Comparative Evaluation of Technologies and Data Sources to Capture Travel Time at Section-Level on Urban Streets

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# Comparative Evaluation of Technologies and Data Sources to Capture Travel Time at Section-Level on Urban Streets

**by Srinivas S. Pulugurtha, Rahul C. Pinnamaneni, Venkata R. Duddu, R.M. Zahid Reza**

*This paper focuses on capturing section-level (a signalized intersection to the next) travel times on urban street segments using Bluetooth detectors as well as from INRIX data source and comparing it with manual and Global Positioning System (GPS) floating test car methods (test car with a trained technician and GPS unit to capture travel time between selected points) for each travel time run. Results obtained indicate that section-level travel time data captured using Bluetooth detectors on urban street segments are less accurate and not dependable when compared with GPS unit and INRIX. The role of various on-network characteristics on the percentage difference in travel time from GPS unit, INRIX, and Bluetooth detectors was also examined.*

## INTRODUCTION

Travel demand has been increasing with the development of modern civilization, growth in population and need for more travel. The subsequent effect of this increasing travel demand is overcrowding or congestion of the existing transportation network. Addressing congestion has been one of the primary goals of transportation network managers, planners, and engineers. The Federal Highway Administration (FHWA) recommends using the travel time experienced by users to quantify the effect of congestion (AASHTO 2008). Travel time is also a useful measure for motorists or network users to make route choice, mode choice, or departure time decisions.

The most conventional means of collecting travel time data is using a floating test car method. In the floating test car method, a test car is driven by a driver along the study corridor at the speed of traffic. A trained technician in the test car notes down time and position of the test car at regular intervals to calculate travel time between selected points. The sample size from this method is typically very limited. It is also a tedious, expensive, and time-consuming data collection method.

Travel times are also captured using sensors that emit radio waves or a laser beam by installing magnetic loops in pavement that detect the presence of vehicles and by automatically matching license plates through recognition systems, vehicle identification tag reader systems, and video surveillance cameras (Haghani et al. 2010; Vo 2011). A few other means of collecting travel time data include cell phone tracking, Global Positioning System (GPS) equipped floating test cars, and transit buses with GPS or automatic vehicle location units (Kim et al. 2011).

Besides the aforementioned technologies, Bluetooth detectors are an alternative and inexpensive means of accurately estimating travel time (Vo 2011). Bluetooth detectors compute the travel time based on Media Access Control (MAC) addresses (a unique identification number for each Bluetooth enabled device) of Bluetooth enabled devices in the vehicles. In recent years, private sources of data pertaining to travel time and average speed, such as INRIX, Tom Tom, and HERE, have emerged as a valuable source of travel time information. The sources of data such as INRIX provide real-time, historical, predictive traffic services, and incident data on freeways, highways, and secondary roadways, including arterial and side streets of North America and Europe (INRIX 2013). Data provided by the private sources are captured using GPS unit equipped vehicles, from mobile devices, sensors, or other electronic mechanisms. The archived traffic data are used to

facilitate traffic management, traveler information, and planning activities for both local and long distance travelers.

The applicability of INRIX and Bluetooth detectors to accurately collect travel time on all types of facilities (in particular, urban arterial streets) is still unclear though their use has rapidly increased in recent years. The key objectives of this research, therefore, are: 1) to collect and evaluate the accuracy of estimated section-level travel time data on urban streets from a GPS equipped floating test car, INRIX and Bluetooth detectors and compare them with data obtained using manual floating test car method, 2) research and compare the ability to capture temporal variations in travel time from the selected technologies/data sources of travel time, 3) examine the correlation between travel times collected manually and using various technologies/data sources, and 4) recommend the best technology or the best combination of technologies/data sources to capture travel time on urban streets. The data collected manually are considered as the most accurate in this research (as it does not involve any technology in collecting the travel time data). It is collected for each travel time run by trained technicians exactly at the locations where travel time from other technologies and data sources are captured. Also, the trained technicians made sure there were no other factors (example, incidents) influencing the results.

## LITERATURE REVIEW

Methods and technologies such as using test (or probe) vehicles, installing magnetic loops or sensors at intersections, automatically matching license plate numbers, and electronically reading vehicle identification numbers (say, at toll booths) were used to collect travel time data on freeways and arterial streets in the past (Vo 2011). However, all these methods have intrinsic disadvantages. For instance, capital and operating costs of license plate matching are low, but this method cannot provide real-time travel time or incident data (Turner 1998). Travel times by matching vehicle license plate or tag numbers at toll booths can acquire a larger sample size than test vehicle studies. However, it requires complex planning and implementation (Courage et al. 1998).

Past studies, such as those performed by Quiroga and Bullock (1999), Chu (2013), and Bel-O-Mar Regional Council (2013), show that the GPS floating test car method is an efficient method to collect accurate travel time data. Fewer staff requirements, minimal human error, detailed data collection opportunity, good accuracy, and automatic location identification procedures are some of the many benefits of using a GPS floating test car or vehicle for travel time data collection. Signal loss, retrieving the base map, necessary and updated equipment identification, limited sample, and high cost per unit of data are some of the drawbacks of this data collection method (Turner 1998).

Bluetooth detectors can be set up on the side of a street to track users' Bluetooth enabled device through its electronic identifier (Wasson et al. 2008) and collect data without causing any interruption to traffic flow. Moreover, the cost of the travel time data point from Bluetooth detectors can be as low as 1/300th of the cost of comparable floating test car data (Traffic Technology International 2013). The Bluetooth detectors are easy to install, efficient, and cost-effective considering unitary price and the number of units needed to collect data (Rivey 2013). The type of antenna and its placement affects the performance of Bluetooth detectors. Vertically polarized antennas that radiate a radio frequency signal in all directions (Porter et al. 2010), placing two omni-directional antennas (that radiate or intercept a radio frequency signal equally well in all horizontal directions) at the same location on opposite sides of the street (Malinovskiy et al. 2011), and placing the antenna at 8- to 10-feet height (Brennan Jr. et al. 2010; Vo et al. 2011; Robert et al. 2012) increases the number of Bluetooth enabled devices detected and data quality. Findings from Schneider et al. (2010) and Vo et al. (2011) indicate that placing the detectors at one to two miles apart on arterial streets would yield accurate travel time estimates. The travel time, obtained by recording MAC addresses at upstream and downstream Bluetooth detector locations (Martchouk et al. 2011), are of good quality and

better than floating test car and license plate recognition system-based data gathered along freeways (Puckett and Vickich 2010; Haghani et al. 2010). While Quayle et al. (2010) and Sidhaye (2013) showed that larger datasets from the Bluetooth detector can more effectively capture performance characteristics of the arterial street than the traditional GPS floating test car method, Wasson et al. (2008) reported that data from arterial streets showed a significantly larger variance compared with data from the freeways due to the effect of traffic signals.

