Feasibility of Bluetooth Data as a Surrogate Analysis Measure of Traffic

By

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ABSTRACT

Background

The proliferation of portable electronic devices among consumers has created in recent times new opportunities for traffic data collection. Many of these devices contain short range Bluetooth radios in addition to other electronic equipment. The included Bluetooth radio on each device was intended to provide a low-power communications protocol to connect devices such as cell phones, headphones, music players, and more to each other. The presence of a unique identification number as part of the Bluetooth protocol on each device, that when activated can be discovered electronically, unintentionally creates anonymous probes in the traffic stream. This research explored possibilities of using Bluetooth technologies for various traffic data collection studies to expand the tools available to traffic engineers.

Data Collection

This study began with testing Bluetooth roadside data logger hardware configurations. Controllable variables included Bluetooth antenna selection and roadside placement options. Through the use of controlled conditions, detection areas for five antenna options were mapped, and their detection reliabilities were assessed. Other tests were conducted to assess the impacts of roadside antenna placement, vehicular speeds and in-vehicle source placement.

This research then builds on the data collected about Bluetooth hardware performance metrics by investigating the feasibility of using Bluetooth data as a surrogate for traditional traffic engineering data for several traffic study applications. These studies included: urban

corridor travel time monitoring, freeway travel time monitoring, origin-destination studies, and estimating turning movements at roundabouts. Each of these studies was parallel in nature to each other and showed how the same technology could be applied to different study objectives.

Analysis

The data collected during each of the studies provided valuable insight into Bluetooth technology. The hardware evaluations showed that a dipole antenna placed 6-12 feet from the edge of the roadway with at least 3 feet of elevation performed the best. The antenna power of the dipole could be changed to increase or reduce the coverage area as needed. The urban corridor study found that the Bluetooth data collection method provided similar results in a before-after analysis as GPS probe vehicles. The urban freeway corridor study found statistically significant differences in travel time data compared with permanent travel time sensor data provided by the regional traffic management center for seven of the eight freeway corridor segments tested. However, these differences were small and appeared not to be practically significantly different. The origin-destination study found no significant differences for either travel times or percentage or through trips between Bluetooth data collection and video re-identification of vehicles. Finally, the roundabout study showed that estimates of turning movement counts could be successfully accomplished, but in one case was significantly different than manual count data; additional research is needed to better understand the differences in roundabout turning movement counts.

Conclusions

The use of Bluetooth technology showed new possibilities for data collection. The data collected allowed for an automated process for identifying and re-identifying vehicles along a corridor. Traditional traffic study methodologies, such pairing of vehicular data or simply observing (counting) traffic flows, required many hours of labor intensive data collection that could be replicated with Bluetooth technology in a matter of minutes. Additionally, Bluetooth data sets opened up new potential analyses of the data. Such additional analyses included being able to separate frequent (repeat) travelers from occasional travelers along a corridor.

While this technology was found to have enormous potential, it was not found to be completely stand-alone. The chief weakness of the technology was that it was found to sample around 5 percent of the available traffic. The implication of this was that Bluetooth data were not always available or sufficient in size for analysis. This could be a particular issue when one needs to delineate a day into small time frames. Furthermore, because of this unintentional use of Bluetooth technology, there was not any way to guarantee data to be available at the time periods needed. Also, in order to extrapolate volumetric data from the Bluetooth data, a secondary source was needed to assess a Bluetooth penetration rate. Thus the abandonment of current technologies and methodologies would undermine this data collection technique.

A key assumption was that each Bluetooth source detected represented a separate independent vehicle. While this assumption could be violated with multiple discoverable Bluetooth devices in a single vehicle (e.g. a transit bus), this was not found to be an issue. Through this research it has been shown that the use of Bluetooth technology has earned its place in an engineer’s toolbox.

ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION & BACKGROUND

The collection of traffic flow metrics is older than the automobile itself. In 1868, J.P. Knight recognized a congestion and safety problem with horse drawn carriages near London's House of Commons which resulted in the world's first traffic signal (*1*). While issues of congestion and traffic safety are still just as relevant today as they were in 1868, many of the methodologies technologies used for traffic studies have evolved over time. The same evolution in technology continues with traffic studies. From days of paper and pencil to handheld computers, engineering technology has constantly evolved to not only make the life of engineers easier, but also to facilitate new methods of data collection that were previously unavailable.

Modern traffic studies have many forms for many needs. Study types cover a wide range of needs including addressing roadway capacity, travel speeds, travel delay, origin-destination, and predicting future roadway utilization. For each application, an engineer culls through available tools to design a study that best suits the given purpose and need. Common study tools include pneumatic tube counters, video cameras, radar, inductive loops, and human observers.

Recognizing a change in the technical landscape in consumer electronics, several researchers have developed experimental Bluetooth based data loggers for collecting traffic data. Designed to augment an engineer's toolbox, these data loggers leverage the increasing presence of cellular phones and other devices among motorists. Many modern cellular phones include a Bluetooth wireless radio, that permits it to connect to other Bluetooth enabled devices in close proximity. If set as discoverable each Bluetooth wireless radio communicates a unique twelve character identification number (Media Access Control address; "MAC address"). Setting a

Bluetooth device to be discoverable enables other Bluetooth devices to electronically ‘see’ the device and allows them to connect to each other. However, in order actually to complete a device-to-device pairing, a security pin code was often required (*2*).

As noted by its industrial trade group, the Bluetooth Special Interest Group (SIG), the Bluetooth wireless protocol was first published in 1998 (*3*). By the year 2010, over 13,000 companies had joined the SIG; the listing of members includes almost every major commercial electronics manufacturer (*3*). The established Bluetooth protocol for the technology included specifications for frequency (spectrum), interference, range, and power. The SIG created three range classes that specify over what distance communications between Bluetooth devices was intended to work reliably.

Table 1 Bluetooth Classifications (*2*)

Bluetooth Classification	Range
Class I	300 feet
Class II	33 feet
Class III	3 feet

The SIG group was over thirteen years old at the time of this research, and the specification had evolved into a fourth generation. It was safe to say at the time of this research that Bluetooth was a mature technology. This was evident in the proliferation of Bluetooth enabled devices, including cellular phones, hands-free phone devices, portable music players, headphones, computers, computer keyboards, computer mice, printers, navigation devices, and even automobiles. Many of these products were commonly found in automobiles that travel roadways every day. One example was that many of the printers found in parcel or express delivery trucks were Bluetooth enabled such that it permitted the driver to print off a label wirelessly from a handheld computer (*4*).

In the context of collecting traffic data, the use of Bluetooth technology was a close parallel to the use of capturing license plate information. In both cases a unique identification number was recorded at one location and paired to itself at a second known location. A Bluetooth data logger was able to record the MAC addresses of nearby “electronically discoverable” devices along with a time stamp. These data were then stored on a memory card for processing, or could be transmitted via cellular modems to a processing facility.

At the time of this research there were two principal suppliers of Bluetooth data collection equipment intended for roadside usage. The products from both vendors were compared and their specifications were similar. This was not surprising as the industry trade group for Bluetooth governs much of the technical aspects of the technology. The criteria for equipment selected for this research were that the units had to be self-contained, portable, have interchangeable parts, and have a Global Positioning System (GPS) receiver integrated into the package. In addition, the unit must include an internal rechargeable battery instead of requiring a hardwired connection to the electrical grid to ensure maximum flexibility in deploying the units.

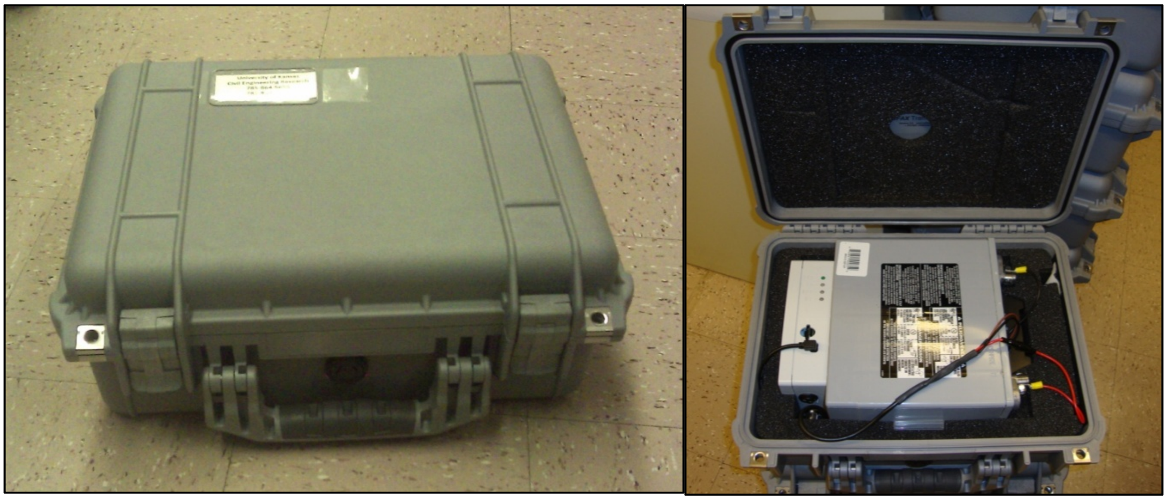


Figure 1 Bluetooth data logger used in the experiments.

