COMPARATIVE EVALUATION OF LINK TRAVEL TIME FROM DIFFERENT TECHNOLOGIES AND SOURCES

by

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ABSTRACT

RAHUL CHOWDARY PINNAMANENI. Comparative evaluation of link travel time from different technologies and sources. (Under the direction of DR. SRINIVAS S. PULUGURTHA).

Accurate travel time information is required to efficiently plan and effectively manage transportation network. Technologies and data sources such as Bluetooth detectors and INRIX offer the potential to continuously collect the data and use it for long-term transportation planning as well as real-time traffic condition monitoring. However, their ability to accurately collect travel time data is still unclear. First phase of this study focused on capturing and estimating link/section level travel times using manual floating car method, Global Positioning System (GPS) floating car method, Bluetooth detectors, and INRIX. A comparison between travel times collected manually and using various technologies (GPS, Bluetooth detectors and INRIX) was performed. Results showed that both Bluetooth detectors and INRIX gave promising estimates for freeways. However, travel time data captured for arterial streets using Bluetooth detectors were less accurate and not dependable when compared to other technologies. Moreover, data from Bluetooth detectors showed a significant number of outliers. Therefore, the second phase focused on filtering raw sample of Bluetooth detectors data, estimating travel time, and then comparing with manual data to recommend filtering and data capturing criteria.

DEDICATION

I dedicate this work to my parents Mr. Radha Krishna Pinnamaneni and Mrs. Sukanya Pinnamaneni, my brother Mr. Rohit Chowdary Pinnamaneni, my friends and professors at University of North Carolina at Charlotte.

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DISCLAIMER

The contents of this report reflect the views of the author and not necessarily the views of the University of North Carolina at Charlotte. The author and project team are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the CDOT, NCDOT, INRIX, UMD, or USDOT at the time of publication. This report does not constitute a standard, specification, or regulation.

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CHAPTER 1: INTRODUCTION

1.1. Introduction

Traffic demand has been progressively increasing with the development of modern civilization and need for more travel. The subsequent effect of this increasing travel demand is overcrowding of the limited road network. Addressing congestion has been one of the primary objectives of transportation system managers, planners, and engineers. The Federal Highway Administration (FHWA) recommends using the travel time experienced by users on our road system to quantify the effects of congestion (AASHTO, 2008). It is also a useful measure for motorists or system 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. However, the sample size from this approach is very limited. It is also a tedious, expensive, and time-consuming process. Travel time data is also captured using on-road traffic sensors, loop detectors, automatic license plate recognition (ALPR) systems, Radio Frequency Identification (RFID) tag reader systems, and video surveillance cameras in the past (Vo, 2011; Haghani et al., 2010). A few other technological means of collecting travel time data include cell phone tracking, Global Positioning Systems (GPS) equipped probe vehicles, and transit buses with GPS or automatic vehicle location (AVL) units as probe vehicles (Kim et al., 2011). These devices or methods are used by transportation agencies along with the participation of motorists for effective transportation planning, safety analysis, resource allocation, and security surveillance.

Besides the aforementioned technologies, Bluetooth detectors are an alternative and inexpensive means of accurately measuring travel time (Vo, 2011). Bluetooth detectors compute the travel time based on Media Access Control (MAC) addresses of Bluetooth enabled devices in vehicles. Recently, INRIX has emerged as a new private source of data pertaining to travel time and average speed. INRIX provides accurate real-time, historical, predictive traffic services, and incident data on freeways, highways, and secondary roadways, including arterial streets and side streets of North America and Europe (INRIX, 2013). The sources of INRIX data are GPS equipped vehicles, mobile devices, and traditional road sensors. The archived traffic data is being used by the agencies to facilitate traffic management, traveler information, and planning activities for both local and long distance travelers. While the use of Bluetooth detectors and INRIX has rapidly increased in recent years, their applicability to accurately collect travel time on all types of facilities is still unclear.

1.2. Need for Research

Effective monitoring of traffic performance is very important for transportation agencies. It assists in short-range and long-range transportation planning decisions. In addition, real-time traffic performance measurement provides travelers and transportation agencies with accurate data that are used to make decisions on their current trips, especially for roadways that experience high variability in traffic flow. Typical performance measures used by practitioners and system users include travel times and travel speeds. The effectiveness of decisions made depend on reliably estimating these performance measures.

Travel time is a fundamental measure in transportation. It is a simple concept understood and communicated by a wide variety of audiences, including transportation engineers and planners, business persons, commuters, media representatives, administrators, and consumers (TTI, 1998). Travel time studies are important among all other measures because it is common in all studies and is easily understandable term to non-technical persons (e.g., politicians, advocacy groups, and the general public) who are involved in decision making process related to transportation planning and policy. Also, certain transportation related analyses compare various transportation modes for a common funding source which is fulfilled by travel time as the element.

Travel time studies are also important from transportation planning perspective as it depicts the level of congestion on a particular link or arterial. Travel time is used by planners in travel demand forecasting and analysis for traffic impact studies. A comprehensive database of real time travel is also collected and disseminated by transit authority management and freight logistics for marketing analysis, patronage forecasting, and efficient on-time goods delivery. Travel time is a major measure of quality/level of service to motorists and passengers, and also of relative congestion along the section of roadways. Many demand-forecasting models require good and accurate travel time measures (Roess, 2011).

1.3. Research Objectives

The key objectives of this research, therefore, are:

1. to collect and evaluate the accuracy of estimated micro-level travel time data from manual procedure, GPS equipped vehicle, Bluetooth detectors, and INRIX for both arterial streets and freeway segments,
2. to research and compare the ability to capture temporal variations in travel times from the selected sources of travel time data,
3. to develop new methods to filter data obtained from Bluetooth detectors for accurate travel time estimation,
4. to examine the correlation between travel times collected manually and using various technologies (GPS, Bluetooth and INRIX),
5. to examine the correlation between travel times and roadway characteristics such as the number of lanes, speed limit, traffic volumes, number of signalized and un-signalized intersections, and the number of bus stops for each link considered in this research, and
6. to recommend the best technology or the best combination of technologies to capture travel time.

1.4. Organization of the Thesis

The remainder of this thesis comprises four chapters. A review of existing literature on travel time studies and different technologies and sources used in the past are discussed in Chapter 2. Methodology and data collection procedure is discussed in Chapter 3. Comparison and evaluation of travel times from various technologies and sources are presented in Chapter 4. Conclusions from this research are presented in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

The review of past research on the use of Global Positioning Systems (GPS), Bluetooth detectors, and INRIX for travel time studies is divided into three sub-sections: 1) GPS for travel time studies, 2) Bluetooth detectors for travel time studies, and, 3) INRIX for travel time studies. They are presented next.

2.1. GPS for Travel Time Studies

2.1.1. Introduction

Travel time studies are conducted to estimate delay and severity of congestion on roadways. GPS is a satellite-based positioning system that provides precise temporal and spatial information on individual receivers or relative positions between co-observing receivers (Sungchul and Vonderohe, 2011). The Department of Defense (DOD) monitors and maintains GPS closely and can disable the system anytime (TTI, 1998). Quiroga and Bullock (1999) conducted a study on arterial streets to obtain travel time using GPS and dynamic sequestration technique. They used a general data model that includes a spatial model, a geographic location database, and GPS data transfer procedure using dynamic segmentation tools. Accuracy in measuring travel time and speed using this technique improves more than those using traditional techniques.

Positional error in GPS is largely influenced by several sources: satellite and receiver clock biases, atmospheric refraction, satellite ephemeris inexactness, multi-pathing, satellite geometry, and human bias (Sungchul and Vonderohe, 2011). GPS accuracy varies depending on positioning methods. The sampling rate is identified as another error source for transportation data collected from the vehicles. Given a constant vehicle speed, latency between successive GPS points is proportional to sampling rates. With increasing spatial error, decreasing sampling rate increases spatial uncertainties between GPS points and roadway maps and subsequently affects route measures between successive GPS points along roadways.

According to a study by Mauricio (2003) for collecting and utilizing travel time data through GPS and GIS on arterial streets in Philippines, the GPS units should be exposed to at least three satellites for tracing the location. The duration can range from 5 minutes to 30 minutes depending on the GPS unit position regarding the satellite. Day of survey, time of survey, and route information should be recorded while performing the run. Less staff requirements, less human error, detailed data collection opportunity, good accuracy, and automatic geo-coding procedures are some of the many benefits of using GPS based system 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 that system (TTI, 1998; Koprowski, 2012).

2.1.2. Feasibility

Bel-O-Mar Regional Council (2007) conducted a travel time study using GPS on US-250 and SR-331 in Belmont County and portions of US-250 and WV-2 in Ohio and Marshall Counties in West Virginia. They used the floating car technique (a vehicle mounted with a GPS antenna) to obtain average travel time and speed. The GPS data logger recorded the coordinates of the position every two seconds. They concluded that GPS can be used as an efficient and in an advantageous way to collect travel time data.

Wilbur Smith Associates (2007) used GPS units to record the spatial coordinates and time of the test vehicle at every 0.03 mile (158 feet) for analyzing travel time and delay on major local and arterial roadways in Jonesboro, Arkansas. From that the average travel speed was calculated. The data formed the baseline for future assessment of the impacts of development and population increase on mobility.

2.1.3. Implementation Strategies

For calibration and analysis of data collected by GPS, various methods and software's were used in the past. Radford University's GPS website can be used to obtain differential correction data to identify precise location information (RVAMPO, 2000). Trimble's Pathfinder Office Software was used in one of the studies to transfer the GPS file from the TDC-1 collection unit (RVAMPO, 2000). In general, the raw data of GPS system should contain the time stamp, latitude, longitude, speed, Horizontal Dilution of Precision (HDOP), and the number of satellites (Hunter et al., 2006). The information on altitude, heading, vertical dilution of precision (VDOP), and positional dilution of precision (PDOP) may also be collected from GPS receiver.

Faghri et al. (2010) quantified travel time and delay data using a Trimble GPS unit and a laptop computer with Trimble TerraSync and GPS Pathfinder Office software installed for the identification of the severity of congestion. They conducted the study on all major routes surrounding large population centers in Delaware and identified total peak delay and percent time in delay.

Tracy (2012) conducted a study along US-40 heading east from NJ-54 into Atlantic City in New Jersey to collect passenger travel time. The author identified that the GPS antenna is capable of recording the latitude and longitude, and speed of the test vehicle every second. ArcMap and PC Travel software were used as the analysis tools. The data provided direct measure of level of service (LOS) on that road during the run.

Salvatore et al. (2012) presented a model of driver behavior through GPS sampling of the positions of several test drivers in terms of speeds on two-lane rural roads. The model could estimate continuous speed profile that depends on the spot geometry, horizontal, and vertical alignment of the road segment. The model was also able to correctly estimate different speeds for two different curves, mean speed, and any desired percentile of the operating speed. A significant correlation between curvature and the standard deviation of speeds was found. The reported model coefficients can be used to predict operating speed on two-lane rural roads in Italy; however, application of the model outside Italy would require a new calibration based on local speed surveys because of the differences in driver populations, roadway systems, and vehicle fleets.

2.2. Bluetooth Detectors for Travel Time Studies

2.2.1. Introduction

Travel time data using Bluetooth detection technology captures travelers Bluetooth-enabled devices that broadcast unique identifiers known as Media Access Control (MAC) addresses. Invented in 1994 by engineers from Ericsson, a Swedish company, Bluetooth enables the sharing of music, images, and other data wirelessly over a personal area network (PAN) which is defined by the device’s antenna. Many computers, car radios, navigation devices, PDAs, cell phones, headsets, and other personal devices are Bluetooth enabled to allow wireless communication between devices. Generally, manufacturers assign MAC addresses to Bluetooth equipped devices. Bluetooth-based travel time measurement involves identifying and matching the MAC address of Bluetooth-enabled devices carried by motorists as they pass a detector location. Bluetooth device matching can be used to measure arterial travel time, average running speed, and origin-destination patterns of travelers (Cambridge Systematics, Inc., 2012). Because the MAC addresses are not tracked when the device is sold within the marketplace, the MAC addresses can be detected and matched without establishing a relationship to the device owner, therefore keeping the traveling public and their personal or sensitive information anonymous (Cambridge Systematics, Inc., 2012). Travel time data using Bluetooth technology captures travelers Bluetooth-enabled devices that broadcast MAC addresses. By recording the MAC addresses upstream and downstream, the travel time can be obtained (Wasson et al., 2008).

Bluetooth detectors use radio signals over short distances ranging from 3 feet (minimum) for Class 3 radios to more than 330 feet for Class 1 radios used for industrial purposes (Bluetooth, 2010). Class 2 radios found in mobile phones must provide a 33 feet range. These devices operate at a very lower power. For example, class 2 radios operate at 2.5 mW or 4 dBm. However, the low power negatively impacts the rate of data transfer, which ranges from 1 Mbit/s to 24 Mbit/s.

The ability of Bluetooth detectors to capture data depend on their technical specifications, including frequencies and different types of antennas available along with their effective ranges. A radio frequency refers to rate at which radio signals are transmitted. The effective signal range of a Bluetooth device, which is defined by its antenna class, is the range at which other Bluetooth devices may be discovered and connected.

2.2.2. Instruments

Several researchers have used Bluetooth detectors to collect travel time in the last few years. A travel time study conducted in Indianapolis, Indiana by Wasson et al. (2008) showed that matching MAC addresses can be used to report travel time effectively. They also identified several key components of Bluetooth detectors, such as a Bluetooth MAC address detector and processor, a radio capable of reading the MAC address, and a Central Processing Unit (CPU) system to forward data to a central location.