Private data sources such as INRIX (2013) provide a variety of mobile applications and Internet services pertaining to traffic. The real-time data from actual vehicles and mobile devices traveling through the street network are captured to provide a comprehensive, consistent, and timely measure of traffic congestion nationwide. The data are used to conduct studies at a macroscopic level. The typical INRIX data segment lengths for freeways are 1-3 miles in urban areas and 3-10 miles in rural areas. For arterial streets, typical INRIX data segment lengths are 0.5-3 miles in urban areas and 2-5 miles in rural areas (Turner 1998).

In the past, research was conducted to validate travel times obtained from various technologies/ data sources such as GPS unit, INRIX, Bluetooth detectors, etc. based on corridor-level analysis and not based on section-level analysis. The characteristics of a corridor vary from one section to another section along a segment, thus affecting the travel time. This effect can be minimized only by conducting section-level analysis. Also, previous research has shown that Bluetooth detectors can be effectively used for travel time studies on freeways. Their effectiveness as a source of travel time data for urban street segments has not been very clear from the past literature. This paper focuses on a comparison of section-level run-by-run travel time data for urban streets and to address the aforementioned limitations.

## METHODOLOGY

Five segments on major urban streets in the city of Charlotte, North Carolina, were selected as the study segments to collect data and compare the effectiveness of the manual floating test car method, GPS floating test car method, INRIX, and Bluetooth detectors in capturing travel time information. The selected urban streets are connected to the Uptown area. This is the central business district (CBD) with major commercial and industrial zones. Table 1 summarizes the characteristics of each selected urban street segment.

Manual travel time data were collected using the floating test car method along the selected urban street segments. For manual data collection, travel time data collection sheets were prepared for each study segment, for both inbound and outbound direction. Each paper form contained information related to intersections along each segment where the arrival times were noted. The distance from one intersection to next intersection (or location) is defined as a section.

**Table 1: Characteristics of Selected Urban Street Segments**

| Route Number | Route Name | # Lanes | Annual Average Daily Traffic (AADT) | Speed Limit (mph) |
|---|---|---|---|---|
| 11 | N Tryon St | 3 | 25,000-30,000 | 45 |
| 12 | South Blvd | 2 | 20,000-25,000 | 40 |
| 14 | Providence Rd | 2 | 30,000-40,000 | 45 |
| 20 | Queens Rd | 2 | 14,000-20,000 | 35 |
| 22 | N Graham St | 2 | 14,000-20,000 | 45 |

In addition, a GPS unit was placed in the floating test car. An off-the-shelf software package (PC-Travel) was used to process travel time data between the selected intersections of all five urban street segments. The computed details were exported as an Excel file.

Data were collected for two days along each study segment—from 7:00–9:00 A.M., 11:00 A.M.–1:00 P.M., 4:00–6:00 P.M. on day 1, and 7:00–10:00 A.M. and 3:00–6:00 P.M. on day 2. Different time periods were selected to capture the difference in travel time and examine the effectiveness of the selected technologies/data sources in collecting travel time data by time period.

Overall, three trained technicians participated in the field data collection during each travel time run. The first person noted the arrival time on the sheet manually; the second person captured data at the same location using a GPS unit, whereas the third person drove the vehicle at the speed of traffic (overtake as many vehicles that passed the test car). Six to 10 travel time runs (in each travel direction) based on traffic conditions were captured during each time period.

**Data Collection Using Bluetooth Detectors**

Six Bluetooth detectors were provided with Location ID (identifier referring to the intersection) and Group ID (identifier referring to the urban street segment) in addition to name, description, and owner information. The data from Bluetooth detectors were collected in both encrypted and plain text format.

The Bluetooth detectors were installed at selected signalized intersections along each study segment for easy access of power from the signal controller cabinet. A majority of signal control cabinets are close to traffic heading toward the Uptown area. As the objective was to compare travel time from different technologies/data sources, the signalized intersections for the installation of Bluetooth detectors were selected in such a way that the position of Traffic Message Channel (TMC) codes (points where INRIX data are available) matched with the position of these signalized intersections. Manual and GPS data were also gathered at the same points. The mounted height of the antenna to capture data using Bluetooth detectors varied between 10-12 feet along the selected urban streets (based on recommendations from past research as discussed in the Literature Review section). Data were collected using the Bluetooth detectors, continuously for at least 48 hours for each section along each study segment.

After uninstalling the Bluetooth detectors, the raw data were uploaded and processed using the Acyclica Analyzer website (https://cr.acyclica.com/). From the same website, travel times were noted by the travel time run and by time of the day with reference to the manual times obtained from the floating test car method for each section. Travel times for each section were tabulated separately for all the days the Bluetooth detector was installed. By selecting the required time period and direction of travel time run, the average travel time from all the detected Bluetooth enabled devices during that particular time period was noted.

The raw data may include outliers such as Bluetooth detections from bicyclists, pedestrians, transit system users, or customers who stopped at nearby stores/restaurants (includes coffee shops, gas stations, etc.). For an accurate estimation of travel times from Bluetooth detectors (to overcome the effect of data outliers), a filtering technique based on minimum and maximum speeds on a section was developed and incorporated. Maximum and minimum travel times were computed for each section based on these minimum and maximum speeds. The raw data with information for each detected Bluetooth enabled device were processed to then remove outliers for each section.The number of outliers is very small (at most two in a data collection hour for a section).