Considering the technological opportunity, the fundamental research question was if Bluetooth data could be used as a surrogate measure of traffic that would be on par with current study techniques. This question was divided into two principal goals, understanding Bluetooth hardware performance, and devising a suitable methodology for each application. Understanding Bluetooth hardware was a prerequisite for the second goal of creating suitable methodologies for Bluetooth data to be useful. The second goal diverged into parallel paths for the study of four applications, urban corridor travel time, urban freeway travel time, origin-destination studies, and roundabout turning movement estimation.

Dissertation Organization

This research on assessing the feasibility of using Bluetooth data as a surrogate analysis measure of traffic was conducted in several stages. The initial stage was to evaluate a number of hardware related variables including:

- in-vehicle Bluetooth source placement,
- traveling speeds of vehicles with Bluetooth sources,
- variations in detectability among several Bluetooth sources,
- horizontal and vertical roadside Bluetooth antenna placement options, and
- Bluetooth antenna selection.

These objectives were tested in various combinations to establish performance metrics upon which the rest of the research could utilize. Following the collection of these performance metrics, the research diverged into four parallel paths as seen in Figure 2. Each of the chapters following parallel paths (Chapters 4-7) and shared a general overall null and alternate hypotheses which were as follows:

- H_o: Data acquired using Bluetooth technology were not statistically different from data gathered using traditional means (as appropriate for each test), and
- H_a: Data acquired using Bluetooth technology were statistically different from data gathered using traditional means (as appropriate for each test).

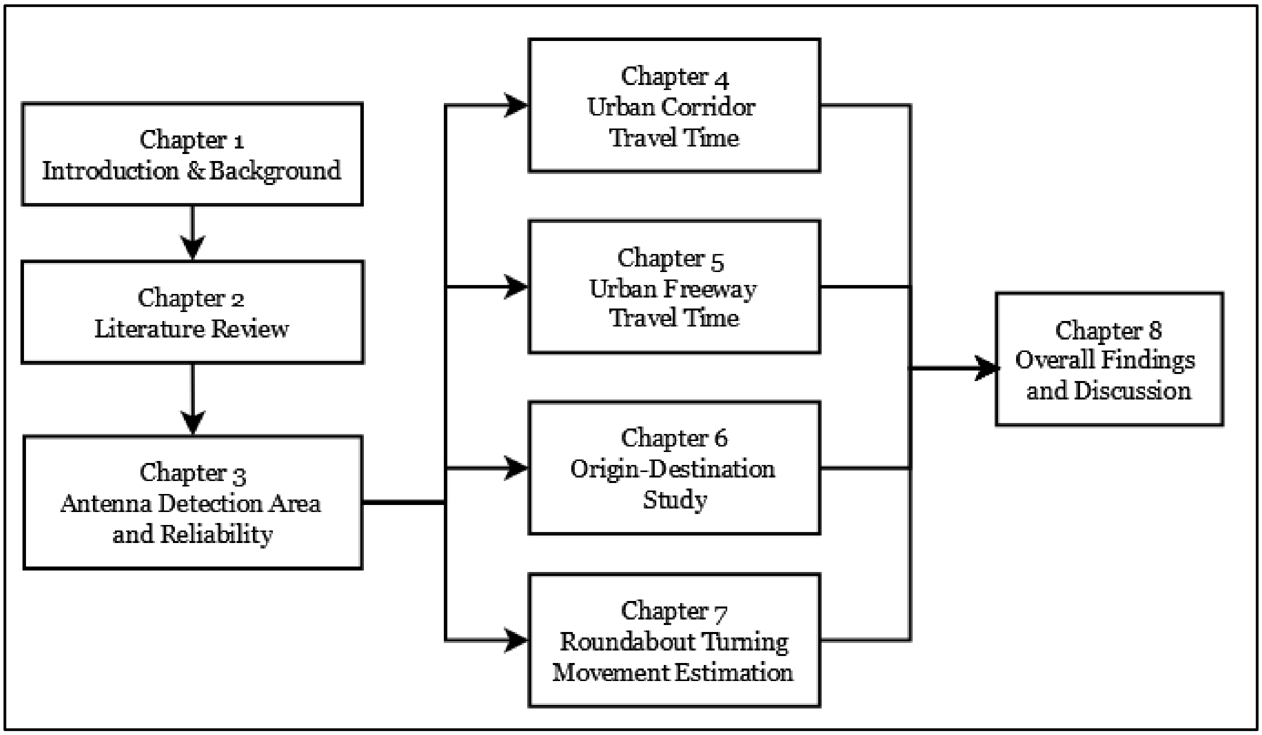


Figure 2 Organization of dissertation chapters.

CHAPTER 2
LITERATURE REVIEW

Combining an engineer’s need for trustworthy data and evolving technology formed a nexus whereupon the opportunities and limitations of Bluetooth technology could be evaluated. This had become a recognized research need in Kansas which was the impetus of this research.

The idea of applying Bluetooth technology to collecting traffic data originated in 2002 by authors Pasolini and Verdone of Bologna Italy (*5*). Their paper, entitled “Bluetooth for ITS?” was presented at the 5th IEEE International Symposium on Wireless Personal Multimedia Communications held in Honolulu, Hawaii. Pasolini and Verdone saw an opportunity to experiment with new wireless technologies that were coming to market in alternative applications. The authors did a proof-of-concept test, over-and-above simply reading MAC addresses, and verified that data could be transmitted to moving in-vehicle sources. They concluded noting that the obstacle for further implementation was the signal-to-noise ratio of the Bluetooth transmission.

Welsh, Murphy, and Frantz of Rice University considered how to improve the Bluetooth protocol to decrease connection times between moving devices to create a mesh network (*6*). In their study they considered how moving vehicles could exchange data while in-motion. The authors found that indeed moving small amounts of data (less than 4 megabytes) could be accomplished at low speeds, however this dropped off as speeds (and following distances) increased. The limitation found by the authors was in the way the Bluetooth discovery mode operated in a non-optimal manner taking extra seconds to complete a connection.

Extending Welsh, Murphy, and Frantz’s concept of using Bluetooth for moving Bluetooth mesh networks, Ahmet, El-Darieby, and Morgan of the University of Toronto looked to further this concept (*7*). They envisioned that Bluetooth could be utilized to create a static mesh network for the collection of Intelligent Transportation System (ITS) data. Not only would the Bluetooth devices be collecting traffic data, but they would be able to transmit such data back to an operations center using existing communications infrastructure. By connecting the Bluetooth sensors into a larger communications network, they would be able to track vehicles over longer trips throughout the network. To test their concept, a proof-of-concept test was conducted in Regina, Saskatchewan, and they concluded that it “seems promising,” and that future work should be done to refine speed accuracy, assessing hardware selection impacts on data collected, and for enabling bi-directional communication to transmit data back to vehicles for navigational purposes.

A number of significant players in the field of Bluetooth based traffic data collection gathered in Houston, Texas in February 2010. This one-time summit was convened for the purpose of sharing on-going research needs in the field and included researchers from the California Department of Transportation, Houston-Galveston Area Council, Texas Transportation Institute, University of California at Berkeley, University of Kansas, University of Maryland, and University of Virginia. The Houston Bluetooth summit showcased several on-going tests and implementations around the country, along with a lively discussion of current research needs in the field.

Young of The University of Maryland noted the advantages of Bluetooth technology, and that it represented a significant advancement over four other similar technologies (*5*). Other technologies that it could be compared against were passive loop detectors, GPS data from fleet vehicles, cellular phone locations, and automated toll tag readers.

Table 2 University of Maryland Slide Comparing Traffic Study Technologies (*5*)

				Coverage	
Technology	**Costs**	**Privacy**	**Travel Time Accuracy**	**Freeways**	**Arterials**
Bluetooth	$2,000-$4,000 per mile	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Conventional Detectors	$7,500-$20,000 per mile	✓✓✓✓		✓✓✓✓	✓✓✓✓
GPS Fleets	$500-$1,000 per mile per year	✓✓✓✓	✓✓✓✓	✓✓✓✓	
Cell Phone Location	$500-$1,000 per mile per year			✓✓✓✓	✓✓✓
Toll Tags	$20,000 per mile		✓✓✓✓	✓✓✓	✓✓✓

Each of these competing technologies were considered by Young to have a number of shortfalls compared to Bluetooth based technologies. Conventional loop detectors did not permit the ability to calculate travel times (only spot speeds). Data from GPS units in fleet vehicles were only available for routes that the fleet traveled regularly and could be subject to other biases inherent in the types of vehicles from which the data were acquired. One example of a bias due to fleet vehicle limitations was that a number of truck fleets were known to incorporate governors that limit maximum travel speeds (*6*). The detection of electronic toll road tags was only practical in areas where toll roads were present; for example the use of toll tag readers in metropolitan Garden City, Kansas would not be practical as the nearest toll road was over 200 miles away (*7*).

The other technology mentioned by Young that lent itself for comparison was geolocated cell phone data. The significant shortcoming of this was that it was not possible to limit the collection of data to only be along specific corridors. Cellular phone data were customarily available as a blanket data set across the geography of any area. The implication of this was that it was possible to track a phone to a specific residence, and be able to identify patterns of travel between specific businesses in the area and specific residences. While specific trip points were possible, because the data were collected in intervals, assignment of trips to a specific route was not possible. As seen in Figure 3, exact driveways could be determined from geolocated cell phone data.