The Smart Transportation Applications and Research (STAR) Lab devices Bluetooth detectors that contain a constant scanning Bluetooth chipset, a processing module to record MACs, and a communication module to transmit data in near real time (Malinovskiy, 2011). It takes 10.24 seconds at a minimum to discover all Bluetooth devices within range. During the process in which a Bluetooth device is discovered (inquiring process), the device hops on 32 channels consisting of 16 channel subsets (trains). It takes 0.01 seconds to scan each train. Each scan is repeated 256 times for providing necessary time to collect inquiry responses from other Bluetooth devices. In addition, two iterations of each train occurs due to the specification of at least three train switching, which overall results in 10.24 seconds to identify a Bluetooth device within range (Woodings et al., 2002).

In contrast to more commonly used radio signals (TV, radio, etc.) which are broadcasted over large areas, Bluetooth sends radio signals over short distances ranging from a minimum of 3 feet (1 meter) to more than 330 feet (100 meters) (Bluetooth, 2013). The radio waves are sent at frequencies from 2.402 GHz to 2.480 GHz as internationally agreed for the use of industrial, scientific, and medical (ISM) devices (Franklin and Layton, 2000).

Although Bluetooth technology does not require line of sight, the signal attenuation of a Bluetooth device is influenced by physical obstacles. Bluetooth signals are able to travel through glass and may propagate off of other reflective surfaces to establish a wireless connection. However, objects that obstruct the line of sight between two Bluetooth detectors may decrease the likelihood that the devices will be able to connect (Kim et al., 2011).

Like all wireless connections, Bluetooth sends signals that may be susceptible to interception by those who are wishing to access data without permission. Bluetooth’s automatic connections are a benefit in terms of convenience, but may serve as a gateway through which unwanted data are received. Consequently, manufacturers will typically provide the option to enable and disable Bluetooth capabilities on their devices. Commonly known as “discovery mode,” this mode enables the device to be detected by other Bluetooth detectors and establish a connection.

Bluetooth technology uses the MAC-48 identifier format as defined by the Institute of Electrical and Electronics Engineers (IEEE, 2002). Consequently, every Bluetooth device is uniquely identified by a 48-bit MAC address, which consists of six pairs of hexadecimal digits. The first three groups of numbers are known as the organizationally unique identifier (OUI) which is specific to the device manufacturer, while the last three groups of numbers are unique to the device. In Bluetooth travel time measurement systems, the MAC address of every Bluetooth device that is detected is recorded along with a time-stamp. Thus, a MAC address detected at more than one

Bluetooth site represents a unique Bluetooth device which traveled from one site to the next, and its travel time may be determined by calculating the difference in the time-stamps.

Research in the field of Bluetooth technology for travel time measurement has been developed substantially in recent years, and several vendors have developed Bluetooth products to provide travel times to their clients more effectively and inexpensively. The studies reported in this summary exemplify the development of Bluetooth technology in traffic monitoring.

2.2.3. Issues and Challenges

Bluetooth detection technology can allow up to eight devices to be connected at the same moment by using the adaptive frequency hopping (AFH) and frequency hopping synchronization (FHS) (Franklin and Layton, 2000). The probability of interference between any two devices is reduced down by FHS as it is highly unlikely for these two devices using the same transmitting frequency at the same time. Bluetooth detectors communicate over a personal area network (PAN) or piconet after connecting automatically. Physical obstacles that obstruct the line of sight between two Bluetooth detectors influence the signal attenuation of a Bluetooth device and reduce down the likelihood of getting connected (Logitech, Inc., 2005). However, Bluetooth signals can travel through glass and propagate off of other reflective surfaces.

However, high implementation cost, multiple readings from a single vehicle, and inclusion of bypass trips are some of the issues associated with using Bluetooth detectors for travel time data collection (Koprowski, 2012). Signal delay and non-uniform traffic flow can cause errors in Bluetooth travel time measurements in case of arterial streets

(Nelson, 2010; Van Boxel et al., 2011). As it takes 10.24 seconds to detect a Bluetooth device, it can be a source of error in travel times though the inaccuracy decreases as the spacing between Bluetooth station increases (Malinovskiy et al., 2010; Puckett and Vickich, 2010). Wang et al. (2011) observed 2.4 to 11.4 seconds (4% to 13%) of average errors while performing the travel time data collection along the 0.98-mile-long arterial study corridor in Washington. They identified that absolute errors are dependent on sensor configurations and surrounding conditions, and independent of length of the study corridor. They concluded that longer corridors tend to allow a better performance for this technology based data collection process. A negligible amount of signal degradation occurs when the devices are more than 2 meters apart transmitting wirelessly (Logitech, Inc., 2005).

According to Fredman (2002), the operation of Bluetooth detectors can be inversely affected by other higher power devices (802.11b (Wi-Fi), cordless phones, two-way radios, and microwave ovens) while using the unlicensed 2.4 to 2.483 GHz industrial, scientific and medical (ISM) spectrum. Frequency dynamic noise occurs due to the interference of established Bluetooth piconets with the test Bluetooth piconet. When two or more Bluetooth detectors try to use same transmitting frequency channel, the signal degradation occurs, such as 5%, 11%, and 21% efficiency loss due to the presence of 4, 10, and 20 piconets, respectively. The transmission failure can also result from frequency collision of two overlapping piconets using the same transmitting frequency at the same time (Lynch Jr., 2002).

The outliers are another source of errors. For freeway data collection, the following situations should be filtered: (1) vehicles exiting and returning to the freeway between two stations, (2) vehicles that stop on the shoulder temporarily, (3) vehicles traveling slowly due to repair requirements, and (4) vehicles recorded at the upstream station but missed at the following station, detected at the second station traveling in the opposite direction later on in the day (Martchouk et al., 2011). Nelson (2010) preformed a travel time data collection comparison study on local and arterial roads, intersections, and interchanges in Washington, DC. The author recommended using minimum and maximum travel time filters to identify outliers. However, this procedure is not suitable for the roadways with high variability in travel times throughout the day. Roth (2010) developed a travel time data cleaning methodology collected by Bluetooth detectors based on a time series approach. The study compared the number of outliers detected by modified Z-Test, Grubbs' Test, and Chauvenet's Criterion, and identified that modified Z-Test detected the most outliers. The author recommended a modified Z-test to identify and remove outliers in an inexpensive way, which require only a single iteration. Malinovskiy et al. (2010) and Puckett and Vickich (2010) have addressed the issue of MAC address groups that are produced by the data collection units (DCUs) by utilizing the time stamp for the first MAC address in a group as a solution to that problem. Quayle et al. (2010) performed an arterial performance measurement study on Tualatin-Sherwood Road in Portland, Oregon. They also acknowledged that multiple detections of Bluetooth devices are possible while passing by a DCU. They identified that MAC address group sizes depend on the DCU to road distance and time duration of the device within DCU range. Haghani et al. (2010) suggested using appropriate DCU spacing for the minimization of redundant detections for freeways. An average of the detection time can be used in case of multiple detections. According to Wasson et al. (2008), the travel time sample errors are negligible for the distances between DCUs that they examined (2-3 miles) on arterial streets.

Though, Bluetooth detection technology has been found to have acceptable accuracy to estimate the travel time under homogeneous traffic conditions, there are a few limitations. Pedestrians and bicyclists with detectable devices and buses with multiple Bluetooth devices onboard are sources of outliers (Malinovskiy et al., 2010). The data collected from arterial highways showed a significantly larger variance compared to data from motorways due to traffic signals and vehicle diversion to side roads (Wasson et. al., 2008).

Malinovskiy et al. (2010) investigated Bluetooth MAC address-based travel-time detectors with Automated License Plate Recognition (ALPR) sensors indicating that Bluetooth detectors tended to be biased towards slower vehicles. So the calculated travel time can be slightly overestimated. A methodology is needed to be identified for the correction of the inaccurate travel times due to Bluetooth biasness (Wang et al., 2011). Extraneous delay sources, such as traffic signals and nearby bus-stops, should be considered to avoid undesirable factors while conducting the travel time analysis on arterial streets (Wang et al., 2011). Length of the corridor can significantly affect the performance of the Bluetooth-based travel time collection system. A short corridor is more prone to errors and inaccurate results for arterial streets (Wang et al., 2011).

2.2.4. Feasibility

Low cost per unit of data, continuous data collection, and no disruption of traffic are some of the benefits of using Bluetooth detectors as travel time data collection technology. According to a travel time study by Tarnoff et al. (2009), Bluetooth-based method is found to be one of the most cost-effective approaches for travel time data collection. The Bluetooth detectors are found to be hundred times cheaper than equivalent floating car runs on both arterial streets and freeways. Phil Tarnoff, CEO of Traffax Inc., stated in 2010, that the estimated cost per travel-time data point of the Bluetooth detector data was just 1/300th of the cost of comparable floating car data (Bradley, 2010). The Center for Advanced Transportation Technology (2008) performed a travel time data collection and analysis study along I-95 between Baltimore, Maryland and Washington, DC. They estimated the Bluetooth detector based process is 500 to 2,500 times cost effective than floating car data collection based on the data points produced.

Blogg et al. (2010), from an O-D study, conducted on Centenary Motorway in southwest Brisbane and an arterial street network in north Brisbane between Stafford and Strathpine in Australia, found that the MAC data collection by Bluetooth detector technology is a cost effective way to collect vehicle O-D in small and controlled networks. However, for extensive networks, the MAC O-D data can be used as supplement to the traditional methods as a cost effective measure.

Wasson et al. (2008) conducted two different field tests in Indianapolis on U.S. 31 and I-69 in early 2008 which proved the feasibility of matching MAC addresses to report travel times. A study was conducted in Oregon along a two mile segment of Tualitin-Sherwood Road to determine changes in travel time and travel time variability as a result of a signal timing change (dePencier, 2009). Six Bluetooth readers were used to show that both metrics were improved.

Puckett and Vickich (2010) found out from a study to identify real time travel time data for freeways and arterial streets that utilization of Bluetooth detectors on arterial streets is feasible. The accuracy of measuring travel times using Bluetooth detector is an important factor in the decision making processes. Malinovskiy et al. (2010), in their study to measure the travel time on SR-522 in Washington using Bluetooth detectors, found that the devices were representative of the ground truth travel time data obtained by the Automated License Plate Recognitions (ALPRs).

Haghani et al. (2010) aimed to use Bluetooth detectors as a new and effective mean of freeway ground truth travel time data collection by comparing the Bluetooth detector based data with floating car data. They conducted their study on I-95 between Washington, DC, and Baltimore, Maryland and found out that ground-truth provided by the new Bluetooth detectors and the actual travel times are not significantly different. KMJ Consulting, Inc. (2010) conducted a study to evaluate the ability of Bluetooth detector to collect and report travel times along I-76 at locations coincident with EZPasstag readers. The study found out that travel times measured by the Bluetooth detector technology were comparable to those obtained by EZPass tag readers. Haseman et al. (2010) collected 1.4 million travel time records over a 12-week period for the evaluation and quantification of travel mobility for a rural Interstate work zone along I-65 in Northwestern Indiana. They used Bluetooth detectors to identify travel time delay in work zones. The Bluetooth detectors can be used to estimate O-D pairs. The system can also be used for route choice (Hainen et al., 2011).

Martchouk and Mannering (2011) used Bluetooth units to analyze travel time reliability for the Indiana DOT along Interstate 69 in Indianapolis. It was determined that Bluetooth technology was effective in measuring travel times.

2.2.5. Implementation Strategies

Kim et al. (2010) performed a study to evaluate the accuracy of estimated travel time using various technologies, such as TRANSMIT (RFID) readers, Bluetooth detectors, and INRIX. They concluded that Bluetooth detectors provided accurate results compared to TRANSMIT readers and INRIX system.

Martchouk et al. (2011) analyzed inter-vehicle and inter-period variability. They combined speed and volume data collected by using side fire microwave detectors with the Bluetooth travel time data. They also developed duration models of travel time to identify when the traffic breakdown occurs.

According to a travel time estimation study by Araghi et al. (2012) on a selected road link in Sauersvej, Denmark, the Bluetooth detector technology has been found to have acceptable accuracy to estimate the travel time under homogeneous traffic conditions. The MAC address can provide the information of type of Bluetooth-enabled device (mobile phone or laptop) referred to as Class of Device (CoD) and can also be used to identify the type of vehicle carrying that Bluetooth device as a way to separate out motorized and non-motorized traffic.

Haghani et al. (2010) found that the accuracy of the travel speeds in freeways generated from the collected MAC addresses increases with the increase of distance between Bluetooth detectors and the decrease of vehicle speed. Malinovskiy et al. (2010) recommended the detection area on the road should be large enough for the detection of nearly all vehicles with Bluetooth-enabled devices traveling at different speeds. Schneider IV et al. (2010) compared Bluetooth to floating car methods on Interstates, urban arterial streets, and state highways. They found that arterial tests had much lower number of matches than the interstate tests. They suggested one to two miles spacing between Bluetooth stations for increasing the number of matches. Large detection zones, such as Class 1 radios, can be a source of error in short corridors as any Bluetooth device within the detection range may be detected by the Bluetooth detectors (Vo, 2011). However, according to Malinovskiy et al. (2010), in spite of loss in accuracy in travel time measurements, larger detection zones provide higher matching rate. This improves the sample size and reduces random error rates for both freeways and arterial streets.

The sample size of data is another important aspect in providing accurate and up-to-date travel times. The study by Wasson et al. (2008) produced 0.7 to 1.2% match rates (percentage of Bluetooth devices detected at two or more Bluetooth detector locations out of the total traffic volume in the corridor). According to Neal Campbell, CEO of TrafficCast, BlueTOAD system can achieve match rates of 3 to 6% of the traffic stream (Bradley, 2010); which is found to be 4% by another study on arterial streets (KMJ Consulting, Inc., 2010).