The default filtering procedure captures all Bluetooth enabled devices during a travel time run period. This could lead to erroneous travel time estimates. Therefore, the use of ±1.5 min, ±2.5 min, and ±5 min as data filter ranges for each travel time run was examined. These data filter ranges were applied for each travel time run. For example, if a manual run starts at 8:00:00 A.M. and ends at 8:03:00 A.M. on a particular section and data filter range is ±1.5 min, the samples (Bluetooth enabled

devices) that are detected by the Bluetooth detector from 7:58:30 A.M. to 8:01:30 A.M. at the start and 8:01:30 A.M. to 8:04:30 A.M. at the end were taken into consideration for that particular travel time run. Based on these data filter ranges, the average travel times for each travel time run were estimated from Bluetooth detectors installed along the study segment and compared with travel time from other technologies/data sources.

### INRIX Data Collection

INRIX data were obtained for the same days on which manual and GPS data were collected, for each selected urban street segment through the web interface.

The data from INRIX were also available for two complete days. For better comparison of technologies / data sources for travel time data collection, the travel time from INRIX was extracted for each travel time run on each data collection day. Like in the case of Bluetooth detectors, data were also filtered using ±1.5 min, ±2.5 min, and ±5 min as data filter range for each travel run.

## RESULTS

As mentioned previously, data were collected and gathered along five urban street segments, for two days, during morning (AM), mid-day (Mid-day) and evening (PM) time periods.

Table 2 shows the sample sizes based on time-of-the-day. For INRIX, the sample sizes shown are not the actual counts but are equivalent to the travel time runs for which data were captured. In the case of Bluetooth detectors, the sample sizes are based on the number of detections summed up for all the sections.

The number of detections from Bluetooth detectors is lower during the morning time period and higher during mid-day and evening time periods. This may be because of higher noise levels/ disturbance, traffic signals, weather and environmental conditions, or varying traffic volumes during different time periods.

**Table 2: Sample Size by Time-of-the-Day**

| Technology/Source | | AM | Mid-day | PM |
|---|---|---|---|---|
| Manual/GPS | | 332 | 140 | 296 |
| INRIX | | 332 | 140 | 296 |
| Bluetooth (# of Detections) | Default filtering | 301 | 3,936 | 6,454 |
| | ±1.5 Min Filter | 63 | 704 | 1,222 |
| | ±2.5 Min Filter | 83 | 933 | 1,550 |
| | ±5.0 Min Filter | 122 | 1,458 | 2,426 |

### Comparison of Travel Time Estimates by Study Segment and Time-of-the-Day

Table 3 shows travel times collected manually and the percentage difference observed from the GPS unit, INRIX, and Bluetooth detectors during mid-day and evening time periods on day 1 along South Blvd (inbound) study sections. It can be noticed from Table 3 that travel times from the GPS are very close to those collected manually except for Run 1 at 4:46 P.M. This is because the GPS travel times have been collected from the same floating test car that was used for the manual data collection. The absolute value of the percentage difference in travel time from Bluetooth detectors are observed to be greater than INRIX for 9 out of the 24 travel time runs on sections along South Blvd (Table 3).

To better assist in comparing the results, the absolute value of percentage difference in travel time from the GPS unit, INRIX, and Bluetooth detectors when compared to the manual floating test

car were categorized into six different percentage range categories (0-10, 10-20, 20-30, 30-40, 40-50, and >50). The percent of travel time runs that fall in each category were summarized for each study segment. Figure 1 shows the percent of travel time runs by range of percentage difference in travel times (absolute values) for selected technologies/data sources and study segments during the morning time period.

The absolute value of percentage difference between GPS and manual travel time is less than 10% for all sections along the five segments during the morning time period (Figure 1). The figure also reveals that travel time readings from INRIX and Bluetooth detectors differ from manually collected data. The absolute value of percentage difference is observed to be reasonably high in some cases. For instance, out of the total 408 travel time runs gathered along N Graham St, more than 100 travel time runs have absolute value of percentage difference in travel time greater than 70% for the Bluetooth detectors.

**Table 3: Percentage Difference in Travel Time by Travel Time Run Compared to Manual Travel Times During Mid-day and Evening Time Periods Along South Blvd**

| Section | Manual (Sec) | GPS (%) | INRIX (%) | Bluetooth (%) | Manual (Sec) | GPS (%) | INRIX (%) | Bluetooth (%) | Manual (Sec) | GPS (%) | INRIX (%) | Bluetooth (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5/29/13 | Run 1 (Time) 11:15 AM | | | | Run 2 (Time) 11:49 AM | | | | Run 3 (Time) 12:17 PM | | | |
| 1 | 82.5 | 0.6 | 8.7 | 49.0 | 91.1 | 1.0 | 11.8 | -18.3 | 90.0 | 1.1 | 31.3 | -27.3 |
| 2 | 128.3 | 0.6 | 2.0 | 72.1 | 115.8 | 0.2 | 15.0 | 120.3 | 137.5 | 0.4 | -7.1 | 77.7 |
| 3 | 323.4 | 0.2 | -40.5 | -29.5 | 323.8 | 0.1 | -35.0 | -22.3 | 246.7 | 0.5 | -14.6 | 14.2 |
| 4 | 126.6 | 0.3 | -24.2 | 7.7 | 123.9 | 0.9 | -17.2 | 40.0 | 119.8 | -2.3 | -22.4 | 50.0 |
| 5/29/13 | Run 1 (Time) 4:46 PM | | | | Run 2 (Time) 5:28 PM | | | | Run 3 (Time) 6:20 PM | | | |
| 1 | 150.5 | 16.3 | -36.5 | -5.3 | 184.0 | -3.8 | -49.7 | 1.8 | 173.0 | 1.2 | -46.5 | 21.7 |
| 2 | 146.3 | 36.7 | 5.0 | 66.6 | 225.8 | -0.4 | -22.9 | 4.7 | 211.1 | 0.4 | -32.4 | 57.1 |
| 3 | 244.2 | -40.2 | -11.1 | -6.1 | 319.8 | 0.1 | -46.0 | -22.2 | 380.2 | -0.1 | -31.8 | -28.9 |
| 4 | 157.9 | -43.6 | -16.8 | -1.3 | 163.1 | 0.6 | -37.1 | -0.7 | 146.5 | 0.3 | -50.9 | -5.0 |

To account for the effect of traffic and examine the performance over time, the average travel time considering all travel time runs are computed for each technology/data source by time period. The percentage difference based on these averages are then computed and summarized by time period (Figure 2). In the figure, AM, MD, and PM indicate morning, mid-day, and evening time periods, respectively. The percentage differences shown in Figure 2 for GPS unit, INRIX, and Bluetooth detectors are in comparison to manually collected travel times. N Tryon St, South Blvd, and Providence Rd showed higher percentage difference during the evening time period (almost -44%, -27%, and -24%, respectively) in the case of INRIX data. The percentage differences for INRIX and Bluetooth detectors are reasonably close to each other irrespective of the time of day along Queens Rd. For N Graham St, the percentage difference for Bluetooth detectors varied by 200%, 240%, and 94% during morning, mid-day, and evening time periods, respectively.