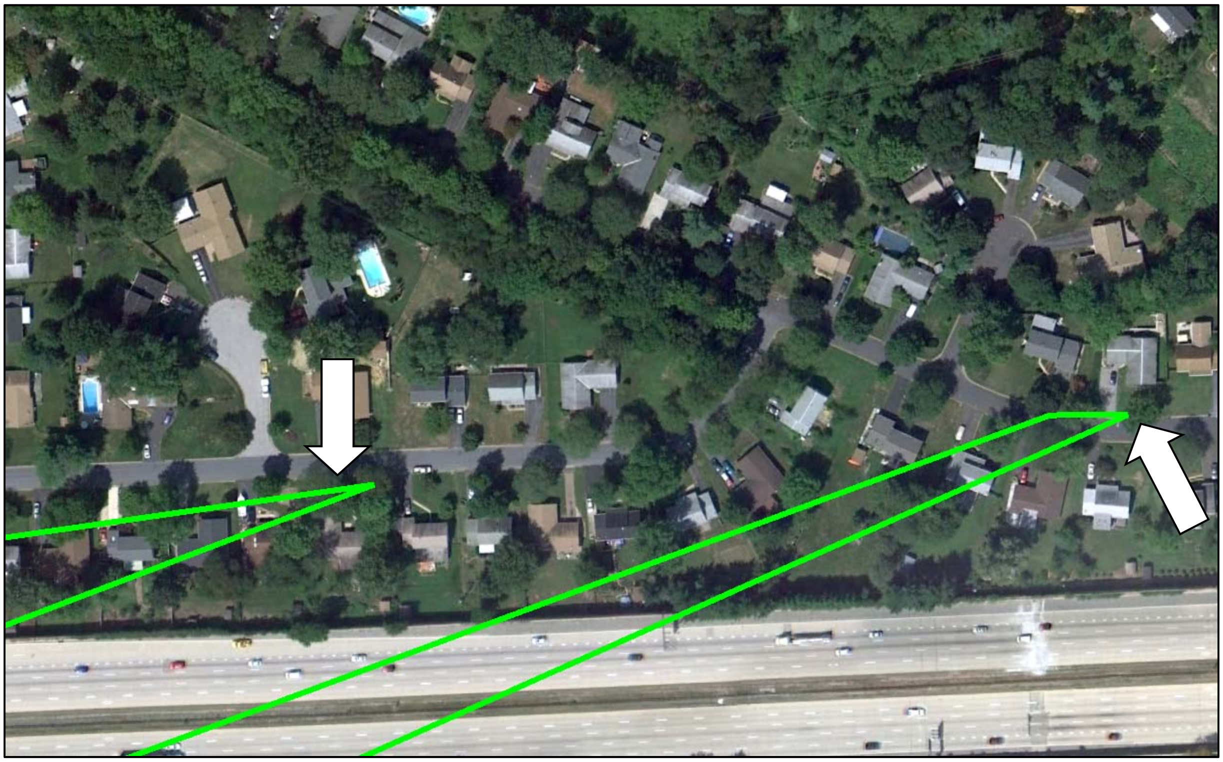


Figure 3 Geolocated cell phone travel data for trips to/from FedEx Field in Landover, Maryland on September 15, 2009 that identified traveler origins (*7*).

What set Bluetooth based detection apart from cellular phone technology was the low power strength of the radio signal, and that data could only be acquired at specific locations that would systematically prevent the identification of individuals. The Bluetooth methodology at most could only tell if an individual device passed within a short distance of a given point where a data logger was deployed and nothing more specific. Thus, as long as the Bluetooth data was not able to be matched to other identifying data sources, personal privacy issues were much less of an issue compared to geolocated cellular phone data.

In 2007, Young had begun experimenting with repurposing Bluetooth technology for the acquisition of traffic data (*8*). He had recognized that a discoverable Bluetooth device publicly emits a unique identification number (MAC address), and that, when paired with a time stamp and collected at a known location, it could be paired with similar data collected elsewhere. The differences in time between detections and the distance between collection locations could be transformed into a space mean speed. Young also noted that “Studies have indicated that approximately 1 automobile in 20 contains some type of Bluetooth device that can be detected. Not every Bluetooth device is detected at every station so the number of matched detections (a device detected at two consecutive detectors) is lower”.

Several other related studies have also occurred that documented the evolution of traffic data collection techniques and their applications for travel time studies. Tarnoff et al. compared GPS probe data collected by the I-95 Corridor Coalition to Bluetooth data for the same routes (*12*). In this study Tarnoff et al. concluded that Bluetooth data was useful for validating freeway GPS data, but found that third party data providers could provide larger sample sizes of GPS data than what could be obtained by means of Bluetooth data. Haghanhi et al. also worked with the I-95 Corridor Coalition and found similar results (*12*). After compiling 13,300 hours of data they were able to create a four step filtering system to eliminate travel time outliers, and when filtered data was compared to probe vehicle (ground-truth) data, the results were not significantly different. Haghanhi et al. also share that Bluetooth technology was not shown to be useful for distinguishing travel times, and this was particularly important when a segment included both regular and express (carpool) lanes.

Detecting travel time outliers was also explored by Van Boxel, Schneider, and Bakula (*14*). Using a fundamental Greenshield's traffic flow model in conjunction with Least Quantile of Squares statistical model they attempted to filter travel time outliers. Their motivation for creating this model was that they felt that because vehicle arrivals were random, and that travel time was not expected to be stationary, a range of 'reasonable' values would be expected. After testing their model on both interstate highway and urban arterials in the Akron, Ohio area, they concluded that such methodology works best on interstate highways, and that it produced statistically comparable travel times. Seeing shortcomings of the Greenshield's model in the urban environment, they left for future research testing alternative models for such environments.

Wasson and Sturdevant of the Indiana Department of Transportation along with Purdue University faculty Bullock, have also looked at the use of acquiring Bluetooth MAC addresses for collecting transportation data (*9*). In their study they deployed Bluetooth data loggers for six days along a 8.5 miles corridor near Indianapolis, Indiana that included both a signalized arterial and interstate highway segment to test the ability to capture travel time data. They concluded through their testing that "arterial data have a significantly larger variance due to the impact of signals and the noise that is introduced when motorists briefly (or not so briefly) divert from the network" and that their testing "demonstrate[d] the feasibility of using MAC address matching for travel time estimation".

Researchers Quayle, Koonce, DePencier, and Bullock researched arterial travel times in Portland, Oregon (*16*). Data was collected along a 2.5 mile suburban arterial route in an effort to determine the impacts of traffic signal adjustments. Using Bluetooth data loggers, Bluetooth data were collected for 27 days, and a single day's worth of GPS floating car data were also collected. In their study, they found that the GPS floating car data to be similar, although no statistical testing was conducted, were slower than the Bluetooth travel time data. The researchers concluded that Bluetooth did offer a low-cost method for collecting data that otherwise required a labor-intensive effort to capture.

Bullock et al., also applied the technology to other scenarios in addition to the roadside acquisition of traffic data (*10*). In 2009, Bullock et al. used the same technology to estimate passenger queue delays at security areas of the Indianapolis International Airport. They placed Bluetooth detectors in closets on both the unsecure and secure sides of the security checkpoint for Concourse B. Unlike the other studies, this study used Class II Bluetooth receivers. The change in class corresponded with a decrease in power, and a decrease in range; in this case the range was estimated to be 10 meters as opposed to the 100 meter radius of Class I devices. The selection of Class II receivers was due to the close proximity of the two detection stations inside of the airport terminal. Through a reduced detection area, the locational ambiguity of each detected device could be minimized which translated into reduced variations in travel times detected. Bullock et al. concluded that the number of Bluetooth sources recorded corresponded to a range between 5-6.8 percent of passengers if one assumed a single source per passenger, and that changes in passenger travel times through security tracked alongside changes in the number of passengers screened at the checkpoint. However, ground truth travel time data for passenger transit times through security were not available for comparison.

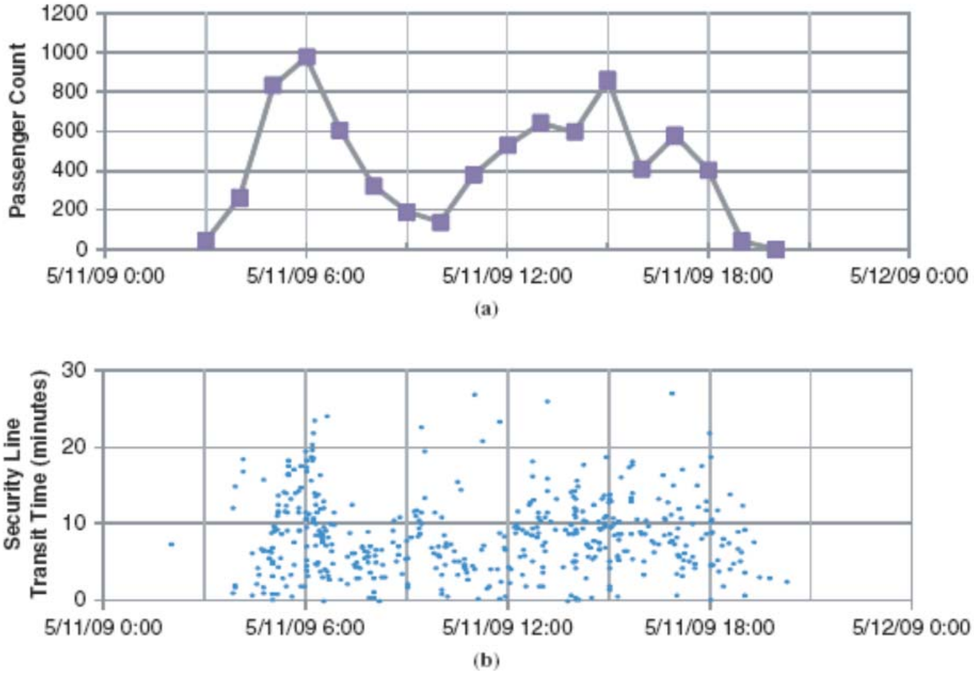


Figure 4 Comparison of passenger counts to security line travel times (*10*).