Haghani and Young (2010) conducted a study to monitor traffic on I-95 in Maryland using Bluetooth detectors and obtained 2 to 5.5% match rates during a validation test in six eastern states. Wang et al. (2010) obtained 2.2% match rates on arterial streets in their study. According to the study by KMJ Consulting, Inc. (2010), these match rates are sufficient enough to identify travel times accurately. They suggested that, for roadways with 36,000 average annual daily traffic (AADT), 9, 36, and

864 matched pairs per 15-minutes, hour, and day (2% match rate), respectively can provide accurate travel time estimation. However, the percentage requirement increases with the decrease in AADT.

Detection rates are comparable to the traffic volume obtained from another method, which can be used as a baseline for that particular location (Nelson, 2010). Schneider IV et al. (2010) also identified that match rates are proportional to the traffic volume on arterial roads. They found that the proportion of Bluetooth devices per vehicle does not depend on the time-of-day (ToD).

Asudegi (2009) conducted a research to identify optimal number and location of the Bluetooth detectors in a network for travel time data collection with a high reliability. The study assumed Bluetooth penetration rate to be 3 to 5% of normal traffic streams of freeways and arterial streets. Haghani and Young (2010) obtained the Bluetooth penetration rate as approximately 5% for freeways. Hainen et al. (2011) performed a route choice and travel time reliability study on arterial streets in Indiana. They estimated 7 to 10% of passing vehicles have detectable Bluetooth devices for arterial streets. Brennan Jr. et al. (2010) performed a study on I-65 in Indianapolis to assess the influence of vertical placement of Bluetooth detectors on data collection quality. They assumed 5 to 10% of the vehicle population on the freeways has MAC addresses that can be discovered.

Porter et al. (2010) conducted a study to assess the suitability of different antennas to support a Bluetooth based travel time data collection system on Oregon Route 221 (Wallace Road NW) in Salem, Oregon. They found that vertically polarized antennas with gains between 9 and 12 dBi are good for Bluetooth based travel time analysis.

According to Malinovskiy et al. (2010), two omni-directional antennas placed at the same location on opposite sides of the road provide the best detection rate. Multiple readers at one site may increase the number of detections. Combinations of sensors in tandem increase the accuracy of the detection and matching rates and reduce error in most cases on arterial streets (Wang et al., 2011).

The height of the Bluetooth detector has an important role in detection rate. Brennan Jr. et al. (2010) conducted a study by placing five Bluetooth detectors at different heights ranging from 0 to 10 feet along I-65 in Indianapolis to identify the sensitivity of sample size to sensor placement. They concluded that 7.5 feet and 10 feet produced similar results while the others performed poorly. However, further research is necessary to test if optimal height depends on site characteristics.

The performance of Bluetooth technology in estimating travel times has been compared to floating car methods and radio-frequency identification (RFID) as an accurate and cost-effective alternative. In 2010, Schneider IV et al. (2010) completed a study comparing Bluetooth to floating car methods. Several tests were conducted to measure the performance of Bluetooth on both interstate highways, urban arterial streets, and state highways. The number of matches for the arterial tests was much lower than the interstate tests. To increase the number of Bluetooth matches, which is the number of MAC addresses detected at more than one site, it is suggested that Bluetooth stations should be installed one to two miles apart. Moghaddam et al. (2013) examined the application of Bluetooth detectors to acquire travel times on arterial streets as it is challenging due to frequent interruptions in the traffic flow because of traffic signals. They combined micro traffic simulation with Monte Carlo simulation to synthesize measurement errors. The results showed that the mean travel time error is essentially zero for all traffic conditions. However, the variance of the error varies as a function of the traffic conditions. The authors developed a multivariate regression model to quantify the standard deviation of the travel time measurement error as a function of the traffic factors, and, using this model show that under some conditions, the 95% confident interval of the travel time measurement error may reach 25% of the true mean travel time.

2.3. INRIX for Travel Time Studies

2.3.1. Introduction

INRIX, a software and Desktop-as-a-Service (DaaS) company established in 2004, provides a variety of mobile applications and Internet services pertaining to traffic and driver services. Currently, more than 200 customers and industry partners worldwide choose INRIX, including the Ford Motor Company, MapQuest, Microsoft, NAVIGON AG, TeleNav, I-95 Corridor Coalition, Tele Atlas, deCarta, TCS, Telmap, ANWB and ADAC. Not much study has been done using INRIX data for travel time analysis and long-term planning.

INRIX offers real-time, predictive and historical traffic information, real-time incident and weather safety alerts to transportation agencies that are under pressure to provide more complete data-powered solutions for measuring system performance, streamlining operations or delivering new and improved services. Currently, 46 states are using their free INRIXTraffic. Also, 16 states in the US I-95 Corridor Coalition teamed with INRIX to improve traffic Operations (INRIX, 2013). Texas Transportation Institute fuels its annual Urban Mobility Report using INRIX data (INRIX, 2014).

INRIX monitors 260,000+ miles of roads in real-time 24x7 including all Interstates, other major roads nationwide, major arterial streets and city streets in all 52 cities with populations over 1 million people. It also detects location and incident type, monitors status and communicates severity of abnormal traffic/travel conditions nationwide (INRIX, 2014).

The INRIX Traffic Scorecard provides a comprehensive analysis of the state of traffic congestion across the world. INRIX 2007 Traffic Scorecard Annual Report was transformative in its ability to illustrate how “Big Data”, crowd-sourced in real-time from actual vehicles and mobile devices traveling through road networks, provide a comprehensive, consistent and timely measure of traffic congestion nationwide. The data is used to conduct studies at a macroscopic level. The INRIX Index for the United States during the first three months of the year showed that traffic congestion in 2013 is already higher than congestion during the same time period in 2012 (INRIX, 2014).

2.3.2. Feasibility

Independently validated by the I-95 Coalition Vehicle Probe Project, INRIX offers 100% detection of all freeway slowdowns, travel time accuracy above 95% and 99.9% availability. The conditions of all freeways are calculated and updated every minute.

Kim et al. (2011) compared the use of Bluetooth readers to TRANSMIT (RFID) readers and INRIX using data collected along I-287 in New Jersey. The Bluetooth detectors produced the most accurate travel times when compared to the RFID readers and the INRIX data, matching the ground truth more closely. Their study further suggests that Bluetooth detectors can be used to provide accurate travel time.

Chaoqun et al. (2013) evaluated alternative technologies to estimate travel time along a segment of Interstate 91 in Western Massachusetts where traffic volumes and corresponding sample sizes are expected to be relatively low. Their means of data collection included global positions system technology (GPS) technology employed by INRIX, Bluetooth technology and field data collected by another vendor, and, BlueTOAD along the I-91 study site. Data collection using a license plate based method was devised by the authors to provide "ground truth" travel time against which the results of the INRIX and Bluetooth technologies were compared and evaluated. The data analysis showed that sufficient sample sizes were collected and that the accuracy of travel times estimated from data provided by both vendors (i.e., GPS-based INRIX and Bluetooth-based BlueTOAD) is acceptable since their mean absolute percentage errors (MAPE) were consistently less than 6 percent.

Chase et al. (2012) compared 5-min speeds from microwave radar and acoustic sensors with link speeds from GPS probes for both directions at five freeway locations. Systematic differences were found at one location. Floating car GPS runs were performed to confirm that the systematic error lay in the point speeds. They presented a comparative evaluation of reported speeds from collocated point- and link-based speed detection systems at five bidirectional freeway locations. Systematic speed differences occurred at nearly all study locations, but the mean speed difference was unique to each site. Speeds from GPS floating car runs closely matched INRIX speeds at locations with large speed differences between INRIX and Traffic.com.

The University of Maryland (UMD) team and State Highway Agency (SHA) plan and investigate the effect of data source on freeway travel time reliability assessment and has unrestricted access to the database on a major corridor covering sections of I-95 South, I-495 West and I-270 North. The area is covered by a number of permanently installed Bluetooth sensors. The data has been constantly reported and archived since September 2011 and the UMD team has unrestricted access to the database. At the same time, SHA has procured INRIX data on the same corridor. Since 2008, the UMD team has published several validation reports on INRIX data performance on both I-95 and I-495 as part of the I-95 Corridor Coalition Vehicle Probe Project (VPP). Their validation results showed that INRIX meets quality standards to be used as a source for travel time data.

2.4. Limitations of Past Research

In the past, research has been done to validate travel times obtained from various sources such as Bluetooth devices, INRIX, GPS etc. based on corridor level analysis and not based on link level analysis, which is covered in this project. Characteristics of a corridor vary from link to link which can alter the travel time studies, which can be addressed only by conducting link level analysis.

Previous research has proven that Bluetooth devices can be affectively used for travel time studies on freeways but only a few researchers have worked on arterial streets and the accuracy of travel times obtained on them. This project focuses more on the arterial streets although travel times on a freeway have also been included. Also, the role of network characteristics in travel time data collection has been looked into in this study.

CHAPTER 3: DATA COLLECTION AND SOURCES

To capture travel time information and to compare the travel times from various data sources such as manual floating car method, GPS floating car method, Bluetooth detectors and INRIX, six corridors that consist of five arterial roads and one Interstate freeway segment in the City of Charlotte, North Carolina were selected as study corridors in this research. The corridors were selected such that they cover major areas surrounding the Charlotte Center City, which is the Central Business District with major commercial and industrial zones (Figure 1). Table 1 summarizes the characteristics of each selected corridor. The selection was basically done based on the link length (at least 5 miles), presence of transit (bus) routes, annual average daily traffic (AADT), schedule of bus service on weekdays or weekends, the number of lanes, type of corridor (arterial, freeway), and speed limit.

The characteristics of study segments were made sure to be different so as to test the effectiveness of various technologies in collecting data under different conditions. One segment is a freeway (I-85), which is actually an express route (Union County Express) providing services on a typical weekday. Two segments are along selected major arterial streets (transit routes 11 and 20), while the remaining three segments are along minor arterial streets (transit routes 12, 14 and 22).

The travel time data was collected for two days along each corridor. Travel times for different time periods were captured to evaluate the effectiveness of the methods and technologies in collecting data by time period. It was collected from 7 AM - 9 AM, 11

AM - 1 PM, 4 PM - 6 PM on day 1 and 7 AM - 10 AM and 3 PM - 6 PM on day 2. With Charlotte Uptown as center, the direction of travel is identified as either Inbound or Outbound. In this study, 7 AM - 10 AM and 3 PM - 6 PM are considered as morning and evening peak, respectively.

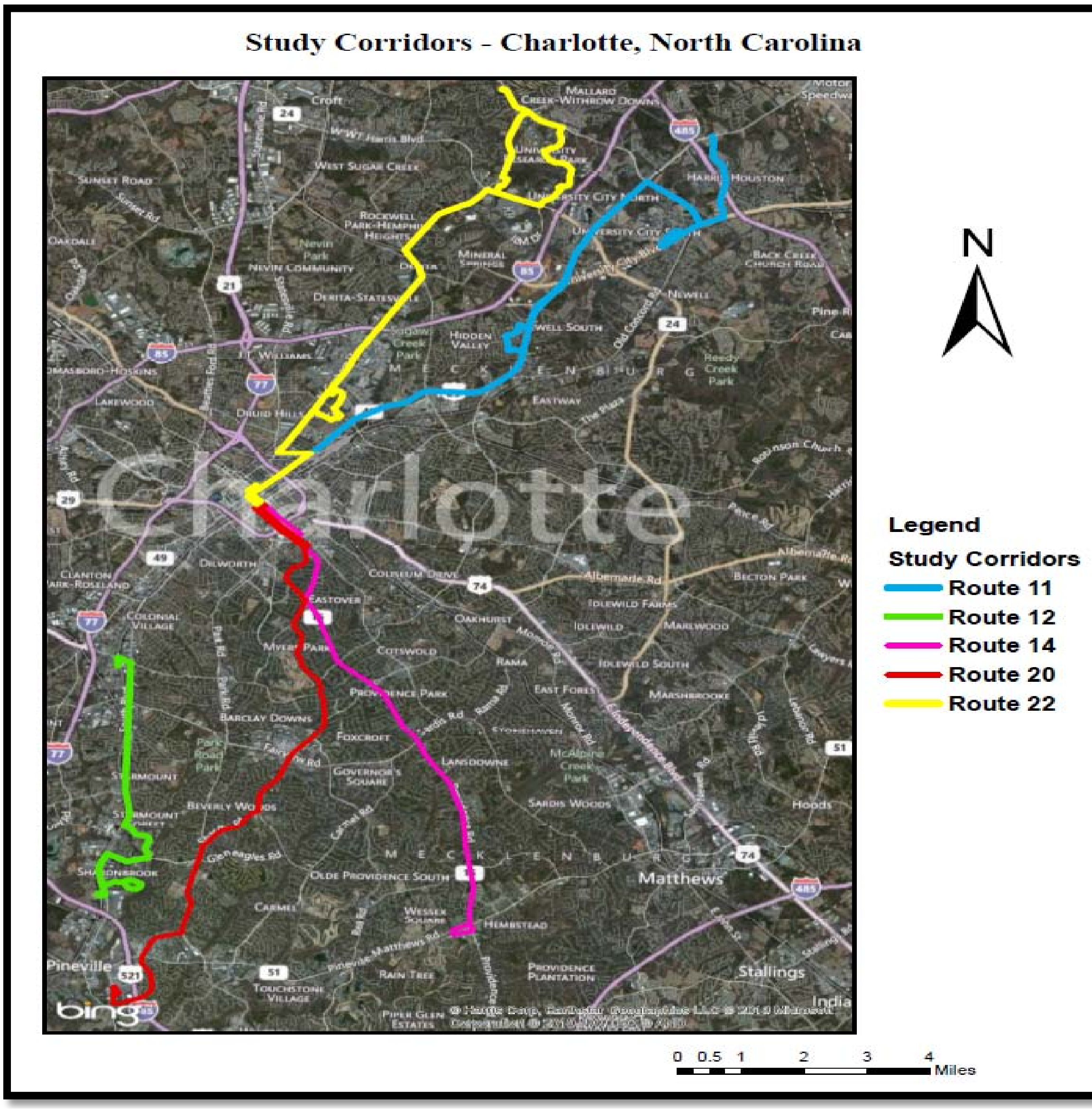

Figure 1: Study Corridors Selected in Charlotte, North Carolina

Table 1: Characteristics of the Selected Six Corridors for the Study

Route Number	Route Name	Type	No. of Lanes	AADT	Speed Limit (mph)
11	North Tryon	Major Arterial	3	25,000-30,000	45
12	South Blvd	Arterial	2	20,000-25,000	40
14	Providence Road	Arterial	2	30,000-40,000	45
20	Sharon Road	Local	2	14,000-20,000	35
22	Graham Street Road	Arterial	2	14,000-20,000	45
I-85	Interstate 85	Freeway	4	30,000-60,000	65

3.1. Manual/GPS Probe Vehicle for Travel Time Studies

Travel time data was collected along selected corridors using floating car method (example, Figure 2). In this study the data collected manually is considered as the ground truth. For the manual data collection, travel time data collection sheets were created for all the segments, for both inbound and outbound direction. Each paper form contained all intersections and bus stops along each selected corridor where the arrival times are noted. The distance from one intersection to the next intersection (or location) is defined as a section. The intersections that were used as the start/end of a segment are identified based on the location of the Bluetooth detectors and Traffic Message Channel (TMC) codes (points where INRIX data are available). The manual data collected are tabulated in the spreadsheets separately for each run and route. The times noted at each intersection are used to compute travel times between each intersection along each route (and run) for morning, afternoon and evening peak hours individually.