The inaccurate travel time estimates from Bluetooth detectors could be due to outliers from the default filtering procedure. Therefore, a micro-level analysis was done by filtering the raw data obtained from the Bluetooth detectors and compared to manually collected travel times. Based on the start and end times of the travel time run, data filter ranges of ±1.5 min, ± 2.5 min, and ±5 min were tested to perform this micro-level analysis and compute absolute value of percentage differences in travel times.

Figure 3 shows the percent of travel time runs by range of percentage difference in travel times (absolute values) from Bluetooth detectors using various data filter ranges. Out of the three data filter ranges, ±1.5 min data filter range was observed to yield a reasonable sample size (though lowest of the three considered data filter ranges, as can be noted from Table 2). However, the sum of the total percent of travel time runs for ranges of percentage difference ≤40 is highest for ±1.5

min data filter range for all the five study segments. As an example, the total percent of travel time runs for N Tryon St is [(25.8% for 0-10 range of percentage difference) + (19.6% for 10-20 range of percentage difference) + (13.6% for 20-30 range of percentage difference) + (10.6% for 30-40 range of percentage difference)] = 69.6% for ≤40 range of percentage difference in the case of ±1.5 min data filter range (compared to ~65% and ~64% for ±2.5 min data filter range and ±5 min data filter range, respectively). This indicates that relatively more accurate results can be obtained using ±1.5 min data filter range.

**Figure 1: Percent of Travel Time Runs by Absolute Value of Percentage Difference in Travel Time for Different Segments During Morning Time Period**