Also present at the same TTI Bluetooth summit were several universities that were actively engaged in statistically validating third party data sources. Haghani and Hamedi of the University of Maryland, had been using Bluetooth technology to validate third party freeway and floating car data, and found that the Bluetooth data closely matched the other data sources (*11*). Haghani and Hamedi also noted a sampling rate between 2-3.4 percent if one assumed a sole Bluetooth source in each vehicle. Along similar lines Schneider et al. of the University of Akron were validating travel time data from a vendor collected using floating car runs on behalf of the Ohio Department of Transportation (ODOT). The data prepared for ODOT included both arterial and freeway segments in and around the Dayton, Ohio metropolitan area. Schneider et al. concluded that travel times were consistently underestimated on signalized arterials, and noted that on short segments, any rounding of travel times to the nearest minute had an impact on the quality of results (*12*). Schneider et al. also felt that Bluetooth-based data provided greater data resolution than the floating car based data.

The city of Houston, Texas, in collaboration with the Texas Transportation Institute (TTI), has undertaken several demonstration projects focused on urban travel times. The impetus for their experimentation was to find an alternative to the use of toll tag readers on urban streets where the prevalence of such toll tags was not sufficient to capture a statistically significant sample size. TTI researchers Puckett and Vickich found that indeed Bluetooth-based traffic data collection technologies were viable for travel time data (*13*). Based on an assumption of a single Bluetooth source per vehicle, they captured 11 percent of the traffic volume with their Bluetooth data collected in Houston, Texas. Puckett and Vickisch showed that their Bluetooth travel time estimates comparably tracked with toll tag data as shown in Figure 5, although a statistical comparison was not available. Their next step was going to be a widespread deployment at signal control cabinets in downtown Houston that would provide blanket coverage at all signals in the deployment area. Another related application was investigated by the TTI's Rajbhandari to estimate border crossing times for vehicles entering the United States at several border crossings near El Paso, Texas (*14*). In addition to working across national borders, he found that sensor placement and location can directly impact the results, and noted that due to specific lane geometry extra considerations had to be made for sensor placements.

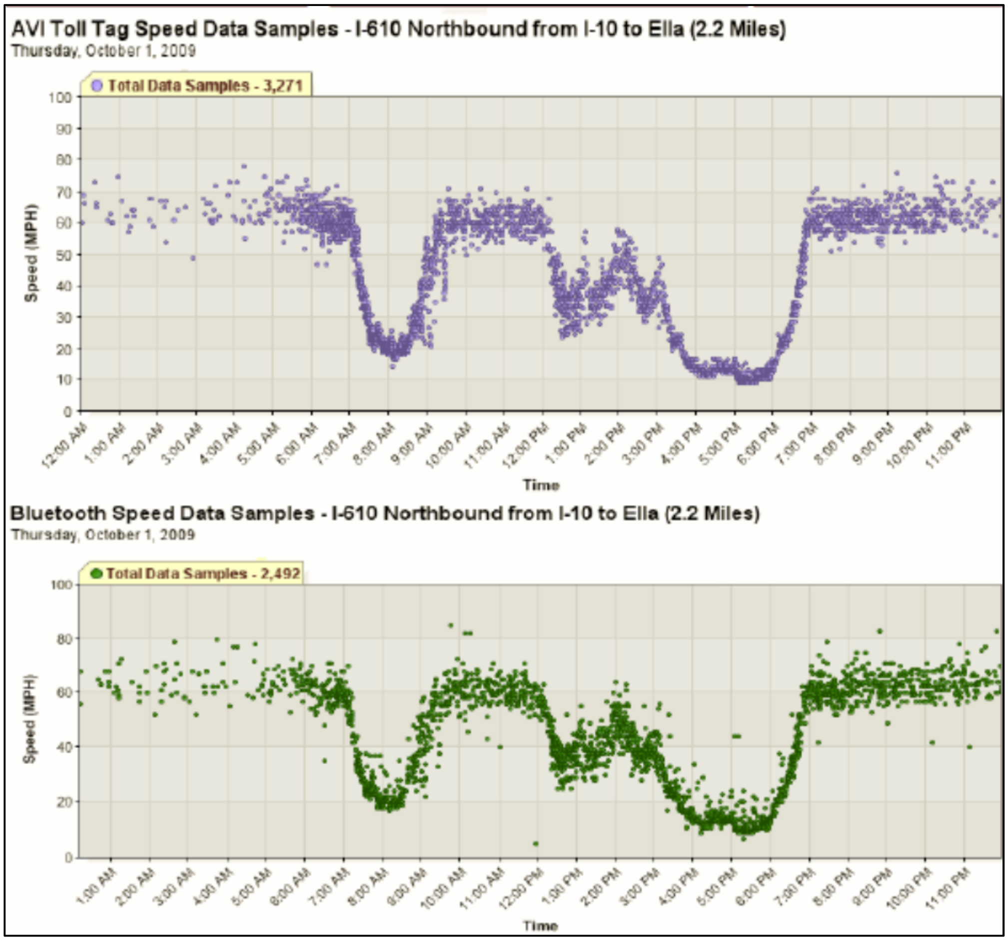


Figure 5 Comparison of Bluetooth and toll tag travel time data in Houston, Texas (*13*).

University of Virginia researchers Venkatanarayana and Ngov along with Fontaine and McGhee of the Virginia Transportation Research Council also have been experimenting with Bluetooth based traffic data collection technologies (*15*). Their research was exploratory in nature as a proof-of-concept test. They choose to conduct their testing for 70 hours along a four mile segment of I-64 east of Charlottesville, Virginia. Venkatanarayana et al. noted concerns over the reliability of the acquisition of available Bluetooth data, and questioned roadside antenna placement options for future research needs as they were only capturing an estimated one percent of traffic with the Bluetooth equipment.

Such research needs were also identified by Kuhn of the University of California Berkeley (*16*). California had been experimenting with Bluetooth technology for work zone travel time estimation, and for dynamic lane management systems. Subsequently, the California-based research was tied to data processing and the issues surrounding the real-time transmission of the data through cellular modems to a data processing center.

The possibility of using Bluetooth data to estimate in real-time delays and travel times work zones was explored by Haseman, Wasson, and Bullock (*20*). These authors evaluated a rural interstate work zone in Northwest Indiana for twelve weeks. The authors sought to determine the feasibility of providing real-time feedback to drivers of travel time information collected via Bluetooth. By instrumenting both the principal travel time segment, and the posted detour, they were able to show that when travel time data was provided, more vehicles utilized the detour route than when no travel time data were available. The authors hoped that by archiving the data collected, in the future they would be able to create better models for predicting queues at planned work zones that could be used when such a work zone and any associated detour routes.

The topic of travel time forecasting was also explored by Barceló, Montero, Marqués, and Carmona (*21*). These authors evaluated a freeway segment 25 miles long north of Barcelona, Spain. Through the combination of Bluetooth data and historical traffic data, a Kalman filter was applied and was able to predict travel times, such that the R^2 value for a regression of the predicted versus actual travel times was 0.986. Further work was conducted to estimate origin-destination patterns along the same highway corridor, however their Kalman filtering approach was not deemed to be sufficient for congested conditions.

Recognizing that the specific antenna used by a Bluetooth data logger was a crucial variable, Brennan et al. set out to quantify this variable (*17*). As recognized in the 2009 Bullock et. al. study at the Indianapolis International Airport, closely spaced detection units need to have clearly delineated areas of detection. Brennan et al. focused specifically on vertical mounting height of a standardized antenna to determine any possible directional biases this could create in the data collected. They recommended an optimal mounting height of at least eight feet for a Bluetooth antenna, and noted that the lower the antenna mounting height was when used adjacent to a bi-directional roadway, the greater the directional bias was observed toward the near lane.

Additional Bluetooth detection work was conducted by Bakula, Schneider, and Roth (*27*). This team of researchers focused their work on detection ranges and reliabilities. Their work was conducted on a divided multi-lane freeway near Akron, Ohio, and found that increasing a Bluetooth antenna would increase the estimated percentage of data acquired. Using theoretical conditions, they estimated that when the effective Bluetooth antenna range was 650 feet, the probability of Bluetooth detection at both trip ends increased to greater than 94 percent; when the range was decreased so too did the estimated rate of dual detection.

Looking beyond traffic applications, several related tasks also appeared in the literature. Understanding that one of the limitations of GPS data was that access to the required satellites was not usually possible indoors, Kotanen, Hannikäinen, Leppäkoski, and Hämäläinen sought out to test using Bluetooth signals as an indoor substitute for GPS data. They found that this not yet feasible due to inconsistent power outputs from Bluetooth receivers (*21*). Following the same concept, Zhou and Pollard sought to use Bluetooth for determining indoor local positioning (*22*). Zhou and Pollard, just like Kotanen et al. found that such a system depended on consistent receiver power outputs which was not always true. They were able to further refine the methodology using regression models to achieve a positing error of approximately four feet.

