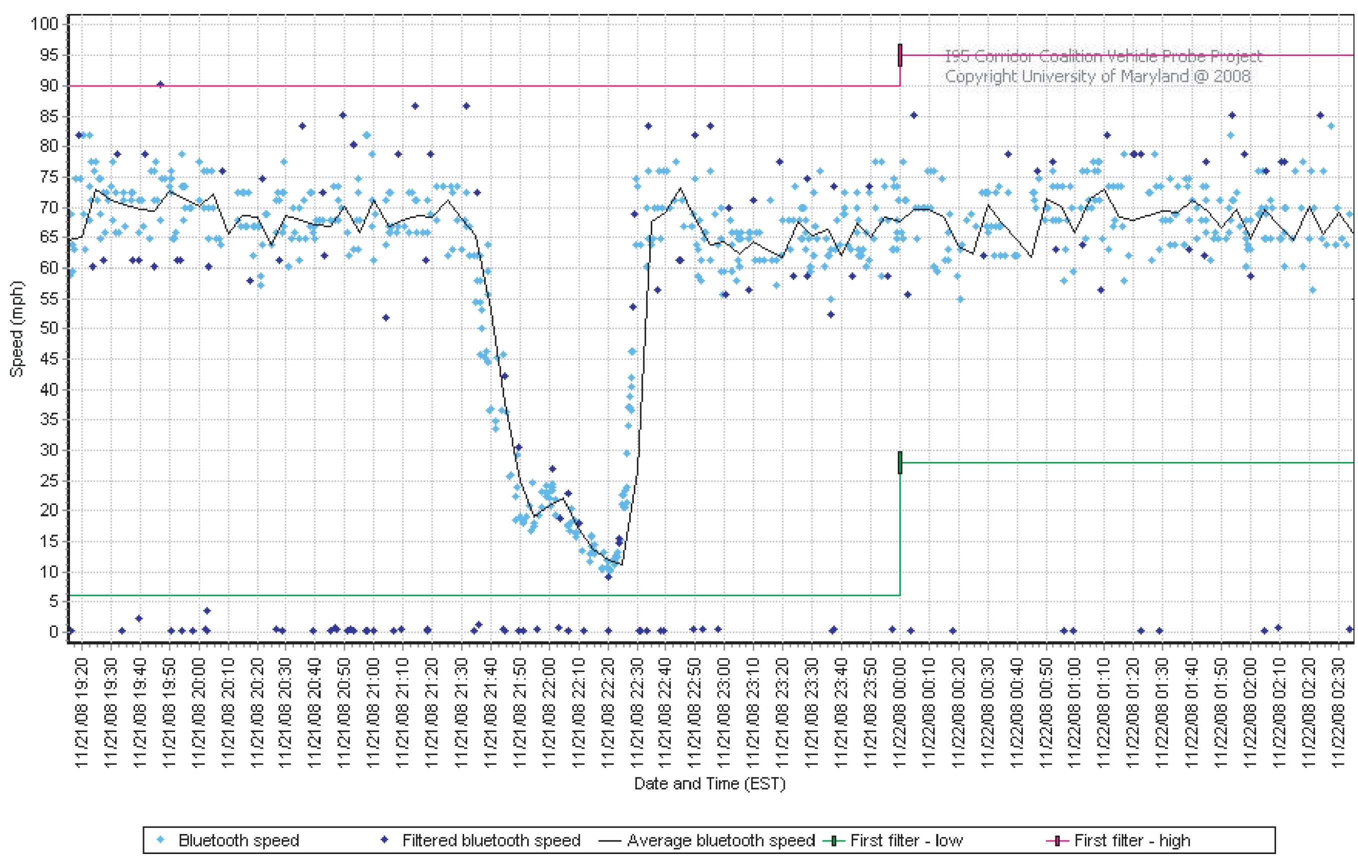

FIGURE 7 Sample results of the offline ground truth speed estimation process.

TABLE 1 Hypothesis Test for Similarity Between Means of Bluetooth and Drive Test Speeds