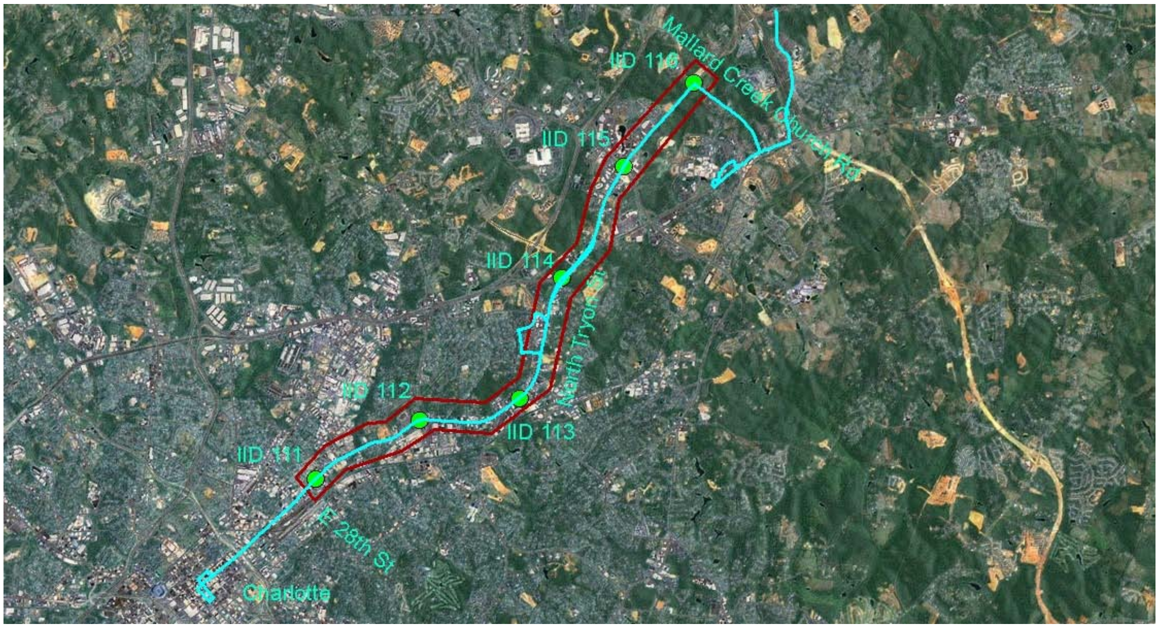

Figure 2: Route 11 (North Tryon) with Intersection Locations

Figure 3: Trained Technicians Collecting GPS and Manual Travel Times

In addition, a GPS unit was placed in the floating test car. The GPS unit is attached to a laptop available in the car to control the runs and download the data as and when required. PC Travel suite was used to process travel time and delay data between the selected intersections of all six segments. This software package has two portions: GPS2LT2 and PC-Travel. While GPS2LT2 collected the field data in GD2 format, PC-Travel processed the data to compute travel speeds and travel times. To get accurate data, GPS unit was detected by at least 3 satellites to locate the car at the right coordinates. TMC codes for the intersections that have Bluetooth detectors installed are exported into the PC Travel software using GIS based files (Figure 4). With the help of these TMC codes the travel times are collected for each section for different runs during different times of the day. The computed details were exported as an excel file.

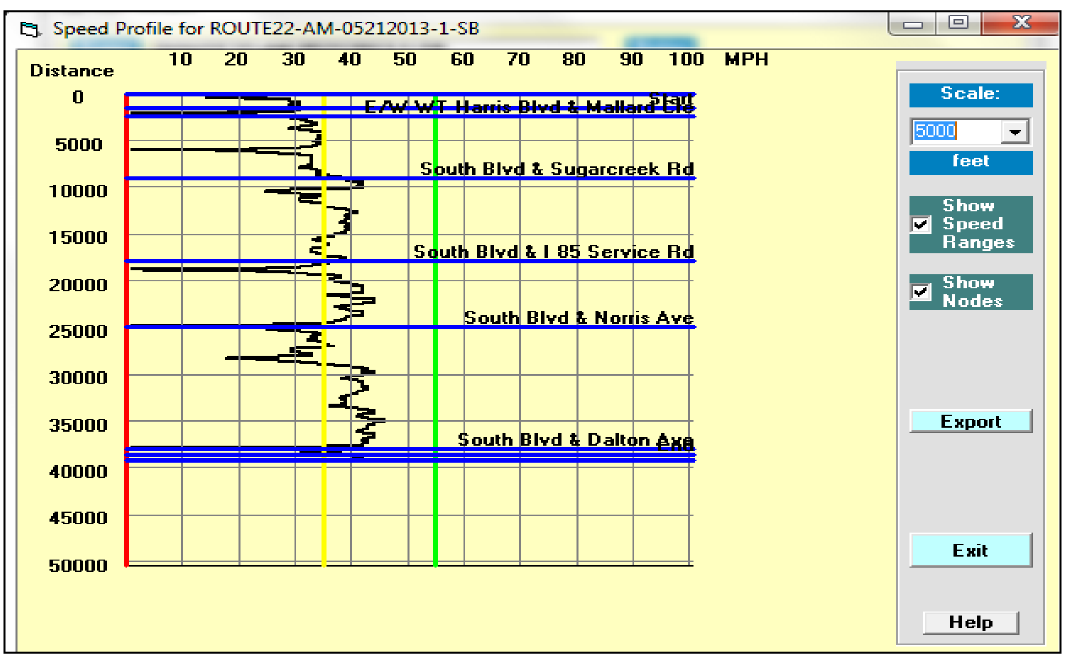

Figure 4: Travel Time Information by Distance using GPS from PC Travel Suite

In the floating car, three trained technicians participated in the field data collection during each run (Figure 3). The first person noted the arrival time on the sheet manually and the second person captured data at the same location using GPS and also runs the stop watch to let the first person note down the time at the start/end of section, while the third person drives the vehicle within the speed limits on a particular corridor.

3.2. Bluetooth Detectors for Travel Time Studies

Travel times were captured using Bluetooth detectors that were placed at 5 to 6 intersections along each corridor. Six Cross Compass (dual Bluetooth and Wi-Fi) detectors with 4GB Acyclica USB Flash Drives were used for Bluetooth data collection. The detectors were provided with Location ID (identifier referring to the specific location of the device), Group ID (identifier referring to a group such as intersection or arterial street), Device Name, Device Description, and Owner information prior to each data collection process. Time Synchronization is a very important factor.

The Bluetooth detectors could encrypt the data at the device level in order to maintain truly anonymous data and provide information using a secure 256-bit hash. As this hash is one-way and each device uses the same algorithm, matching using the encrypted string was as simple as matching individual MAC addresses. The detectors could also provide data in plain text in the form of 6 octets. For this study research, the data was collected in both encrypted and plain text format.

The Bluetooth detectors were installed at 1- to 2-mile intervals along each segment. The detectors were installed near the intersection for easy access of power from the signal controller cabinet or traffic monitoring camera box with the help of North Carolina Department of Transportation (NCDOT) and Charlotte Department of Transportation (CDOT) staff. As one of the research objectives was to compare travel times from different sources, the signalized intersections for the installation of Bluetooth detectors were selected in such a way that the position of TMC codes (points where INRIX data are available) matched with the position of these intersections. As mentioned earlier, manual and GPS data was also gathered at the same points.

The mounted height of the antenna to capture data using Bluetooth detectors varied between 7.5-10 feet along the arterial streets (Figure 5). However, the mounting height along I-85 varied between 10 to 15 feet as the traffic monitoring camera boxes were at higher elevation than the ground level. Data was collected using the Bluetooth detectors, continuously for at least 48 hours, for each section along each segment. They were installed the day before the collection of manual and GPS data (Figure 6). The Bluetooth detectors were uninstalled the day after the manual and GPS data collection was completed.

After uninstalling the Bluetooth detectors, raw data was downloaded from the flash drives connected to the detectors. The data were then uploaded to Acyclica Analyzer website (https://cr.acyclica.com/) for processing the raw data. From the same website, travel times are noted down by the run and by ToD with reference to the manual times obtained from floating car method for each route. Figure 7 shows the travel time variations for section 3 of Route 22 (Outbound). Travel times for each section are shown separately for all the days the device was installed. By selecting the required time and direction of run, the average travel time for all the vehicles at that particular time is noted down.

For an accurate estimation of travel times from Bluetooth detectors (overcome the effect of data outliers), a filtering technique based on minimum and maximum speeds on a corridor is developed and applied. Based on the minimum and maximum speeds, travel

Figure 5: Bluetooth Detector (Left) Installed in a Cabinet by Research Team (Right)

Figure 6: Trained Technicians Installing the Bluetooth Detectors in the Signal Control Cabinets

times are computed and the data obtained from the raw data from Bluetooth detectors was processed for each section. The use of ±1.5 min, ±2.5 min and ±5 min as filter range for each travel run was also examined. These filter ranges were applied to the run time for each run. For example, if a manual run starts at 8:00:00 AM and ends at 8:03:00 AM on a particular section and for filter range of ±1.5 min, the samples that are detected by the detector during 7:58:30 AM to 8:04:30 AM are taken into consideration for that particular run . Based on these filter ranges, the average travel times for each run was collected from Bluetooth detectors. Microsoft SQL Server was used to filter and note down the average travel times.

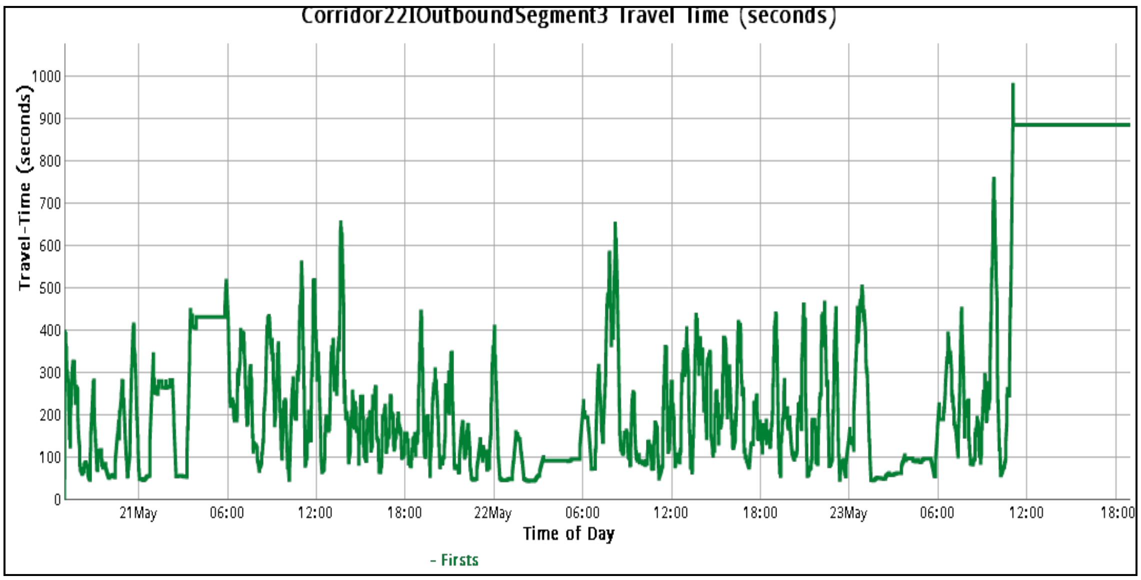

Figure 7: Travel Time Variations for Outbound Section 3 of Corridor 22

3.3. INRIX for Travel Time Studies

Access to the INRIX data is granted once a member agency has signed a Data User Agreement. INRIX delivers files to the customers via a Web Services Application Programming Interface (API). All API requests are made via Hypertext Transport Protocol (HTTP). Requests were made to obtain data for the same days on which manual and GPS data were collected, for each selected road segment through the web interface. The files were received in .CSV format. Each file has the following details.