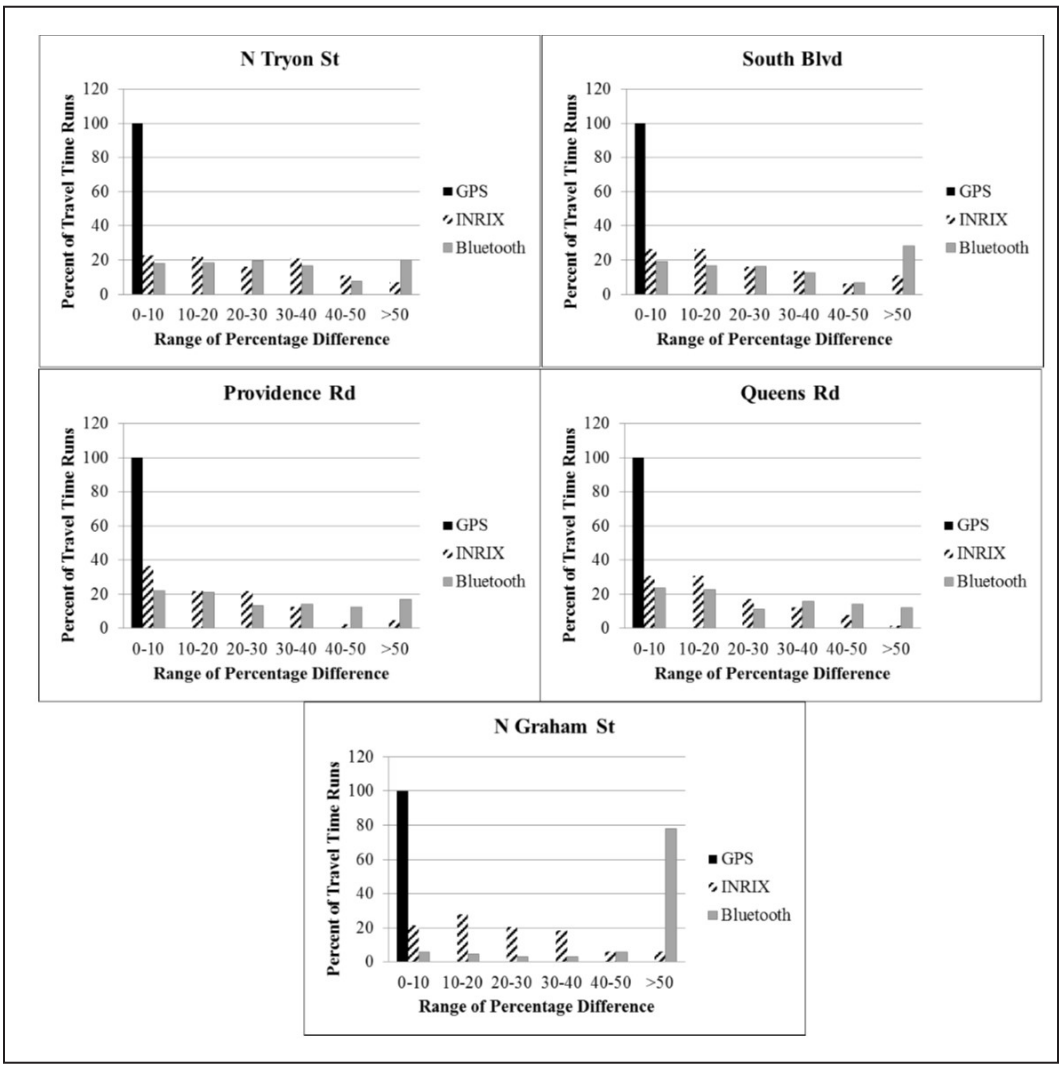


**Figure 2: Percentage Difference in Average Travel Time by Time Period**

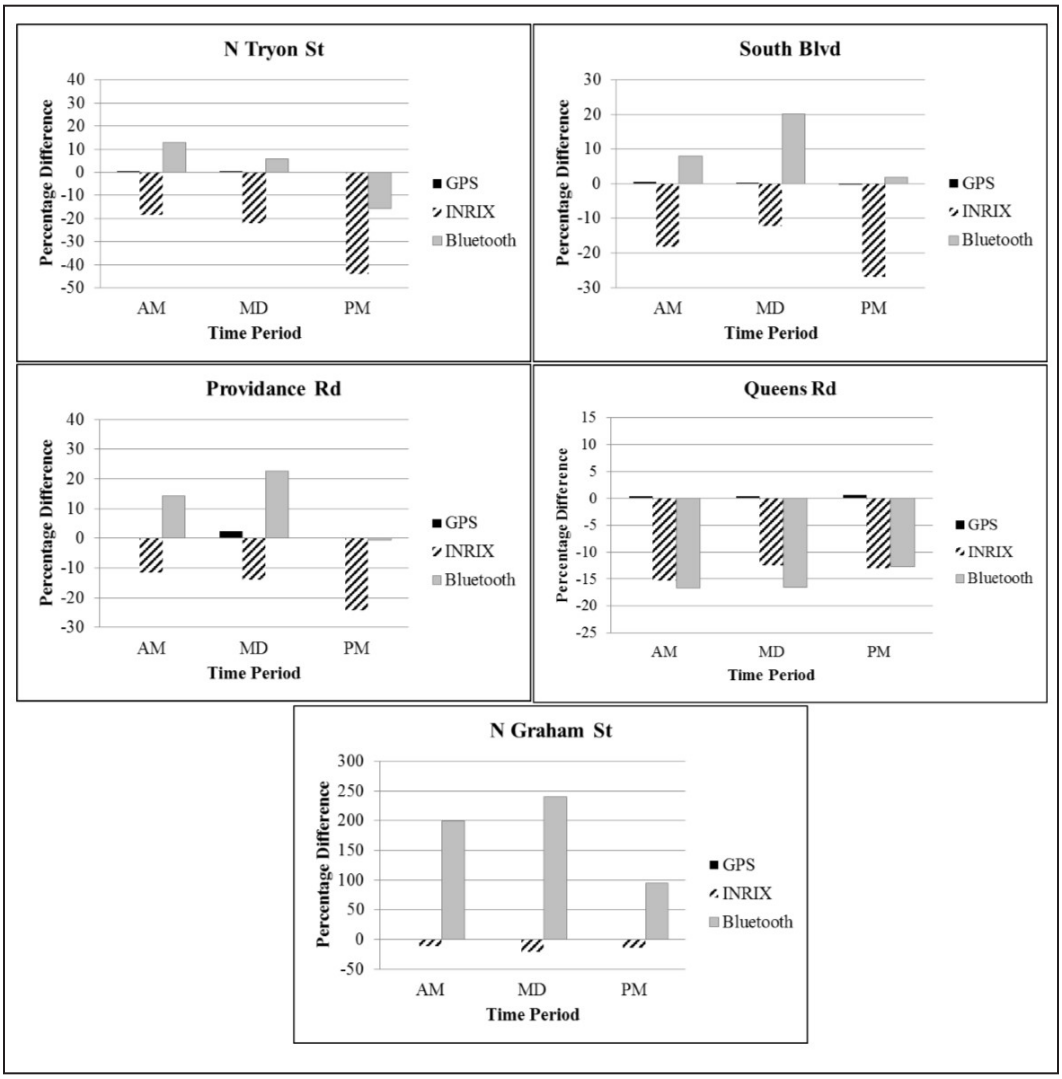
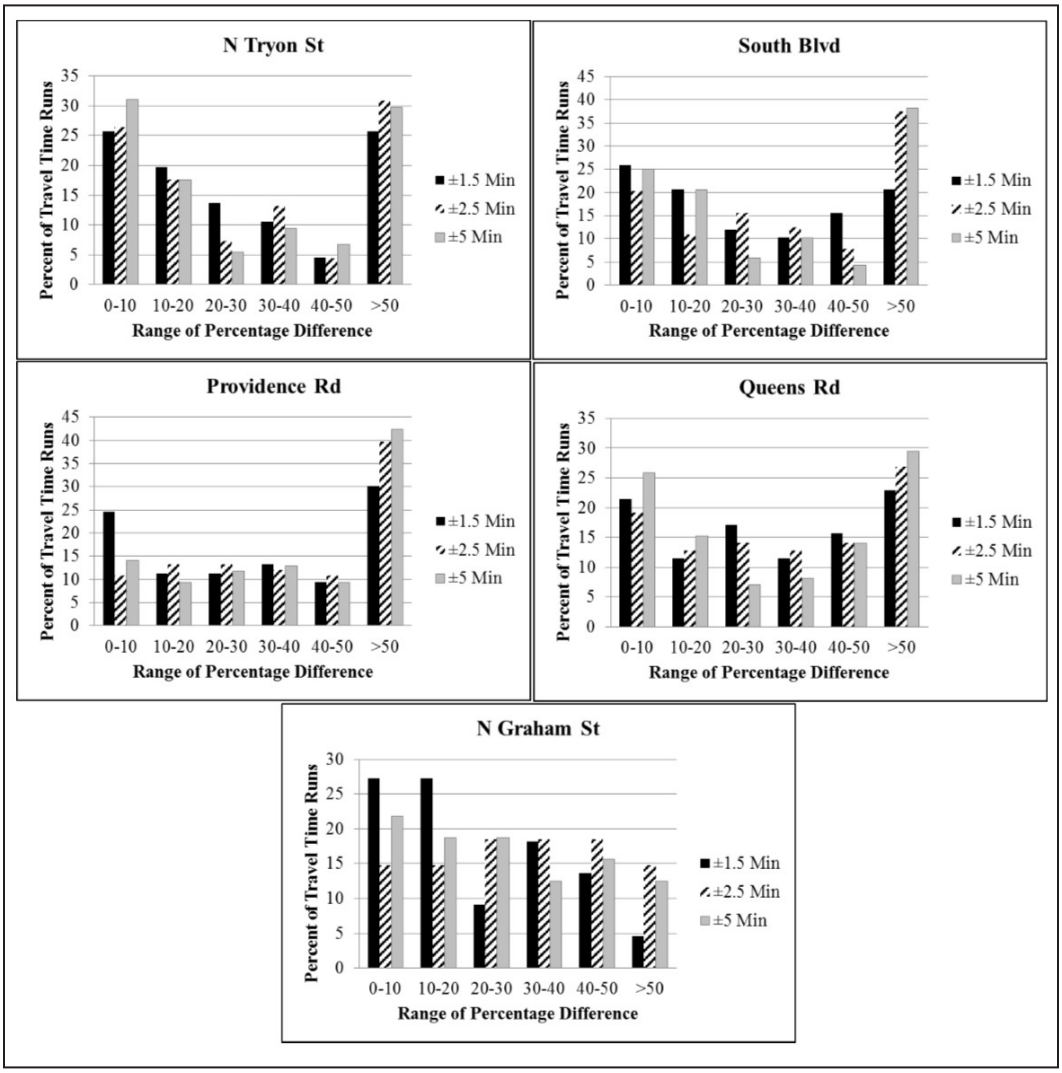