Several other related application was tested by O’Neil et al. in the city of Bath in the United Kingdom (*23*). Fist O’Neil et al. attempted to capture pedestrian volumes through several gates around the city using Bluetooth, and secondly, to estimate dwell times of patrons in a coffee shop by means of Bluetooth data. In order to generate useful data they concluded that Bluetooth data was not a stand-alone proposition, but that it must be used in combination with conventional observational methodologies. They also recognized that the selection and placement of a Bluetooth antenna directly correlated with the quality of their results, but left expanding on that observation for future research.

While there have been a number of other researchers separate from the University of Kansas working with Bluetooth based traffic data collection arena, there were still several shortcomings and opportunities that merited further research. While several of the aforementioned researchers were able to estimate a Bluetooth sampling rate, they still had no idea how accurate that rate was or how likely it was that they sampled all of the available Bluetooth signals, as there had not been any published closed course studies available estimating the reliability of Bluetooth detection. This same sentiment was echoed by Kuhn and Venkatanarayana et al. Along similar lines, there was also no published research on optimal antennas for the detection of available Bluetooth signals. While other studies compared various third party data sources to Bluetooth data (*11, 12*), there also had not been any research comparing publicized travel time estimates to Bluetooth travel time data, nor a comprehensive statistical comparison of urban signalized floating car data to Bluetooth data.

Concluding Thoughts

Through the literature and firsthand experience, several positive and negative attributes for the technology existed. Among the positive attributes where the technology showed successes, were applications over several days' time that:

- estimated speeds, and
- travel times.

However, several negative attributes also came to light, which included :

- data collections being limited by power source capacity,
- small sample sizes, and
- an inconsistent sampling rate.

Recognizing that these limitations could be overcome with additional data sources created opportunities to validate Bluetooth data, and to examine other study possibilities. Among these study possibilities were:

- Bluetooth detection rates,
- effects of Bluetooth antenna selection,
- urban corridor travel time,
- urban freeway travel time
- origin-destination,
- roundabout turning movements,
- long distance corridor studies, and
- vehicular classification studies.

CHAPTER 3
ANTENNA DETECTION AREA AND RELIABILITY

An understanding of the detection range (area) and reliability for various antenna options as a function of phone (source) placement in a vehicle, vehicle speed, and Bluetooth data collection antenna mounting height. A thorough understanding of these variables was crucial for engineer to be able to optimize data collection equipment placement, as well as to provide a comprehensive analysis of the resulting data. This research was intended to fill a knowledge gap among the previous related studies and provide a backdrop against which future studies could be planned, and data analyzed.

One of the specific technical variables that had been previously overlooked was antenna selection. Antennas come in a variety of types where each correspond to variously shaped detection areas. Based on commercial availability, antenna types that were considered for evaluation included stub, dipole, patch, and whip designs. In all cases, the unit of measurement used to describe their power was decibels of gain. The stub, dipole, and whip antennas operate on the same principal that results in a circular radiation pattern emanating out from a circular antenna in all directions in the shape of a torus as shown in Figure 6. The size of the radius corresponds to the gain value. However a patch antenna operates from a flat plane as shown in Figure 7, making it directional in nature with a circular to conic radiation area in front of the plane. In theory, no communications are possible behind the plane (*18*). An overlap between two radiation areas, the radiation area of the Bluetooth data logger and the Bluetooth source, would be required for data to be captured successfully.

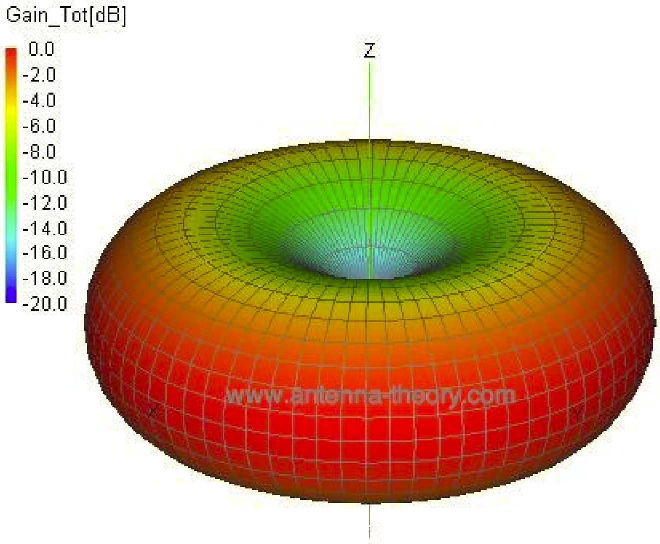


Figure 6 Normalized 3D radiation pattern for dipole and whip antennas (*18*) .

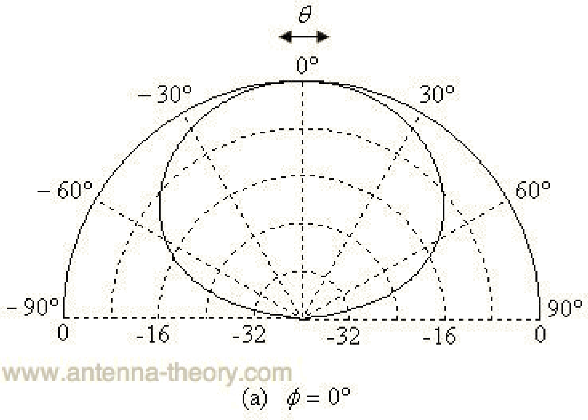


Figure 7 Normalized radiation pattern for a patch antenna (*18*).

Research Objectives

The objectives for this research were twofold. The first objective was to quantitatively measure the detection area for a typical Bluetooth data collection logger with both the manufacturer provided (standard) antenna and various aftermarket antenna options using a selection of commercially-available mobile phones. The second objective was to measure the detection reliability of each antenna based on:

- distance from the roadway,
- height relative to the roadway,
- speed of traffic, and
- the location of the test phone (Bluetooth source) inside a vehicle.

Thus, the five testable pairs of research hypotheses for the study were as follows:

- Comparing antennas:
    - H_{o1}: The Bluetooth detection reliability was not different for any antenna compared to the standard antenna provided with the data logger units.
    - H_{a1}: The Bluetooth detection reliability was different for at least one antenna compared to the standard antenna provided with the data logger units.
- Effects of lateral setback distance of antennas:
    - H_{o2}: Roadside lateral setback distance of Bluetooth data loggers (antennas) did not affect Bluetooth detection reliability.
    - H_{a2}: Roadside lateral setback distance of Bluetooth data loggers (antennas) did affect Bluetooth detection reliability.

- Effects of vertical elevation of antennas:
    - H_{o3}: Roadside vertical elevation of Bluetooth antennas did not affect Bluetooth detection reliability.
    - H_{a3}: Roadside vertical elevation of Bluetooth antennas did affect Bluetooth detection reliability.
- Effects of vehicle speeds:
    - H_{o4}: The Bluetooth detection reliability was not different for any pair of the three tested speeds (30 mph, 45 mph, 60 mph).
    - H_{a4}: The Bluetooth detection reliability was different for any pair of the three tested speeds (30 mph, 45 mph, 60 mph).
- Effects of source location:
    - H_{o5}: The location of a Bluetooth source in a vehicle did not affect the detection reliability of its Bluetooth signal.
    - H_{a5}: The location of a Bluetooth source in a vehicle did affect the detection reliability of its Bluetooth signal.

It was theorized by the researchers that several variables would work together to affect the detection reliability. Initial thoughts were that a phone (source) above a metal door panel might be detected at a higher rate than one placed lower in the vehicle and subsequently shielded by the door panels. It was also thought that the faster a test vehicle traveled, the lower the detection reliability would be as the vehicle would spend less time in the detectable area. These hypotheses were to be tested using paired t-tests with 95 percent confidence.

Work Plan

The work plan for the study consisted of several phases including equipment selection and data collection.

Equipment Selection

The Bluetooth data loggers chosen were commercially available at the time of the study. Each unit consisted of a weather-proof case, power source (battery), a Bluetooth receiver with an interchangeable antenna, a GPS receiver, and a small computer that stored the data onto a memory card. Example units are shown in Figure 1.

Data Collection

The work plan for the project consisted of several set-ups. The first research objective was accomplished by using a flat, open field on the campus of the University of Kansas, a Bluetooth data logger, laptop, an assortment of antenna options, several Bluetooth enabled phones, a set of chaining pins, and a total station. The process of mapping the detection area for each antenna and mounting option was conducted by connecting a laptop computer to the Bluetooth data logger for visible confirmation of presence detection, and an assistant with a Bluetooth enabled mobile phone. The assistant would hold the phone in an outstretched open hand at waist height (about 4 feet off the ground). The assistant would then walk straight out with the phone in hand until the laptop operator gave a signal to stop. Upon receiving the stop signal, the laptop operator and the assistant would fine-tune the location until the phone was no longer electronically visible to the Bluetooth data collection device (as determined by the live readout on the laptop screen) as shown in Figure 8. The assistant would then mark this location with a chaining pin, and then rotate 45° about the data collection device and repeat the process until eight locations were captured encircling the data collector. Following the placement of the chaining pins, a total station was set up directly over the Bluetooth antenna and the location of each detection boundary point (chaining pin) was surveyed. This process was then repeated for each antenna and mounting variation.

Figure 8 Researchers surveying Bluetooth detection areas for various antenna options.