1. C-Value - designed to provide supplemental information to the ‘score’ attribute to best identify the type and confidence of the data being sent by INRIX.
2. Reference Speed (RS) - an uncongested “free flow” speed determined for each road section using the INRIX Traffic Archive.
3. Calculated Speed (CS) - all archived speeds for each minute each day for each road section calculated for each month - e.g., Monday from 6:00 AM to 6:01 AM on April 2012; and, a “calculated speed” for each time slot established for each road section.
4. Traffic Message Channel (TMC) - defines a section of road.

The data from INRIX is obtained for all the study corridors for the entire data collection period (Figures 8 & 9). For better comparison of methods and technologies for travel time data collection, the travel time from Bluetooth detectors and INRIX was extracted for each travel time run on each data collection day. Based on the start and end times of the manual runs, travel times are collected for all the six corridors in both inbound and outbound directions. As an example, if the test car travelled along a section from point “A” and arrived at 8 AM at point “B”, the travel time at point “B” was extracted at 8 AM from Bluetooth detectors and INRIX for analysis and accurate comparison.

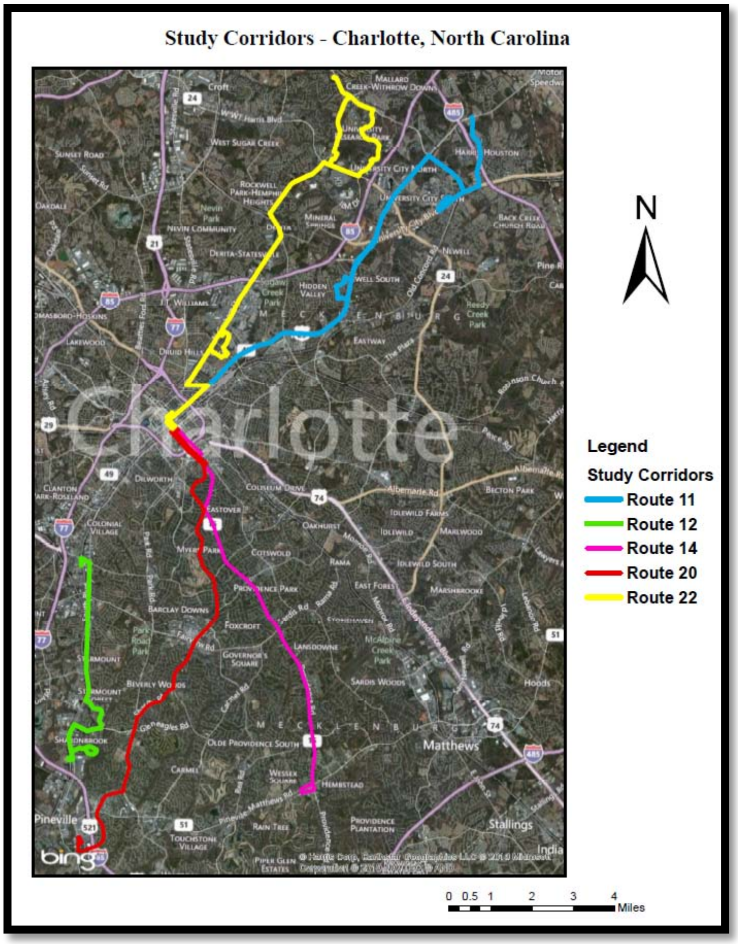

Figure 8: INRIX Data for Charlotte, North Carolina

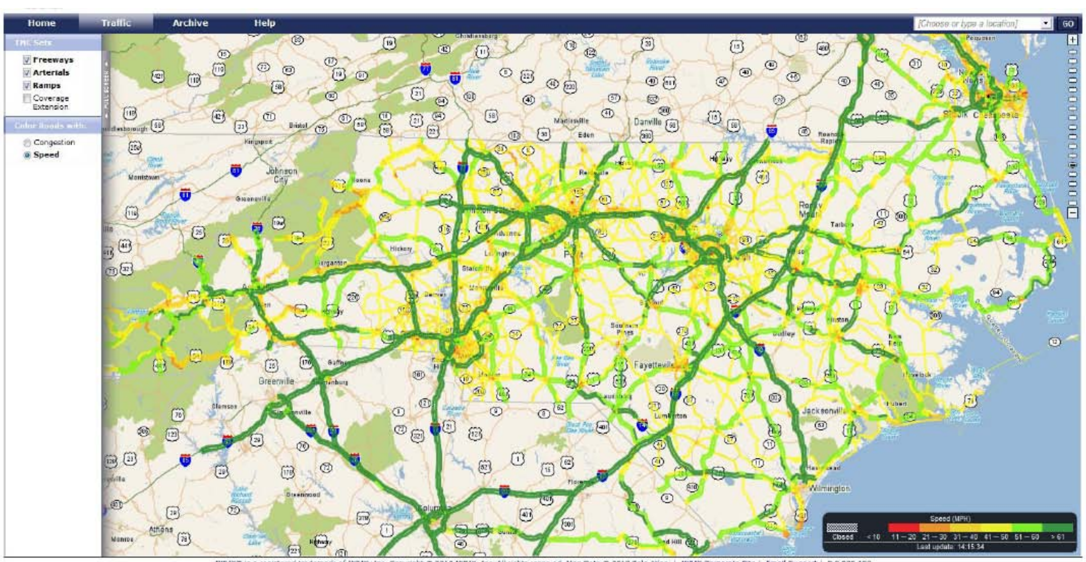

Figure 9: INRIX Data Showing Traffic Trend in North Carolina

CHAPTER 4: RESULTS AND ANALYSIS

The travel times collected manually, using GPS unit, Bluetooth detectors and INRIX are compared for each section for different time periods. In case of Bluetooth detectors, travel times obtained from both Acyclica filtering technique and filtering technique using start and end times are used in comparison with other sources. In addition, the role of network characteristics on travel times obtained from the above mentioned sources is discussed in this chapter.

4.1. Travel Time Comparison based on Acyclica Filtered Bluetooth Data

The travel times are compared at a micro-level- for each run along each section on each segment for different time periods. Table 2 shows travel times collected manually and the percentage difference observed from the GPS unit, Bluetooth detectors and INRIX during mid-day and evening peak periods on day 1 along South Blvd study sections. Similarly, Table 3 shows data collected on day 1 along I-85 study sections.

It can be noticed from the tables 2 and 3 that travel times from GPS are very close to those collected manually. This can be accounted to the fact that the GPS travel times have been collected from the same probe vehicle that was used for the manual data collection. While travel times from Bluetooth detectors and INRIX are fairly close to manual travel times along I-85, travel times from Bluetooth detectors are observed to be significantly higher on sections along South Blvd (Table 2) and other arterial streets.

Table 2: Mid-day and Evening Peak Runs along South Blvd Inbound Direction

ID	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)
5/29/2013	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	89.2	91.1	1.0	11.8	77.2	90.0	1.1	31.3	144.4
2	128.3	0.5	1.9	54.7	115.8	0.2	15.0	77.4	137.5	0.4	-7.1	98.5
3	323.4	0.2	-40.4	-40.1	323.8	0.1	-35.0	-18.4	246.7	0.5	-14.6	-7.9
4	126.6	0.3	-24.2	-27.1	123.9	0.9	-17.2	19.2	119.8	-2.3	-22.4	-18.4
5/29/2013	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	-12.6	184.0	-3.8	-49.7	-12.3	173.0	1.2	-46.5	-6.7
2	146.3	36.7	5.0	46.4	225.8	-0.4	-22.9	-3.0	211.1	0.4	-32.4	-5.7
3	244.2	-40.2	-11.1	-13.3	319.8	0.1	-46.0	-26.8	380.2	-0.1	-31.8	-43.2
4	157.9	-43.6	-16.8	-50.0	163.1	0.6	-37.1	-27.0	146.5	0.3	-50.9	-26.2

Table 3: Mid-day and Evening Peak Runs along I-85 Inbound Direction

ID	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)
6/25/2013	Run 1 (Time) 11:03 AM				Run 2 (Time) 11:28 AM				Run 3 (Time) 11:51 PM			
1	91.2	-0.2	28.1	-38.3	91.5	-1.6	114.4	-38.5	91.7	-0.8	28.0	-39.0
2	92.6	-0.6	-7.6	-38.4	92.6	0.4	-57.9	-33.9	91.2	-0.2	-8.6	-37.5
3	48.6	-1.2	-17.3	-16.5	48.7	-3.5	-19.9	-16.6	50.6	-1.2	-20.6	-24.9
4	104.3	-0.3	-14.9	2.4	102.3	-0.3	-15.0	6.6	105.4	-0.4	-16.9	3.0
6/25/2013	Run 1 (Time) 4:07 PM				Run 2 (Time) 4:33 PM				Run 3 (Time) 5:13 PM			
1	90.7	0.3	-0.1	-27.0	90.8	0.2	29.3	-37.2	90.1	1.0	30.3	-37.3
2	94.1	1.0	-10.1	-33.3	90.3	-0.3	-5.6	-37.3	81.4	2.0	4.7	-34.5
3	53.4	3.0	-27.0	-25.1	49.3	-0.6	-19.7	-22.5	50.1	1.8	-22.2	-26.1
4	104.5	-1.4	-15.0	12.5	102.3	-1.3	-12.6	2.4	103.6	-0.6	-15.6	2.2

To better assist in comparing the results, the percentage difference in travel time from GPS units, Bluetooth detectors, and INRIX when compared to manual data was computed for each run and section. They were categorized into six different percentage range categories (0-10 percent, 10-20 percent, 20-30 percent, 30-40 percent, 40- 50 percent, and >50 percent). The numbers of samples (frequency) that fall in each category were summarized for each section. Figure 10 shows the number of samples in different travel time ranges (range of percentage difference in travel times from various sources when compared to travel times collected manually) by study segment.

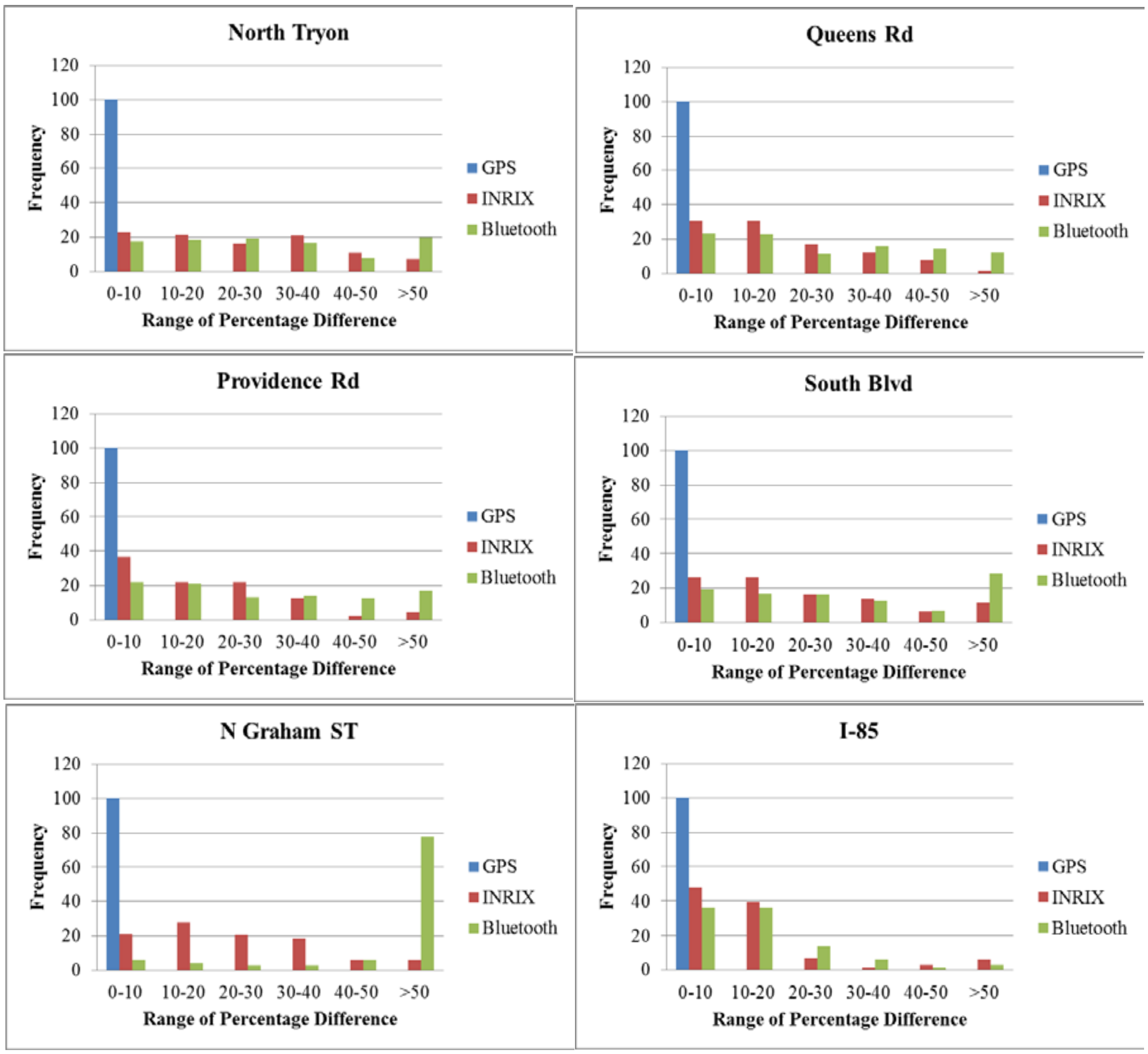

Figure 10: Percentage Difference in Travel Time for Different Segments

From Figure 10, it is evident that travel time obtained manually and from GPS units are close to each other as the percentage variation is always less than 10% for all the six segments. The figure also reveals that travel time reading from Bluetooth detectors