Freeway	Speed Bin	Observations	Bluetooth Mean	Bluetooth SD	Floating Car Mean	Floating Car SD	Speed Error Bias	Average Absolute Speed Error	Null Hypothesis Rejected?
All	0–30	78	23.3	5.8	22.7	5.7	–0.6	2.6	N
	30–45	94	37.8	8.0	37.9	4.3	0.0	4.7	N
	45–60	241	56.8	6.8	54.8	3.7	–2.1	5.1	Y
	60+	359	63.3	5.2	65.6	3.7	2.4	4.8	Y
≥1 mile	0–30	47	23.2	6.4	22.5	5.8	–0.7	2.3	N
	30–45	72	38.0	7.0	38.0	4.1	0.0	4.0	N
	45–60	158	57.5	5.8	54.4	3.8	–3.1	4.9	Y
	60+	223	63.8	4.6	65.2	3.2	1.5	3.9	Y
<1 mile	0–30	31	23.5	4.9	23.0	5.5	–0.5	3.1	N
	30–45	22	37.3	10.7	37.4	4.8	0.1	6.9	N
	45–60	83	55.6	8.2	55.5	3.6	–0.1	5.5	N
	60+	136	62.4	5.9	66.3	4.3	3.9	6.4	Y

in which σ_{FC-BT} is the standard deviation of the difference between the floating car and the Bluetooth speed data in each speed bin and can be derived using the following formula:

$$\sigma_{FC-BT} = \sqrt{\frac{\sigma_{BT}^2}{N_{BT}} + \frac{\sigma_{FC}^2}{N_{FC}}} \tag{11}$$

where

- σ_{BT} = standard deviation of the Bluetooth speeds in a speed bin,
- σ_{FC} = standard deviation of the floating car speeds in a speed bin,
- N_{BT} = number of Bluetooth speed observations in a speed bin, and
- N_{FC} = number of floating car speed observations in a speed bin.

Results of the z-tests that were performed in these hypotheses testing are reported for each speed bin in Table 1. The results are shown for all freeway segments, those that are greater than 1 mi, and those that are less than 1 mi. In freeway segments greater than 1 mi that are the main focus of this study, the null hypothesis could not be rejected at extremely high levels of significance for the two lower speed bins. However, in the two higher speed bins the null hypothesis is rejected. These statistical tests show that, at least at low speeds, the Bluetooth sensor speed data are a good representative of the ground truth. The rejection of the hypotheses at the higher speed levels may be attributed to the fact that the floating car drivers had much more flexibility in traveling at higher speeds than the average speed of traffic. Given that the number of drivers on each segment was limited to one or at most two, the driver behavior and driving habits may have impacted the floating car speed data. In addition, the number of data points obtained from floating car runs is smaller in the top speed bins as a result of higher speeds and thus more floating car runs are needed to test the hypothesis in those bins. Authors have also compared the Bluetooth data with vehicle probe data provided to I-95 corridor coalition by a third party and the results show that the Bluetooth sensors provide an acceptable measure of travel time in the target areas.

SAMPLING RATE

The Bluetooth traffic detectors sample only a fraction of the vehicles in the traffic stream. To approximate the sampling ratio of the new technology, actual traffic volume in a roadway segment is needed. Traffic volume data are available where other sources of traffic surveillance systems are in place. Using Wavetronix and loop detectors data in Maryland and Delaware, Sharifi et al. (*9*) report that the average Bluetooth hourly sampling rate is between 2.0% and 3.4%.

SUMMARY AND CONCLUSION

One of the most important traffic parameters in intelligent transportation system applications and managing the traffic operations is travel time. For evaluating the quality of highway travel time information generated by traffic surveillance systems, floating car data have been used as a proxy for the ground truth. This paper introduces a new travel time data collection methodology based on Bluetooth technology, which is capable of sampling travel time of vehicles in the traffic stream in order to establish the ground truth for evaluation. A four-step offline filtering algorithm is used to eliminate the outlier observations. The filtering scheme has been applied on numerous data sets collected in five states. The performance of the filtering system has been compared with alternative algorithms in another paper and has proven to be a robust and effective method for processing the travel times collected by the Bluetooth sensors. Drive test data were used to measure the quality of travel time data collected by the Bluetooth sensors, and the results show that the ground truth provided by the new sensors is not significantly different from the actual travel times.

In summary, the new technology is capable of providing reliable and high-quality ground truth travel time data on highways. On average, the Bluetooth sensors sample between 2.0% and 3.4% of the vehicles in the traffic stream. So far the authors have collected more than 13,300 h worth of travel time data using the Bluetooth sensors. As a summary of the lessons learned it must be noted that lane-by-lane data are not available using this technology, so it is not appropriate for facilities with managed lanes in its current form. For best performance the sensors must be deployed on the highway segments that are at least 1 mi long. Since the sensors are capable of detecting Bluetooth signals within a 300-ft radius, picking highway segments that are not very close to parallel arterials is recommended. Also, when there is a mix of express and local lanes, the travel data of the two sets will be mixed and are difficult to distinguish. Having a rest area, gas station, toll plaza, or similar facilities between two sensors may also introduce some significant noise to the travel time observations since some vehicles may show larger than normal travel times as a result of using such facilities.

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