Data collection for achieving the second objective was completed at an off-campus location on a rural section of US 56 highway located in Jefferson County just south of the city of Oskaloosa, Kansas. This section of roadway was selected for its relatively low average annual daily traffic (AADT) volume of 2,760 vehicles per day, relatively high speed limits without a minimum speed limit (*17*). It was important that the selected roadway be able to safely accommodate a range of test speeds, and be as free as possible of other competing Bluetooth signals. At this location three sites were located each about 0.25-mile apart from each other so as to ensure each site’s independence. At each site, a Bluetooth data logger was placed at varying distances from the edge line, with various antennas attached to the data logger. Also, a laptop computer was attached to the data logger for real-time confirmation of each Bluetooth detection. With an operator at each testing station (each with a different configuration of antenna and other options), two identical automobiles were driven by the three stations at a various test speeds. Two of the standard mobile phones were placed inside each test vehicle; one taped to the dash board as an analogue to a driver holding a phone above the window line while talking on it, and the second phone placed in the front center console. Using this standardized setup, the two test vehicles each completed fifteen laps (for a total of 30 runs between both test vehicles) at each of the testing speeds of 30, 45, and 60 miles per hour. This process was repeated several times until all speed, antenna, and distance combinations were studied.

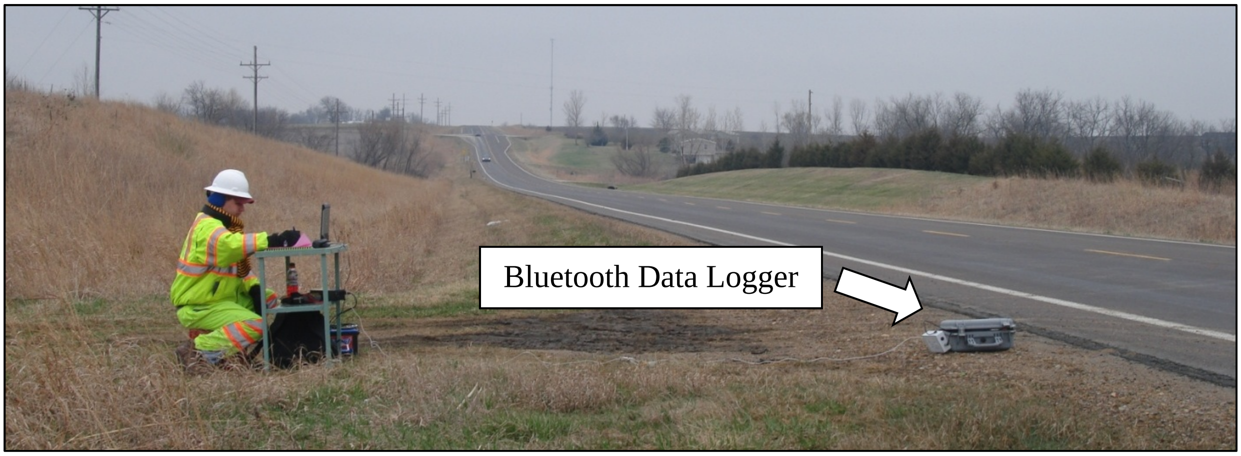


Figure 9 Researcher conducting Bluetooth detection reliability testing.

Field Data Collection

Field data were collected throughout the fall of 2010 and spring of 2011 following the aforementioned procedure. Pursuant to those objectives and procedures, data were acquired and transcribed onto paper logs. The detection range data were then transformed from the raw coordinate data acquired from the total station onto a map. The data were then transcribed out of log books and into electronic form for compilation. For the purposes of establishing consistency, a standard testing phone was chosen as shown in Figure 10. This phone was widely available at the time of the study through retail channels as a pre-paid device.

Bluetooth Detection Area

The first series of tests conducted were to comparatively measure the detection area of the Bluetooth data logger with a standard antenna by using a variety of cell phones that were commercially available at the time of the research as shown in Table 3, Test #1. The specific objective was to determine the detection range of several phones including the standard testing phone.

Figure 10 Bluetooth enabled cell phones used for comparison testing, left to right: Apple iPhone 3GS, Blackberry Storm, HTC Touch Pro2, the standard testing phone Motorola 408g.

All of the remaining tests in Table 3 (Test #2-11) were conducted using the standard testing phone exclusively and removed the phone manufacturer as a variable. The second through sixth tests focused exclusively on the antenna type attached to the Bluetooth data logger from the selection shown in Figure 11. The seventh through eleventh tests focused on mounting/ placement variations of the standard antenna.

These variations included:

- mounting height,
- the addition of a metal shielding plate behind the antenna, and
- the effects of a large metal object located in front of the data logger as shown in Figure 14.

Combining the data together, plots of the data were made showing the results of the tests found in Table 3. Figure 12 shows the results of Test #1, Figure 13 shows the results of Tests #2-6, #8-11, and Figure 14 shows the result of Test #7.

Figure 11 Testing antennas, left to right: 5dB dipole, standard 3dB dipole, 1dB stub, 9dB patch, 3.12 dB whip, 6.12 dB whip.

Table 3 Listing of Bluetooth Detection Area Tests

Test #	Antenna	Mounting Height	Phone Used
1	Standard 3dB dipole	Ground	All
2	1dB stub	Ground	Standard
3	5 dB dipole	Ground	Standard
4	9 dB patch	Ground	Standard
5	3.12 dB magnetic whip	Ground	Standard
6	6.12 dB magnetic whip	Ground	Standard
7	Standard 3dB next to shipping container	Ground	Standard
8	Standard 3dB with reflector plate behind antenna	Ground	Standard
9	Standard 3dB	+3 Feet	Standard
10	Standard 3dB	+9 Feet	Standard
11	Standard 3dB	+16 Feet	Standard

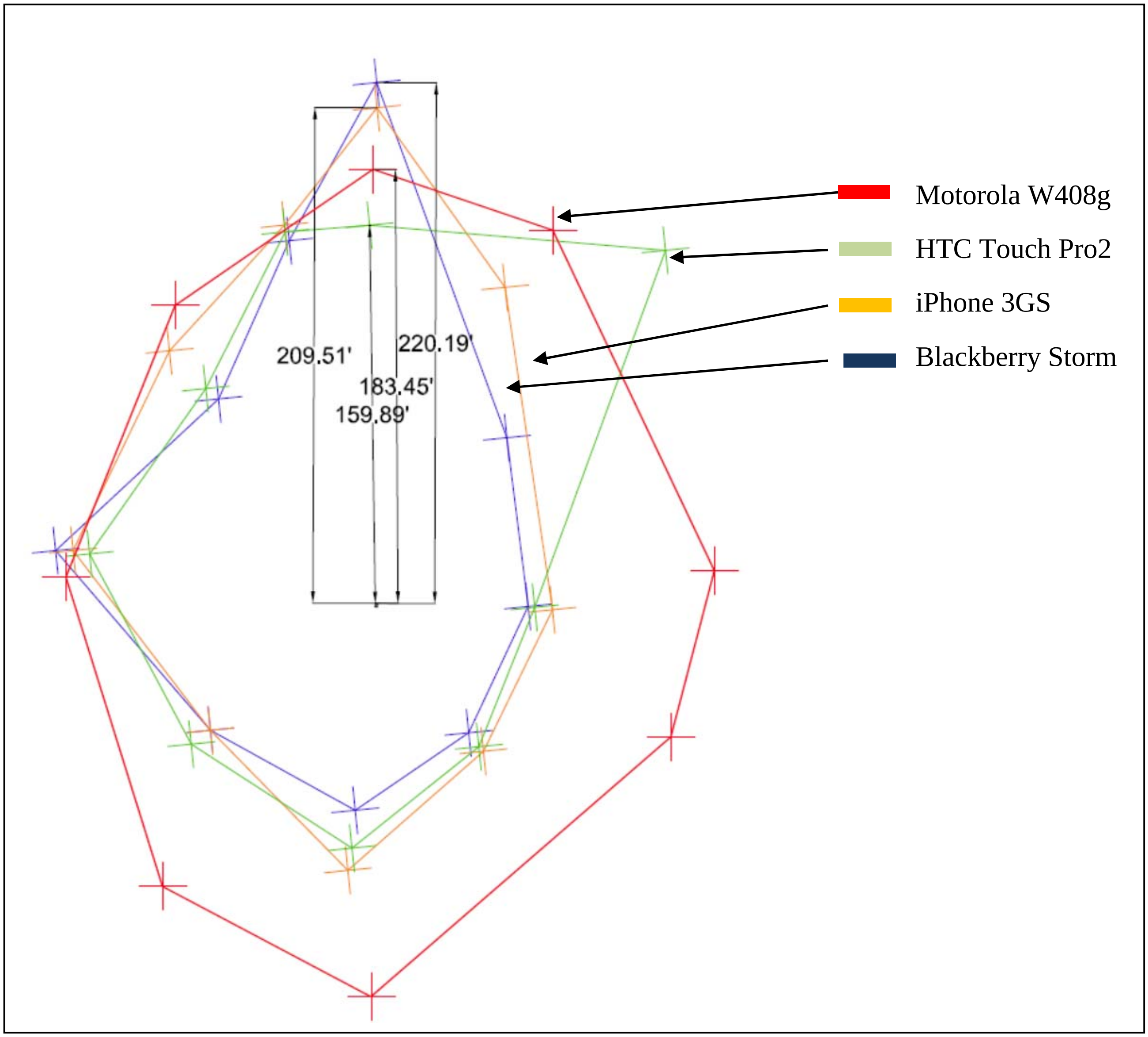


Figure 12 Bluetooth detection areas of selected cell phones used in Test #1.