**Figure 3: Percent of Travel Time Runs by Absolute Value of Percentage Difference in Travel Time from Bluetooth Detectors Using Various Data Filter Ranges**




The computed absolute value of percentage difference in travel times for the selected urban street segments, based on ±1.5 min data filter range, is shown in Figure 4. The INRIX travel times were also extracted and computed based on ±1.5 min data filter range for each travel time run to be consistent with travel times from Bluetooth detectors. The absolute value of percentage difference in travel times from GPS are mostly in the 0-10 range of percentage difference, while they are widely spread in all the ranges for INRIX and Bluetooth detectors. INRIX has higher bars for percentage differences in travel time up to the 30-40 range of percentage difference while Bluetooth detectors has higher bars in the 40-50 and >50 range of percentage differences.

**Figure 4: Absolute Value of Percentage Difference in Travel Times for Different Segments Using ±1.5 min Data Filter Range**

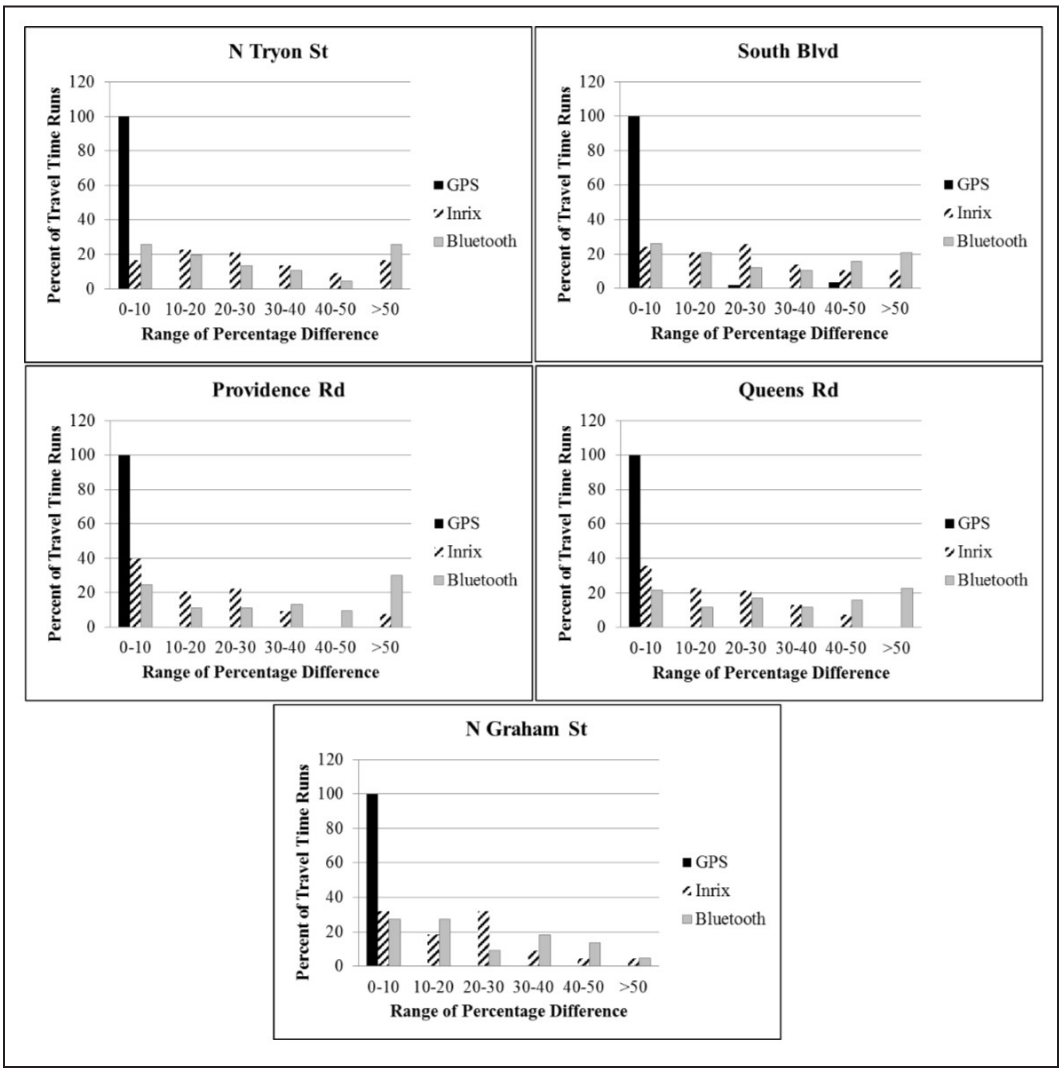



Table 4 summarizes the cumulative percent of travel time runs by absolute value of percentage difference in travel time collected along all study segments using GPS unit, INRIX, and Bluetooth detectors. Overall, the absolute value of percentage difference in travel time is ≤10% for 99.5% of travel time runs collected using GPS unit, indicating that it is the most reliable travel time data collection technology. While the absolute value of percentage difference in travel time is ≤20% for 52.7% of travel time runs obtained from INRIX (no filtering), it is ≤20% for 34.5% of travel time runs collected using Bluetooth detectors (default filtering). Using ±1.5 min data filter range did not yield significant improvements in INRIX outputs. The percent of travel time runs from Bluetooth detectors, with absolute value of percentage difference in travel time ≤20%, increased to 40.8% after using ±1.5 min data filter range. While the proposed data filtering method improved the accuracy of travel time estimates from Bluetooth detectors, it still does not match outputs from INRIX (both with no filtering and ±1.5 min data filter range).