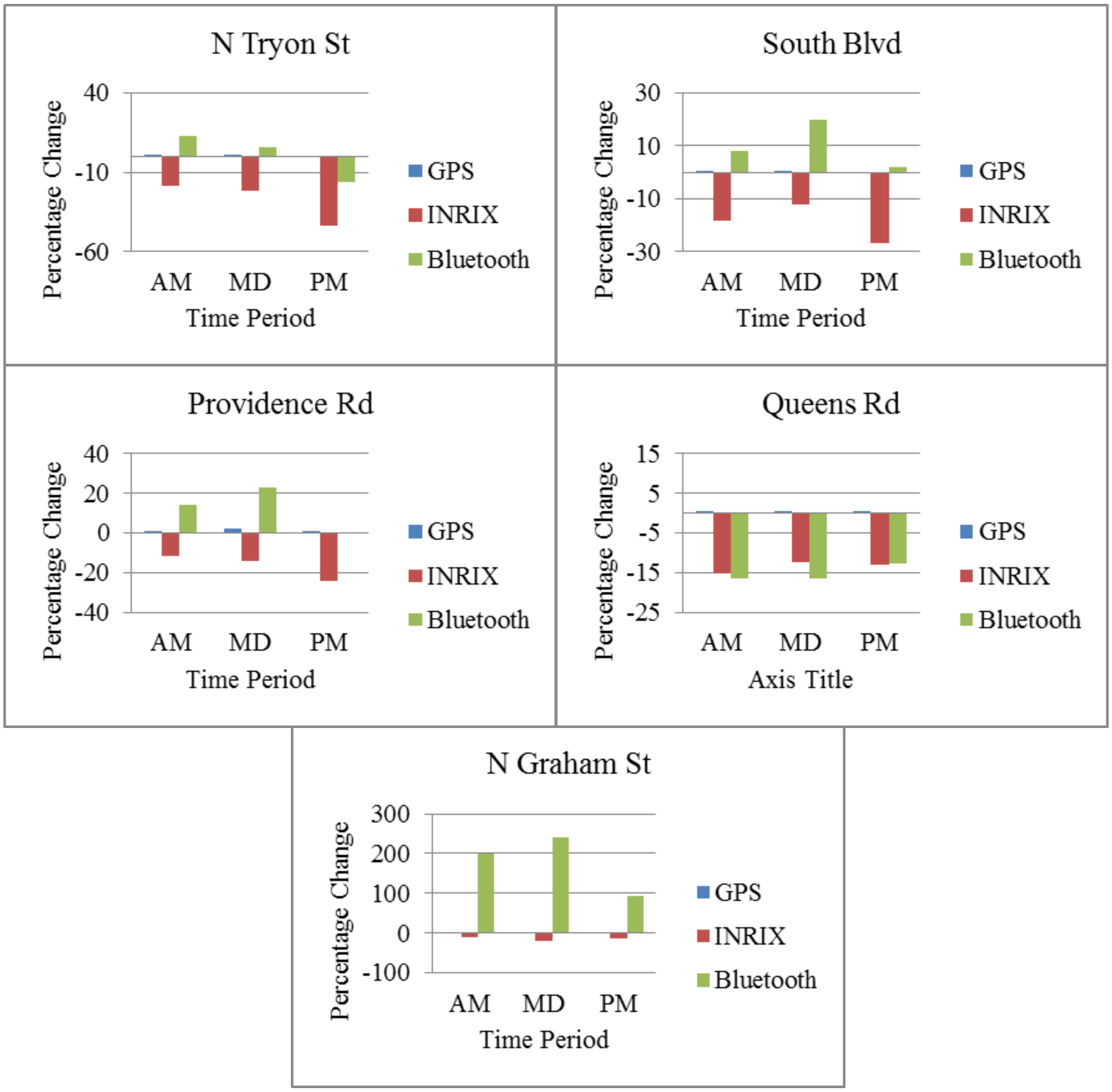

Figure 11: Percentage Difference in Travel Time by Data Collection Period

and INRIX differ from manually collected data. The difference is reasonably high in some cases. For instance, out of the 408 samples gathered along N Graham St, more than 100 samples have percentage difference greater than 50%. To examine the performance over time and account for the effect of traffic on performance, the results obtained were summarized by time period of data collection (Figure 11).

The percentage difference shown in Figure 11 for GPS unit, Bluetooth detectors, and INRIX are in comparison to manually collected travel time. N Tryon St, South Blvd and Providence Rd showed higher percentage difference during evening peak period (almost 30%, 25%, and 45%, respectively) in case of INRIX data. N Graham, Queens Rd, and I-85 showed maximum percentage difference during peak periods in case of Bluetooth detectors. For N Graham St, the percentage difference varied by more than 200%. These results are consistent with those from Figure 10.

To further assess and understand the reasons for the higher percentage differences, Figure 12 was generated for this section on N. Graham St for the entire day. From the figure, it is evident that travel time from manual data collection (based on floating car method) is above the travel time for most of the other vehicles captured using

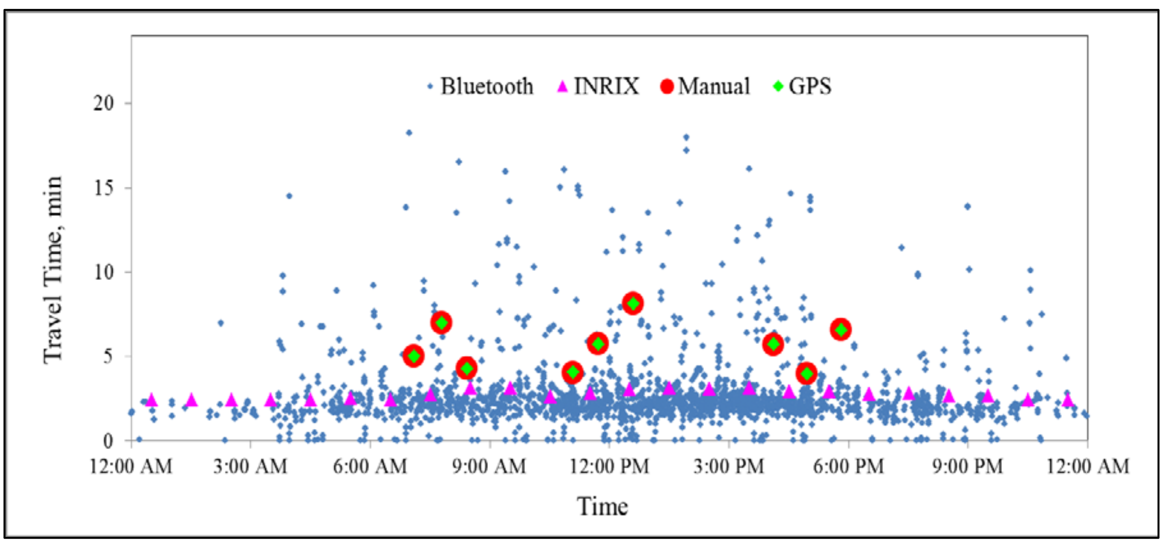

Figure 12: Time Variations along the First Section of N Graham St

Therefore, aggregated travel time shows higher value than the general trend line of travel times when the sample size is low. It is also clear that if the sample size is high, then removing outliers from Bluetooth readings can give almost the same result as INRIX (the trend line of travel time from Bluetooth detectors seems very close to INRIX).

4.2. Statistical Analysis

To compare the travel times obtained from GPS, INRIX, and Bluetooth with the benchmark (manual data), t-tests were conducted at a 95% confidence level. The Null hypothesis, H0: H*Manual* = H*GPS* = H*INRIX* = H*Bluetooth*, while the alternate hypothesis, H1: H*Manual* ≠ H*GPS*≠ H*INRIX*≠ H*Bluetooth*. The results obtained from t-tests are shown in Table 4.

Table 4: Statistical Analyses

For all Routes						
Paired Samples Test						
Pair	Paired Differences					Correlation
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		
				Lower	Upper	
Manual - GPS	-0.44	5.05	0.17	-0.78	-0.10	1.00
Manual - INRIX	37.52	91.96	3.16	31.32	43.72	0.62
Manual - Bluetooth	-66.96	241.56	8.30	-83.24	-50.67	0.30
Arterial Routes						
Manual - GPS	-0.42	5.37	0.20	-0.81	-0.04	1.00
Manual - INRIX	43.18	96.31	3.53	36.25	50.11	0.53
Manual - Bluetooth	-75.27	256.47	9.40	-93.73	-56.81	0.20
Freeway (I-85)						
Manual - GPS	-0.53	0.99	0.10	-0.72	-0.33	1.00
Manual - INRIX	-2.96	27.29	2.68	-8.27	2.34	0.95
Manual - Bluetooth	-7.51	36.07	3.54	-14.52	-0.49	0.98

From the results obtained, the zero is not between the upper and lower bound of 95% confidence Interval. This shows that the difference of the means between manual and GPS, manual and INRIX, and manual and Bluetooth detectors are statistically significant. However, unlike manual and INRIX or manual and Bluetooth detectors, the difference of means between manual and GPS is very low (around 0.4 seconds). The correlation coefficient between manual and GPS is close to 1, which reveals that manual and GPS travel times are almost the same.

The correlation coefficient between manual and INRIX is 0.61, which reveals moderate correlation between the two travel time data samples. For manual and Bluetooth, the correlation coefficient is 0.28 (very low). Considering all the samples of arterial streets, results obtained show a statistically significant difference between the computed means. The correlation coefficient for manual and GPS data on arterial streets is 1 (high correlation), while it is 0.2 for manual and Bluetooth detectors data (very low) and 0.53 for manual and INRIX (moderate). On the other hand, the correlation coefficient is very high for manual and GPS, and, manual and INRIX data for the freeway segment (0.90). It is reasonably high when tested by comparing manual and Bluetooth detectors data for the freeway segment (0.77).

For Interstates, the travel times obtained from Bluetooth are giving slightly better travel time estimates than those collected from INRIX as the correlation with respect to manually collected times are 0.98 and 0.95, respectively. When it comes to arterial streets, Bluetooth detectors performed with lower correlation requiring further data processing and analysis. To improve the accuracy of travel time estimation from Bluetooth detectors, a filtering technique was developed based on start and end times of the probe vehicle used for manual data collection.

4.3. Travel Time Comparison Based on Filtering Technique using Start and End Times

Furthermore, micro-level analysis is done by filtering the raw data obtained from the detectors and compared to travel times collected from GPS and manual runs. Based on the start and end times of the run, 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 to look at differences in travel times.

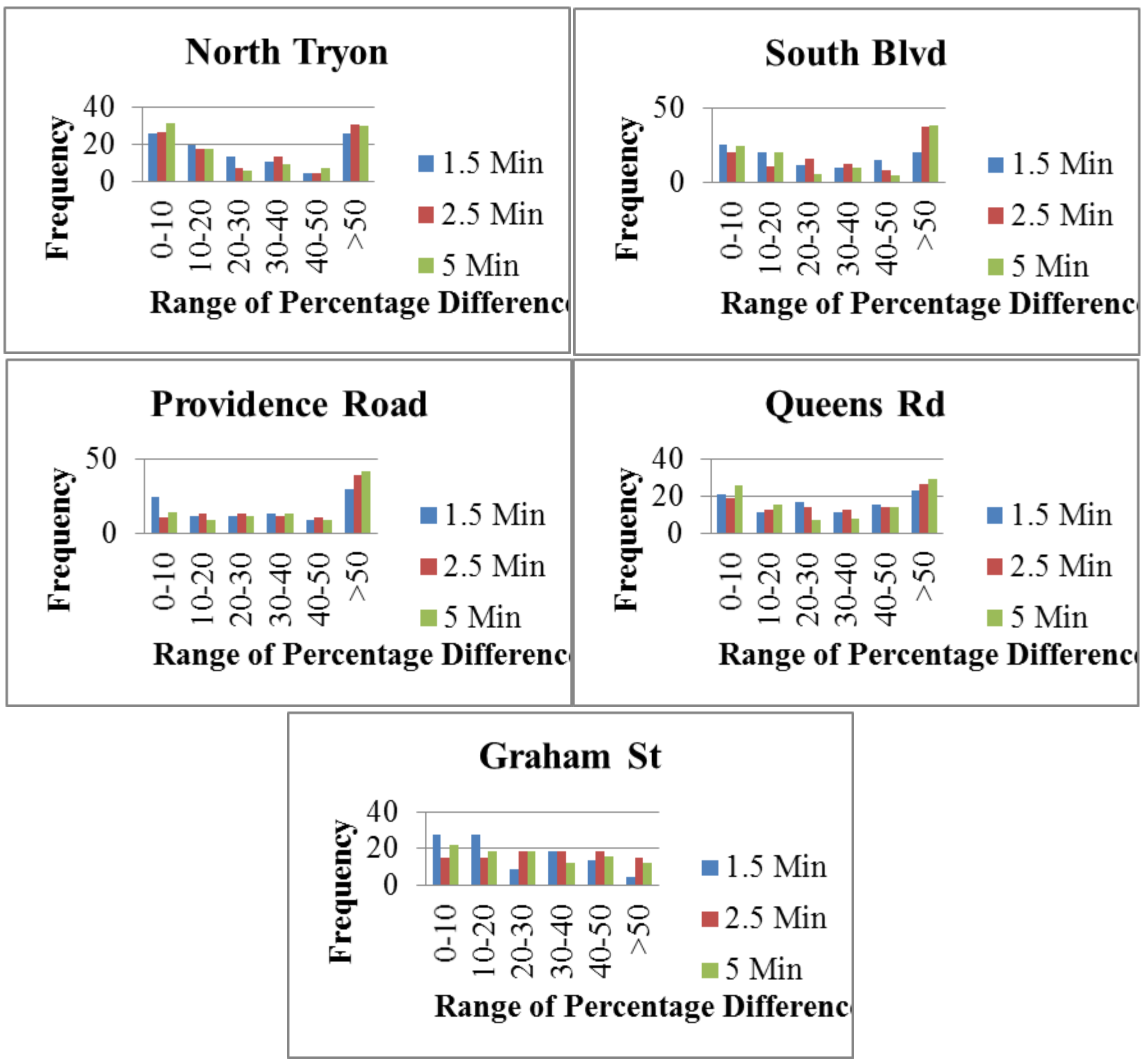

Figure 13: Percentage Difference in Travel Time from Bluetooth Detectors Using Various Filter Ranges

Figure 13 shows percentage difference in travel times from Bluetooth detectors using various filter ranges. Out of the three filter ranges, 1.5 min filter range is observed to yield large sample size and accurate results. Based on 1.5 min filter range, the percentage difference in travel times for arterial streets are graphically represented in Figure 14. As mentioned earlier, the travel times from GPS are in the 0-10% range but the Bluetooth and INRIX travel times are widely spread in all the ranges.