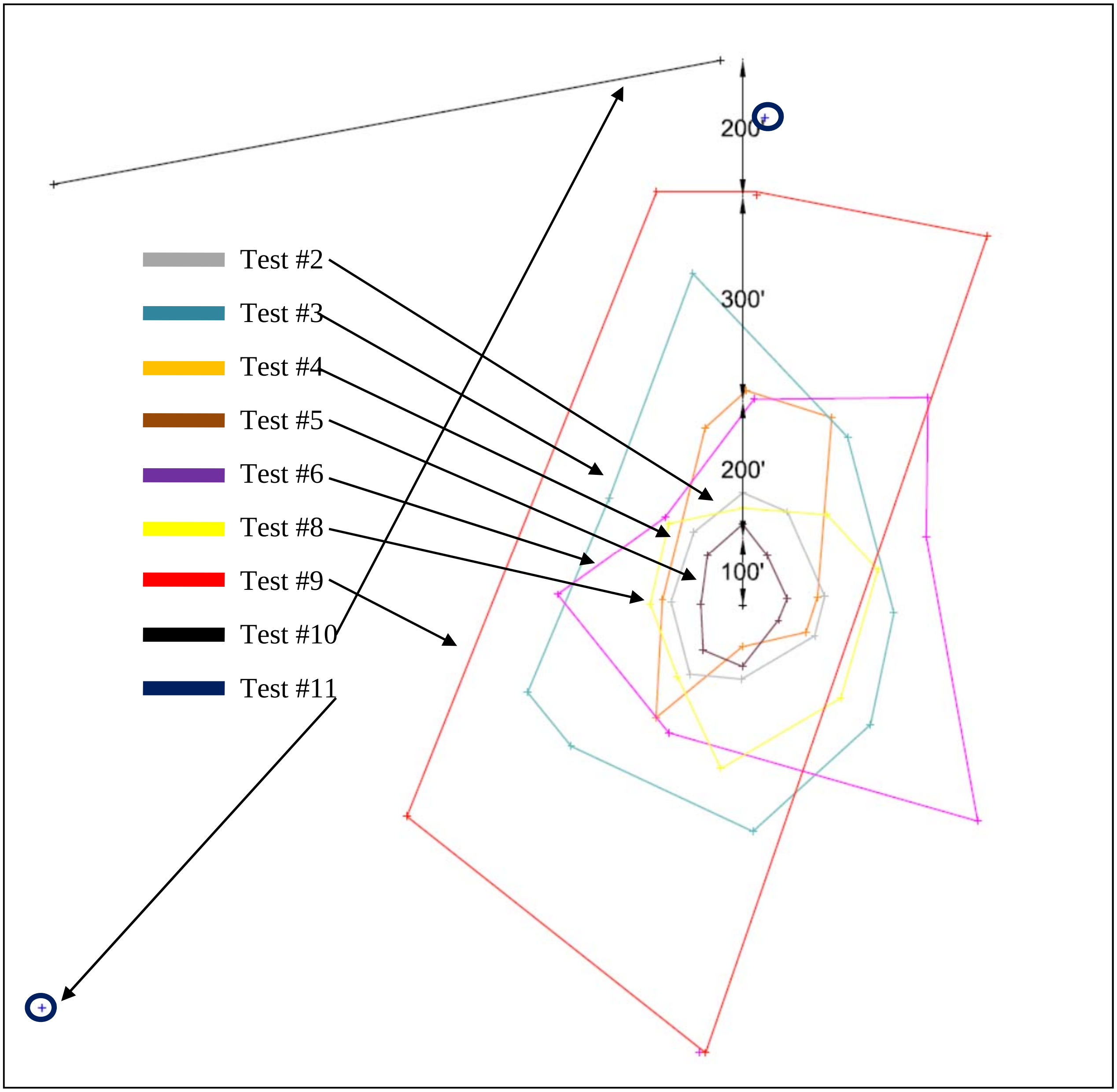


Figure 13 Bluetooth detection areas for various antenna options used with the standardized testing cell phone in tests # 2-6, #8-11.

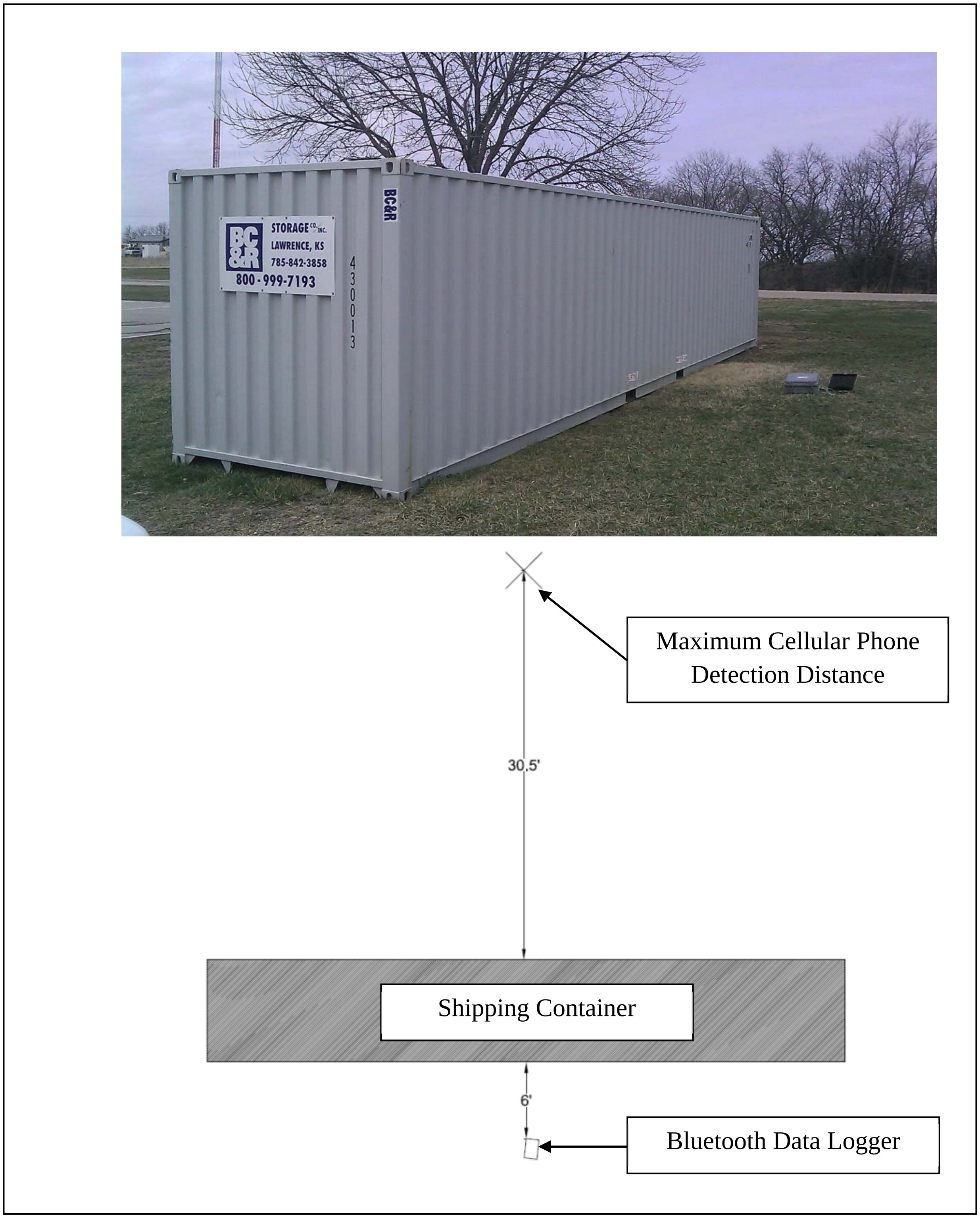


Figure 14 Bluetooth detection distance for Test #7.

Bluetooth Detection Reliability

Each of the reliability testing scenarios shown in Table 4 were evaluated thirty times at each of three speeds: 30 mph, 45 mph, and 60 mph. The test vehicle drivers utilized the vehicles’ cruise control function to maintain the correct speed during testing. During each pass of a test vehicle, there were two Bluetooth sources to correctly identify, a phone on the dashboard, and a second phone in the center console. To ensure that any changes in detection were not influenced by the steady battery drain on the phones, they were fully charged prior to the testing and during testing they were attached to a charging cable to remain at full power throughout all tests as shown in Figure 15.

Table 4 Listing of Bluetooth Detection Reliability Tests and Results

Test #	Antenna	Mounting Height	Edge Line Setback Distance*	Dash Phone Detections Near Lane			Console Phone Detections Near Lane			Dash Phone Detections Far Lane			Console Phone Detections Far Lane		
				30 MPH	**45 MPH**	**60 MPH**	**30 MPH**	**45 MPH**	**60 MPH**	**30 MPH**	**45 MPH**	**60 MPH**	**30 MPH**	**45 MPH**	**60 MPH**
1	1dB Stub	Ground	6 Feet / 18 Feet	30	27	29	30	23	23	29	26	28	29	21	21
2	Standard 3dB	Ground	6 Feet / 18 Feet	30	26	29	30	28	27	30	28	30	30	27	27
3	5 dB Dipole	Ground	6 Feet / 18 Feet	30	29	29	30	29	29	30	28	22	30	27	26
4	9 dB Patch	Ground	6 Feet / 18 Feet	21	20	25	16	14	21	27	19	28	20	17	24
5	3.12 dB Whip	Ground	6 Feet / 18 Feet	27	26	20	24	28	25	23	26	24	28	27	22
6	6.12 dB Whip	Ground	6 Feet / 18 Feet	28	26	26	28	28	22	29	25	24	27	25	24
7	3dB with Plate	Ground	6 Feet / 18 Feet	27	20	14	17	17	12	27	24	15	25	13	14
8	Standard 3dB	Ground	70 Feet / 82 Feet	30	30	30	30	27	23	30	30	30	30	30	30
9	Standard 3dB	+3 Feet	6 Feet / 18 Feet	30	30	30	30	30	30	30	30	30	30	30	30
10	Standard 3dB	+9 Feet	6 Feet / 18 Feet	30	30	30	30	30	30	30	30	30	30	30	30
11	Standard 3dB	+16 Feet	30 Feet / 42 Feet	30	30	30	30	30	30	30	30	30	30	30	30

All tests results shown were out of a total of 30 possible detections.