**Table 4: Cumulative Percent of Travel Time Runs by Absolute Value of Percentage Difference in Travel Time**

| Absolute Value of Percentage Difference in Travel Time | GPS | INRIX (No Filtering) | INRIX (±1.5 Min Data Filter Range) | Bluetooth (Default Filtering) | Bluetooth (±1.5 Min Data Filter Range) |
|---|---|---|---|---|---|
| ≤10 | 99.5% | 27.2% | 28.7% | 17.7% | 24.3% |
| ≤20 | 99.6% | 52.7% | 50.0% | 34.5% | 40.8% |
| ≤30 | 99.6% | 70.8% | 73.2% | 47.7% | 54.0% |
| ≤40 | 99.7% | 86.7% | 85.3% | 60.3% | 65.8% |
| ≤50 | 100.0% | 93.7% | 91.9% | 69.6% | 77.2% |
| ≤100 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |

**Effect of Section Length on Bluetooth Detector Travel Time Estimates**

Figure 5 shows the effect of the number of detections and section length (spacing between signalized intersections with Bluetooth detectors) on travel time estimates from Bluetooth detectors. The section length along the considered segments varied from 0.75 miles to 2.75 miles. Considering higher data filter ranges (±2.5 min and ±5 min) does not seem to lower the percentage difference of Bluetooth-detector-based travel time estimates when compared to manually captured travel time. The maximum percentage difference for shorter sections was observed to increase with an increase in the data filter range. However, the percentage difference tends to decrease with an increase in section length for ±1.5 min, ±2.5 min, and ±5 min data filter ranges (Figure 5) i.e., the accuracy of travel time estimates from Bluetooth detectors was observed to improve with an increase in spacing between the Bluetooth detector locations.

**Statistical Analysis**

To further compare the travel times obtained from GPS, INRIX, and Bluetooth with the manual travel time data, t-tests were conducted at a 95% confidence level. The results obtained from t-tests are shown in Table 5. From the results obtained, the zero is not between the upper and lower bound of 95% confidence interval. This shows a significant difference in the means at a 95% confidence level between manual and GPS, manual and INRIX, and manual and Bluetooth detector travel time estimates. However, unlike manual and INRIX or manual and Bluetooth detectors travel time estimates, the difference in means between manual and GPS travel time estimates is very low (around 0.4 seconds). The correlation coefficient between manual and GPS travel time estimates is close to 1, which indicates that manual and GPS travel times are almost the same.

The correlation coefficient between manual and INRIX travel time estimates is 0.53, which indicates a moderate correlation between the two travel time data samples. For Bluetooth detectors (default filtering) and manual travel time estimates, the computed correlation coefficient is 0.2 (very low). The lower correlation indicates that the default filtering procedure may not be accurate and that the data need further processing and analysis. The difference in the means between Bluetooth detectors based on filtering technique using start and end times proposed in this research and manual travel time was also observed to have a lower correlation as well (0.23), somewhat better when compared with the default filtering procedure. However, the mean, standard deviation and the standard error have reduced significantly when ±1.5 min data filter range was used, indicating overall improved results.

**Figure 5: Relation Between Bluetooth Detector Spacing and % Difference**

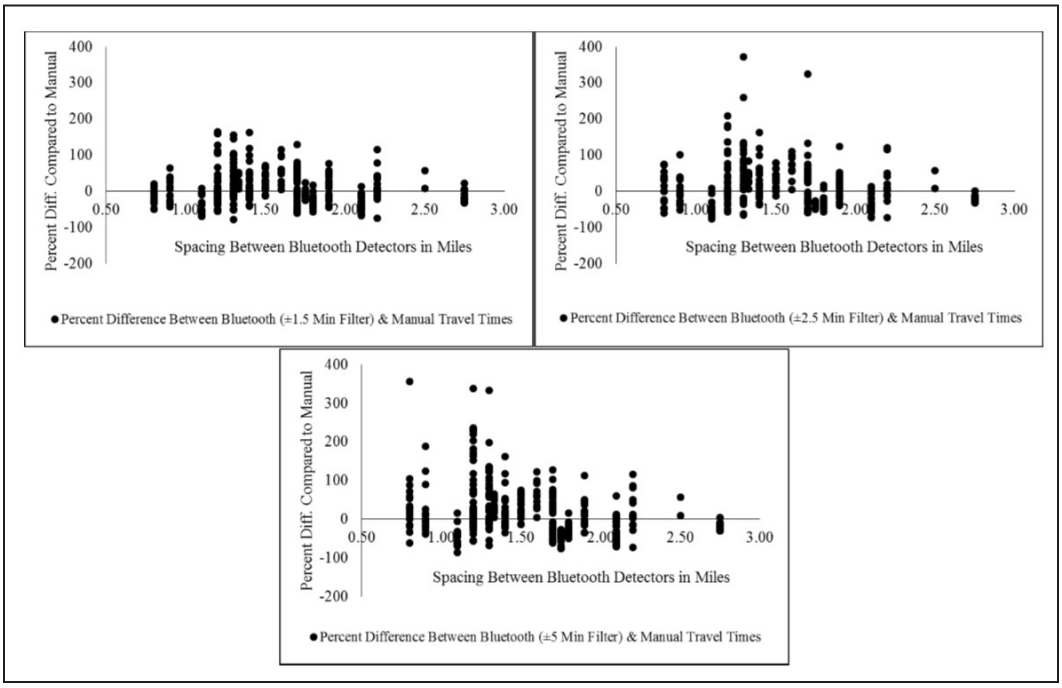



**Table 5: Statistical Analyses Comparing Travel Times from Selected Technologies/Data Sources**

| Null Hypothesis | Paired Differences | | | | | Correlation |
|---|---|---|---|---|---|---|
| | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval | | |
| | | | | Lower | Upper | |
| $H_0$: $H_{Manual}$ - $H_{GPS}$ = 0 | -0.42 | 5.37 | 0.20 | -0.81 | -0.04 | 1 |
| $H_0$: $H_{Manual}$ - $H_{INRIX}$ = 0 | 43.18 | 96.31 | 3.53 | 36.25 | 50.11 | 0.53 |
| $H_0$: $H_{Manual}$ - $H_{Bluetooth\ (Default)}$ = 0 | -75.27 | 256.47 | 9.40 | -93.73 | -56.81 | 0.2 |
| $H_0$: $H_{Manual}$ - $H_{Bluetooth\ (\pm 1.5\ min\ data\ filter\ range)}$ = 0 | 15.35 | 113.08 | 7.86 | 0.14 | 30.85 | 0.23 |

Note: Alternative hypothesis $H_1$: Difference in travel times is not equal to 0.