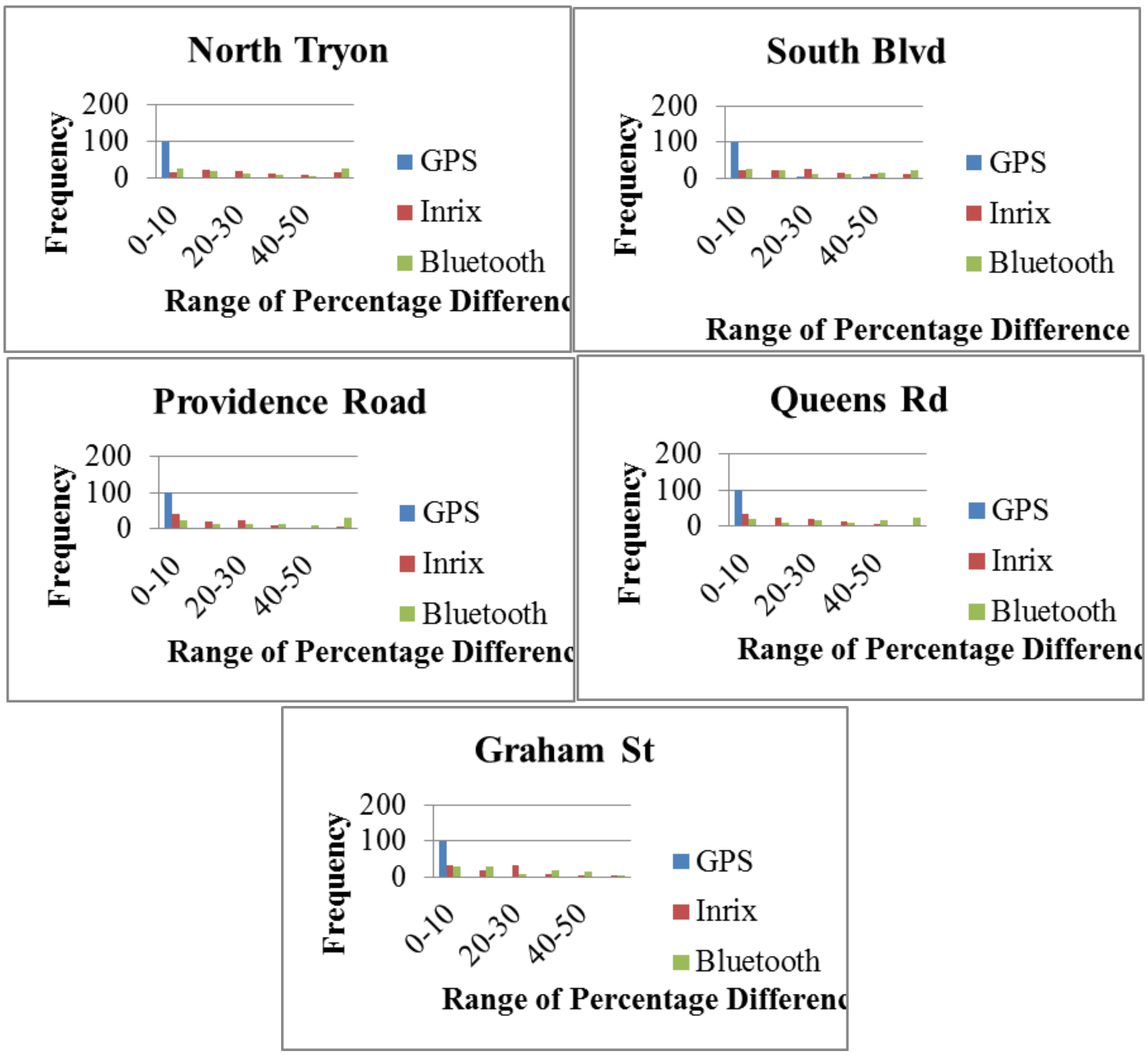

Figure 14: Percentage Difference in Travel Time from Bluetooth Detectors Using 1.5 Min Filter Range

For arterial streets, travel times from INRIX are relatively more accurate than Bluetooth detectors. The frequency in percentage change and periodical percentage change are higher for Bluetooth detectors than INRIX.

Tables 5 and 6 shows the percentage difference in travel time collected using GPS, INRIX and Bluetooth detectors compared to manual run times for both South Blvd and I-85, respectively for 1.5 min filter range.

Travel times collected from Bluetooth detectors and INRIX are observed to have high variations when compared to manual travel times. Travel times collected on freeways are more promising when compared to travel times from arterial streets for both INRIX and Bluetooth detectors. For arterial streets, both Bluetooth detectors and INRIX travel times have higher percentage difference among which travel times from INRIX are found to be better when compared to the travel time from Bluetooth detectors.

Table 5: Mid-day and Evening Peak Runs along South Blvd Inbound Direction

ID	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)
5/29/2013	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	0.5	1.9	72.1	115.8	0.2	15.0	120.3	137.5	0.4	-7.1	77.7
3	323.4	0.2	-40.4	-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
5/29/2013	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

Table 6: Mid-day and Evening Peak Runs along I-85 Inbound Direction

ID	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)	Manual (Sec)	GPS (%)	INRIX (%)	Bluetooth (%)
6/25/2013	Run 1 (Time) 11:03 AM				Run 2 (Time) 11:28 AM				Run 3 (Time) 11:51 PM			
1	91.2	-0.2	28.1	-2.0	91.5	-1.6	114.4	-2.7	91.7	-0.8	28.0	16.2
2	92.6	-0.6	-7.6	-34.1	92.6	0.4	-57.9	-27.1	91.2	-0.2	-8.6	-45.0
3	48.6	-1.2	-17.3	11.0	48.7	-3.5	-19.9	5.3	50.6	-1.2	-20.6	4.9
4	104.3	-0.3	-14.9	-24.0	102.3	-0.3	-15.0	-22.3	105.4	-0.4	-16.9	-30.6
6/25/2013	Run 1 (Time) 4:07 PM				Run 2 (Time) 4:33 PM				Run 3 (Time) 5:13 PM			
1	90.7	0.3	-0.1	21.0	90.8	0.2	29.3	12.9	90.1	1.0	30.3	--
2	94.1	1.0	-10.1	-29.3	90.3	-0.3	-5.6	-43.2	81.4	2.0	4.7	-18.0
3	53.4	3.0	-27.0	0.1	49.3	-0.6	-19.7	12.7	50.1	1.8	-22.2	-6.0
4	104.5	-1.4	-15.0	-32.7	102.3	-1.3	-12.6	-33.2	103.6	-0.6	-15.6	-28.7

4.4. Sample Sizes by Time of Day

To further assess the data, Table 7 and Figure 15 show the effect of sample sizes and link length on travel time estimation from Bluetooth detectors. As the link length increases the sample sizes increases. Further, the percentage error in travel times decreases. For lower sample sizes the percentage errors show no pattern. However, the errors are observed to be on the lower side for higher sample sizes.

Table 7: Effect of Sample Size and Link-length / Spacing on Data Quality

South Blvd Inbound								
	Link1 (1.3 miles)		Link 2 (1.3 miles)		Link 3 (1.9 miles)		Link 4 (0.8 miles)	
	Sample Size	Percent Error	Sample Size	Percent Error	Sample Size	Percent Error	Sample Size	Percent Error
Mid-day	4	89.2	7	54.7	12	-40.1	2	-27.1
	6	77.2	2	77.4	24	-18.4	6	19.2
	4	144.4	8	98.5	12	-7.9	5	-18.4
	9	40.3	6	67.1	15	-23.4	5	-10.2
Evening	6	-12.6	4	46.4	8	-13.3	5	-50.0
	9	-12.3	1	-3.0	12	-26.8	5	-27.0
	5	-6.7	4	-5.7	6	-43.2	2	-26.2
	7	104.6	2	13.1	9	-44.3	16	0.4

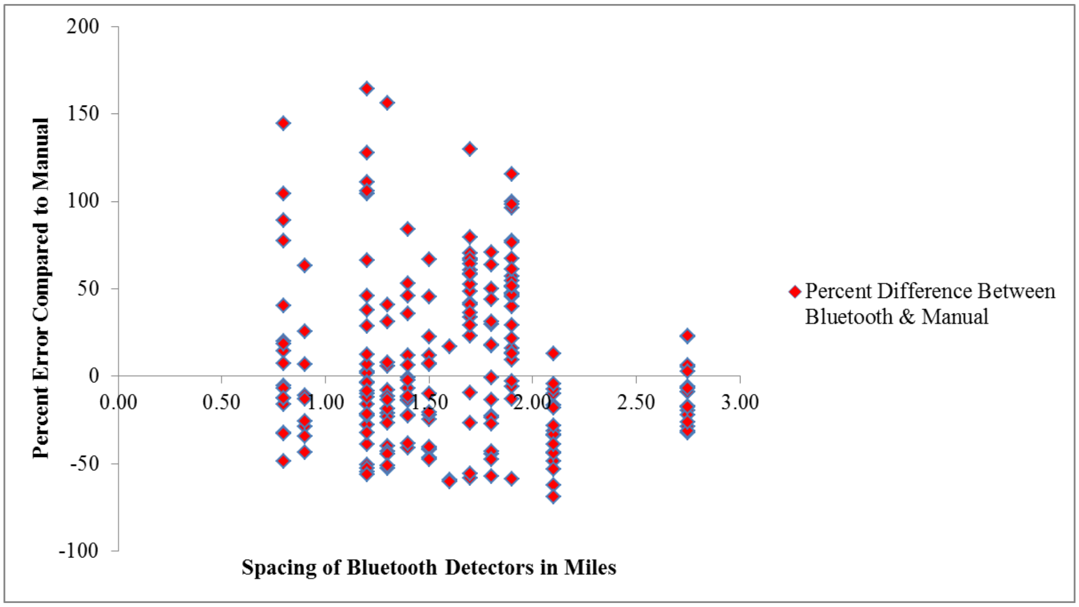

Figure 15: Relation between Bluetooth Detector Spacing and % Difference

Table 8: Effect of Sample Size and Link-length / Spacing on Data Quality for Various Filter Ranges

South Blvd – Inbound Direction Evening Peak									
Filter Ranges	Run	Link1 (1.3 miles)		Link 2 (1.3 miles)		Link 3 (1.9 miles)		Link 4 (0.8 miles)	
		Sample Size	% Error	Sample Size	% Error	Sample Size	% Error	Sample Size	% Error
1.5 Min	1	5	-12.6	4	46.4	8	-13.3	7	-50
	2	10	-12.3	3	-3	11	-26.8	6	-27
	3	5	-6.7	7	-5.7	6	-43.2	5	-26.2
	4	6	104.6	2	13.1	9	-44.3	19	0.4
2.5 Min	1	5	96.1	5	42.4	11	16.7	8	-10.5
	2	11	-32.9	4	94	13	22.1	7	-22.4
	3	5	-48.8	8	21.4	11	-60.4	5	-66.9
	4	6	11.8	4	51.7	12	62	21	335.9
5 Min	1	15	-12.5	7	46.4	18	4.6	19	-58.7
	2	16	7.3	8	44.2	16	-18.6	12	-42.7
	3	12	54.9	12	12.4	13	-30.4	9	18.8
	4	10	177.1	6	13.1	27	-40.8	26	31.7

Table 8 shows the effect of sample sizes and link length on data quality for different filter ranges. Travel times from 1.5 min filter ranges have lesser sample size but the error values are lower when compared to other filter ranges.

Table 9 shows the sample sizes based on ToD. Sample sizes are the number of links for which travel times are available. For INRIX, the sample sizes shown are not the actual counts but are equivalent to the manual runs. In the case of Bluetooth detectors, the sample sizes are the number of detections summed up for all the links. Interestingly, the sample sizes for Bluetooth detectors seem to be less in the morning peaks and higher during mid-day and evening peaks. This may be because of higher noise levels/disturbance, weather and environmental conditions or varying traffic volumes.