On-network characteristics such as speed limit, the number of signalized and un-signalized intersections, the number of driveways, the number of turnings (left or right), the number of bus stops, traffic volume by time period, the direction of travel (toward or away from Uptown area), and time of day may play an important role in travel time differences. These characteristics were collected for all the sections along each study segment through field visits. Since each section is different from others in length, the number of signalized and un-signalized intersections, the number of driveways, the number of turnings, the number of bus stops, and the average travel time during the time period were divided by the respective section length. As the number of lanes are different, traffic volume along a section was divided by the number lanes. Statistical analysis was conducted by computing the Pearson correlation coefficients (Table 6) to examine the role of the selected

variables in the percentage difference in travel time from GPS, INRIX, and Bluetooth detectors (default filtering to maximize sample size). In this research, two variables are considered to be highly correlated to each other if the computed Pearson correlation coefficient is ≤ -0.2 or ≥ +0.2 at a 95% confidence level (indicated by * in Table 6).

**Table 6: Correlation Between the Percentage Difference in Travel Times from Selected Technologies/Data Sources and the Variables**

| On-network Characteristics | Percent Diff. between GPS and Manual Travel Time per Mile | Percent Diff. between INRIX and Manual Travel Time per Mile | Percent Diff. between Bluetooth and Manual Travel Time per Mile |
|---|---|---|---|
| Inbound | -0.04 | 0.01 | -0.02 |
| Outbound | 0.04 | -0.01 | 0.02 |
| Speed Limit (35mph) | -0.02 | 0.01 | 0.17 |
| Speed Limit (45 mph) | 0.02 | -0.01 | -0.17 |
| # of Signalized Intersections per Mile | -0.09 | -0.08 | 0.16 |
| # of Unsignalized Intersections per Mile | -0.10 | -0.02 | -0.12 |
| # of Commercial Driveways per Mile | -0.05 | -0.16 | 0.11 |
| # of Residential Driveways per Mile | 0.10 | 0.21* | -0.25* |
| # of Turnings per Mile | 0.16 | 0.22* | -0.05 |
| # of Bus-stops per Mile | -0.06 | -0.19 | 0.12 |
| # of Lanes | 0.18 | 0.20* | -0.20* |
| Traffic Volume per Lane | -0.20* | -0.22* | -0.20* |
| AM Time Period | 0.11 | 0.11 | 0.00 |
| Mid-day Time Period | 0.04 | 0.09 | 0.10 |
| PM Time Period | -0.15 | -0.21* | -0.10 |

* Correlation is significant at a 95% confidence level (probability value ≤ 0.05 level; two tailed test).

The percentage difference between GPS and manual travel time per mile is highly correlated to the traffic volume per lane at a 95% confidence level. The negative sign for traffic volume per lane indicates that an increase in traffic volume leads to a decrease in the percentage difference between GPS and manual travel time.

The percentage difference between INRIX and manual travel time per mile is highly correlated with the number of residential driveways per mile, the number of turnings per mile, the number of lanes, traffic volume per lane, and evening time period at a 95% confidence level. The negative sign for the traffic volume per lane indicates that an increase in traffic volume value leads to a decrease in the percentage difference between INRIX and manual travel time. Likewise, the negative sign for the evening time period indicates that the percentage difference between INRIX and manual travel time per mile would be lower during the evening time period. The positive sign for the number of residential driveways per mile, the number of turnings per mile, and the number of lanes indicate that an increase in their values leads to an increase in the percentage difference between INRIX and manual travel time.

The percentage difference between Bluetooth and manual travel time per mile is highly correlated with the number of residential driveways per mile, the number of lanes, and traffic volume

per lane at a 95% confidence level. The negative sign indicates that an increase in their value leads to a decrease in the percentage difference between Bluetooth and manual travel time.

## CONCLUSIONS AND RECOMMENDATIONS

This paper presents an analysis and evaluation of the quality and accuracy of travel time estimates obtained from a GPS unit, INRIX, and Bluetooth detectors by comparing it with manual data. A GPS unit is the most reliable travel time data collection technology for urban street segments. The travel times from INRIX are more promising when compared to the travel times from the Bluetooth detectors. The Bluetooth detectors showed more samples in higher percentage difference range than INRIX. These findings were supported by t-tests conducted at a 95% confidence level.

Based on the start and end times of the run, data filter ranges of ±1.5 min, ±2.5 min, and ±5 min were tested to perform micro-level analysis of the raw sample from Bluetooth detectors and examine the percentage differences in travel times. Out of the three data filter ranges, ±1.5 min data filter range yielded better results but the lowest number of detections. The travel times from INRIX, however, are more promising than those obtained from Bluetooth detectors even after filtering data using the proposed method (based on minimum and maximum travel time for each section and data filter range).

The relationship between the spacing of locations at which data are captured using Bluetooth detectors indicate that the percentage difference in travel time estimates decreases with an increase in the spacing between the Bluetooth detectors.

The ability to capture accurate travel time data using the selected technologies/data sources seems to increase with an increase in traffic volume (which could be associated to a higher number of samples in the case of INRIX and Bluetooth detectors). Time of day seem to play a role in the number of samples captured (detection rate) using Bluetooth detectors. The numbers of detections are lower during the morning time period when compared with the evening time period (though the placement of Bluetooth detectors is mostly in signal control cabinets close to traffic heading toward the downtown area). The cause of difference in detections by time of day merits investigation and further research.

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**Disclaimer**

The views, opinions, findings, and conclusions reflected in this paper are the responsibility of the authors only and do not represent the official policy or position of the USDOT/OST-R, NCDOT, UMD, INRIX, or any other state, or the University of North Carolina at Charlotte or other entity. The authors are responsible for the facts and the accuracy of the data presented herein. This paper does not constitute a standard, specification, or regulation.

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