Table 9: Sample Size by Time-of-Day (ToD)

Sample Sizes for Arterial Roads				
Technology/Source		AM Peak	Mid-day	PM Peak
Manual/GPS		332	140	296
INRIX		332	140	296
Bluetooth	1.5 Min Buffer	63	704	1222
	2.5 Min Buffer	83	933	1550
	5.0 Min Buffer	122	1458	2426

Sample sizes based on time of day for the arterial routes have been compiled together to see which routes have better results and what might be the reason for lower sample sizes during morning peak period. Figure 9 shows the sample sizes collected during each hour using Bluetooth detectors on arterial streets. As stated above the sample size during the morning period was way lesser then that compared to other time periods.

Route 12 and 20 gave better results compared to other routes. The sample size collected from all the other routes are on the lower side when compared to route 12 and 20. Table 10 and Figure 17 shows the sample sizes based on time periods on arterials. As the filter range increases the sample sized tend to increase. As the day progresses the size of detections have also increased.

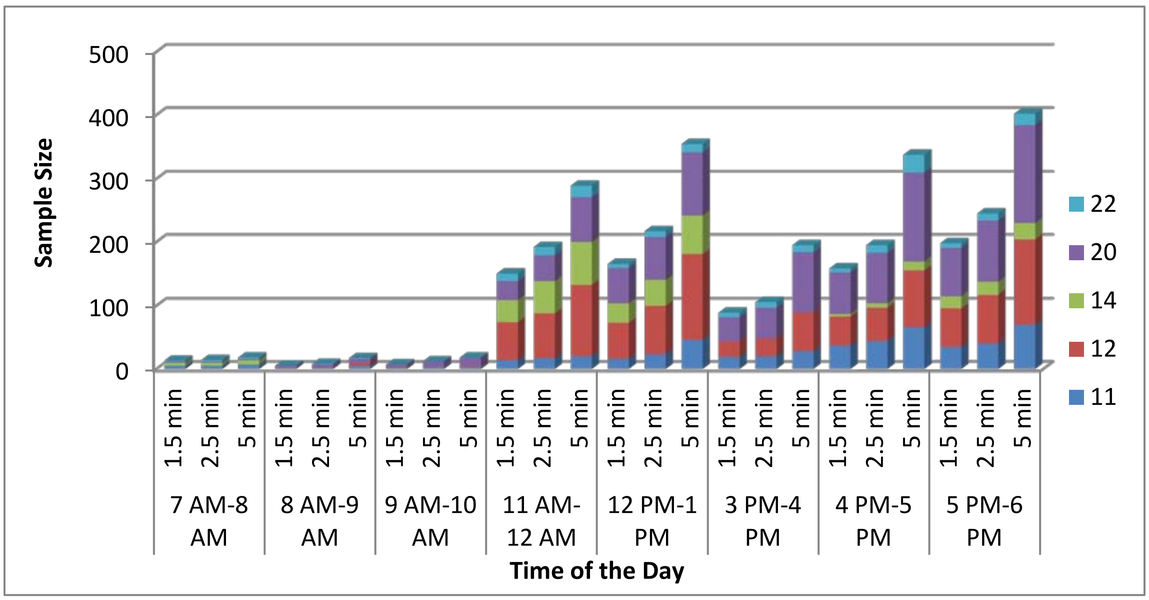

Figure 16: Sample Sizes Collected During Each Hour from Bluetooth Detectors

Table 10: Sample Sizes Based on Time Period for Arterials

Route	AM Peak (7 AM-10 AM)			Mid-Day (11 AM-1 PM)			PM Peak (3 PM-6 PM)		
	1.5 min	2.5 min	5 min	1.5 min	2.5 min	5 min	1.5 min	2.5 min	5 min
11	6	9	15	30	40	66	91	104	164
12	1	2	7	117	148	247	132	158	284
14	5	5	7	66	90	129	23	27	40
20	12	15	21	84	109	171	179	225	391
22	1	3	3	18	22	31	20	32	56
All	25	34	53	315	409	644	445	546	935

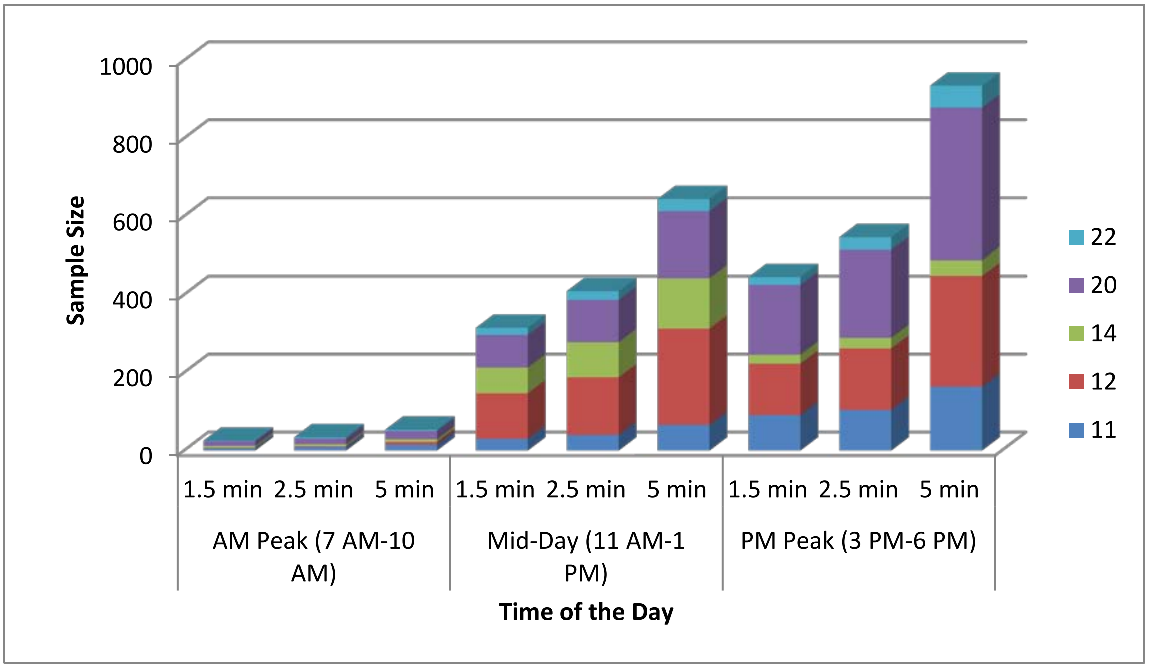

Figure 17: Sample Sizes Based on Time Period for Arterials

4.5. Statistical Analysis Based on Filtering Technique using Start and End Times

To compare the travel times obtained from GPS, INRIX, and Bluetooth based on filtering technique using start and end times with the benchmark (manual data), t-tests were conducted at a 95% confidence level. The Null hypothesis, H0: H*Manual* = H*GPS* = H*INRIX* = H*Bluetooth*, while the alternate hypothesis, H1: H*Manual* ≠ H*GPS*≠ H*INRIX*≠ H*Bluetooth*. The results obtained from t-tests are shown in Table 11.

From the results obtained, the zero is not between the upper and lower bound of 95% confidence interval. This shows that the difference of the means between manual and Bluetooth detectors based on filtering technique using start and end times are statistically significant. From the results shown in Table 4 and Table 11, one can infer that by using this filtering technique the mean, standard deviation and the standard error mean have reduced significantly. This shows that the method can be used to filter

Bluetooth data. The correlation between manual and Bluetooth travel times has increased to 0.49 from 0.3 by using this technique. Out of the three filter ranges used, 1.5 min filter range gave better results.

Table 11: Statistical analyses of Travel Times Obtained by using 1.5 Min Filter range

Paired Samples Test						
Pair	Paired Differences					Correlation
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		
				Lower	Upper	
Freeways and Arterial Streets Combined Together						
Manual - Bluetooth	17.33	107.41	6.20	5.13	29.54	0.49
Arterial Routes						
Manual - Bluetooth	15.35	113.08	7.86	0.14	30.85	0.23

4.6. Role of Network Characteristics

Network characteristics such as speed limits, the number of signalized and un-signalized intersections, the number of turnings, the number of bus stops, vehicular volumes, direction of travel, and time of day play an important role in variation of travel times. These characteristics are collected for all the section along each study segment. Statistical analysis is done to examine their role in variations of travel times collected manually, GPS, INRIX and Bluetooth detectors.

Statistical analysis software, SPSS, was used to generate a correlation matrix between the above mentioned characteristics. Correlation between the dependent variable and the other roadway characteristics was determined. A Pearson correlation value less than -0.3 or greater than 0.3 is considered to be significant. Further, multi-collinearity between variables was considered. From the correlation matrix, it was determined which variables should be used to create the model.

Since the travel times are linear and are not normally distributed generalized linear models were developed. Before developing the models, correlation is developed between all the variables. Table 12 shows the correlation between dependent variable (travel times) and other variables used in the models. Although a few other variables are correlated with the travel times, they are not used in the models due to multi-collinearity.

Table 12: Correlation Matrices for Travel Times from Various Sources and the Variables Used in the Models

Correlations

		M_TT	SIG	TURN
M_TT	Pearson Correlation	1	.248**	.214*
	Sig. (2-tailed)		0.005	0.016
	N	127	127	127
SIG	Pearson Correlation	.248**	1	0.083
	Sig. (2-tailed)	0.01		0.352
	N	127	127	127
TURN	Pearson Correlation	.214*	0.083	1
	Sig. (2-tailed)	0.02	0.352	
	N	127	127	127

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		GPS_TT	DR_R	TOD
GPS_TT	Pearson Correlation	1	.320**	.233**
	Sig. (2-tailed)		0	0.01
	N	126	126	126
DR_R	Pearson Correlation	.320**	1	0
	Sig. (2-tailed)	0		1
	N	126	126	126
TOD	Pearson Correlation	.233**	0	1
	Sig. (2-tailed)	0.009	1	
	N	126	126	126

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

		B_TT	SIG	BUSTP
B_TT	Pearson Correlation	1	.311**	.230*
	Sig. (2-tailed)		0.001	0.014
	N	115	115	115
SIG	Pearson Correlation	.311**	1	-0.091
	Sig. (2-tailed)	0		0.334
	N	115	115	115
BUSTP	Pearson Correlation	.230*	-0.09	1
	Sig. (2-tailed)	0.01	0.334	
	N	115	115	115

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		L_TT	SIG
L_TT	Pearson Correlation	1	.525**
	Sig. (2-tailed)		0
	N	129	129
SIG	Pearson Correlation	.525**	1
	Sig. (2-tailed)	0	
	N	129	129

**. Correlation is significant at the 0.01 level (2-tailed).

Table 13 shows the parameter estimates and the models developed to check the effect of the selected variables on travel times. The results from the table state that as the number of signalized intersections increase on a section of roadway the time taken to travel on that intersection increases. In case of travel times collected from INRIX, residential driveways are significant too.

Table 13: Parameter Estimates for Different Travel Time Sources

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	84.301	4.5973	75.29	93.311	336.251	1	0
SIG	11.491	2.4615	6.667	16.315	21.793	1	0
DR_R	1.859	0.2671	1.335	2.382	48.428	1	0
(Scale)	477.100[a]	66.4822	363.076	626.933			

Dependent Variable: I_TT
Model: (Intercept), SIG, DR_R
a. Maximum likelihood estimate.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	136.858	24.8402	88.172	185.544	30.355	1	0
SIG	36.334	14.7043	7.514	65.153	6.106	1	0.013
(Scale)	18248.651[a]	2542.89	13887.3	23979.6			

Dependent Variable: BT_TT
Model: (Intercept), SIG
a. Maximum likelihood estimate.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	114.713	8.7131	97.635	131.79	173.332	1	0
SIG	17.009	5.1578	6.9	27.118	10.875	1	0.001
(Scale)	2245.258[a]	312.869	1708.65	2950.38			

Dependent Variable: GPS_TT
Model: (Intercept), SIG
a. Maximum likelihood estimate.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	114.206	8.6997	97.155	131.257	172.332	1	0
SIG	17.295	5.1499	7.202	27.389	11.279	1	0.001
(Scale)	2238.374[a]	311.91	1703.42	2941.34			

Dependent Variable: M_TT
Model: (Intercept), SIG
a. Maximum likelihood estimate.

CHAPTER 5: CONCLUSIONS

This thesis presents an analysis and evaluation of the quality and accuracy of travel times obtained from GPS unit, Bluetooth detectors, and INRIX by comparing it with manual data (ground-truth). Travel time obtained manually and from GPS units are close to each other as the percentage variation is always less than 10% for all the six segments. The travel time data from both Bluetooth detectors and INRIX are reasonably close to manually captured travel time data along the freeway segment than that when compared to arterial street segments. For arterial streets, travel times from INRIX are more promising when compared to the travel times from the Bluetooth detectors. The Bluetooth detectors showed more frequency in higher percentage difference (for most time periods considered) 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, 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 to look at differences in travel times. Out of the three filter ranges, 1.5 min filter range seems to yield large sample size and accurate results. The travel times from INRIX are more promising than those obtained from Bluetooth detectors.

The sample size collected from Bluetooth detectors was low in the morning period and has increased as the day progresses the reasons for which are unknown. This may be because of higher noise levels/disturbance, weather and environmental conditions or varying traffic volumes. The number of samples collected on few routes is low when compared to others.

The reasons for the difference in travel time for both arterial streets and freeway using Bluetooth detectors and INRIX could be the source of data, outliers and network characteristics. The relationship between spacing of locations at which data is captured and the characteristics of the network and travel time data from these sources have been compared. The number of signalized intersections on selected segments played significant role in travel times collected from all the sources. For INRIX both signalized intersections and residential driveways are significant in travel time.

Overall, it can be concluded that INRIX and Bluetooth technologies are promising methods in capturing travel times on freeways. However, for arterial roads, INRIX is found to be a better data source to extract travel time than when compared to Bluetooth detectors.

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