*The smaller setback distance was for the near lane; the larger setback distance was for the far lane.

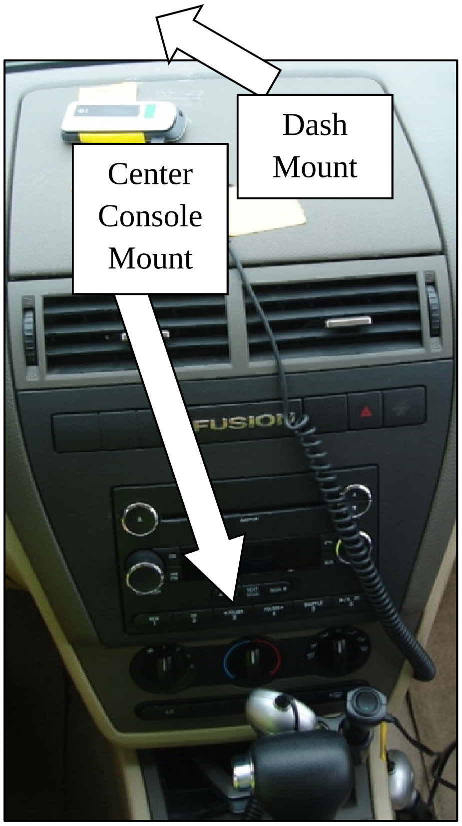


Figure 15 Bluetooth source (cellular phone) placements in test vehicle.

In most cases, the lateral setback distances tested were 6 and 18 feet. When the test vehicles were in the nearer lane the setback distance was 6 feet, and then when the vehicle was completing the lap, it was in the far lane corresponding with the 18 feet setback distance. Test number eight was conducted such that the data logger was at the edge of the available right-of-way, thus constituting the maximum tested setback distance at this testing location. The above-ground mounting heights were chosen to simulate possible antenna attachment to several common items found along the roadside:

- a guard rail post (+3 feet),
- an advisory sign (+9 feet), and
- a large sign overhead or adjacent to the roadway (+16 feet).

The 16 feet elevation was only tested at a 30 / 42 feet lateral setback from the edge line. This was due to the Kansas Department of Transportation's guidelines regulating the roadside placement of fixed objects. The 16 feet tall testing structure was deemed a safety hazard and thus was required to be located at the edge of the roadside clear zone. This large setback distance was deemed to be a worst-case scenario for this elevation. A sign bridge traversing the roadway, with its vertical supports outside the clear zone, would permit a Bluetooth antenna to be placed directly overhead any of the lanes and closer to traffic than the roadside placement used in the testing.

Analysis

The analysis of the data took part in several stages as follows.

Comparing Antennas

When conditions were standardized and differences between various antennas could be identified, the first null hypothesis was tested. The data collected show that antenna selection can have impacts both in terms of detection area and detection reliability. As the power of the antenna decreases so too does the detection area. However, several anomalies were observed in Table 4 for Tests #4-6. Test #4 utilized a directional patch antenna which had a long narrow detection area that limits a vehicle's time in the area; Tests #5 and #6 utilized magnetic whip antennas instead of dipole antenna designs, and Test #6 utilized a reflector plate placed behind a 3dB dipole antenna that was intended to create a directional dipole antenna. These tests resulted in decreased detection rates compared to other antenna options. Using Test #2 as the base condition, all of the other testing options that focused exclusively on antenna differences except for Test #3 (Tests 1, 4-7), with 95 percent confidence using a paired t-test, exhibited a statistically significant decrease in reliability compared to the standard 3 dB antenna as seen in Table 5. Test #3 was not shown to be statistically different from the baseline (Test 2) using the same test (p-value 0.751). As a result of these data, the null hypothesis H_{o1} was rejected.

Table 5 Bluetooth Detection Reliability and Comparisons to Base (Standard) Condition

Test #	Antenna	Vertical Mounting Height	Roadside Setback Distance	Detections	Reliability (%)	P-Value	Reject H_{o1}
1	1 dB Stub	Ground	6 Feet / 18 Feet	316	88	0.012	Yes
2	Standard 3 dB	Ground	6 Feet / 18 Feet	342	95	-	-
3	5 dB Dipole	Ground	6 Feet / 18 Feet	339	94	0.751	No
4	9 dB Patch	Ground	6 Feet / 18 Feet	252	70	<0.001	Yes
5	3.12 dB Whip	Ground	6 Feet / 18 Feet	300	83	0.002	Yes
6	6.12 dB Whip	Ground	6 Feet / 18 Feet	312	87	0.001	Yes
7	3 dB with Plate	Ground	6 Feet / 18 Feet	225	63	<0.001	Yes
8	Standard 3 dB	Ground	70 Feet / 82 Feet	350	97	0.305	No
9	Standard 3 dB	+3 Feet	6 Feet / 18 Feet	360	100	0.005	Yes
10	Standard 3 dB	+9 Feet	6 Feet / 18 Feet	360	100	0.005	Yes
11	Standard 3 dB	+16 Feet	30 Feet / 42 Feet	360	100	0.005	Yes

n = 360 detections possible per antenna

Effects of Lateral Setback Distance of Antennas

The horizontal and vertical placement distances for a Bluetooth antenna under standardized conditions were shown to affect changes on the data. Compared to a baseline roadside antenna placement as shown in Table 5 Test #2, a greatly increased setback distance, such as Test #8 in Table 5, was not shown to decrease the detection rate using a paired t-test with 95 percent confidence (p-value 0.305). Therefore, the null hypothesis H_{o2} was not rejected.

Effects of Vertical Elevation on Antennas

An above-ground placement of the standard antenna height between three and sixteen feet, such as Tests #9-11 in Table 5, was shown to increase the detection rate. These elevation increases were statistically significant with 95 percent confidence when considered across all speeds studied, set back distances, and source locations using a paired t-test (p-value 0.005). Thus the null hypothesis H_{o3} was rejected.

Effects of Vehicle Speeds

Carefully controlling all variables other than the vehicular speeds resulted in an additional way to analyze the data. When looking across all antenna options, placements, and source locations, the absolute number of detections decreased as speed increased. At 30 mph, 93 percent of the possible detections were observed; at 45 mph, the detections decreased to 87 percent, and at 60 mph the number of detections decreased again to 86 percent as shown in Table 6. The detection rate drop-off between 30 and 45 mph, using a paired t-test with 95 percent confidence, was statistically significant along with the drop off between 30 and 60 mph, however the decrease between 45mph and 60 mph was not statistically significant using the same test. Thus the null hypothesis H_{o4} was rejected for the drop off between 30 and 45 mph, 30 and 60 mph, but it was not rejected for the drop off between 45 and 60 mph.

Table 6 Bluetooth Detection Reliability at Various Speeds with Statistical Comparisons

Speed (mph)	Detections	Reliability (%)
30	1,232	93
45	1,151	87
60	1,133	86

n = 1,320 detections possible per speed

Comparison	P-Value	Reject H_{o4}
30 mph – 45 mph	< 0.001	Yes
30 mph – 60 mph	0.001	Yes
45 mph – 60 mph	0.442	No

Effects of In-Vehicle Bluetooth Source Location

Under standardized testing conditions, the data showed the dash-mounted mobile phone was detected 91 percent of the time compared with a detection rate of 87 percent for the center console-mounted mobile phone as seen in Table 7. Using a paired t-test with 95 percent confidence to control for the other variables, the drop in detection rate was statistically significant (p-value 0.001). Thus the null hypothesis H_{o5} was rejected.

Table 7 Bluetooth Detection Reliability for Dash and Console Mounted Bluetooth Sources

Source Location	Detections	Reliability (%)
Dash	1,801	91
Console	1,715	87

n= 1,980 detections possible per source location

Effects of Obstructions

A worst case scenario could be constructed with a large object between the Bluetooth data logger and the Bluetooth source that could obstruct the signals. This scenario was tested in Test #7 that utilized a shipping container as the obstruction. The detection area results showed that the mobile phone signal was still robust enough to have over thirty feet of electronic visibility on the opposite side of a shipping container. In this test the container was on the ground, while in a real scenario such a truck would have several feet of ground clearance for the tires that would allow for the detection area to not be impeded as much as in this test.

Findings and Discussion

A thorough understanding of the impacts that controllable variables could have on the collection of Bluetooth data is critical for traffic studies. Controllable variables of antenna choice, mounting height, and roadside setback distance were carefully examined, along with uncontrollable variables of source traveling speed, and source placement in a vehicle.

Antenna selection directly correlates to the quantity and quality of the data collected, which are at the heart of any engineering traffic study. In some cases having a smaller detection area might be desirable such as if one wanted to capture travel times on an interstate highway when neighboring ramps were present. In this scenario one would want to make sure that vehicles queued on a ramp were separated out from mainline vehicles. Unintentionally including delays incurred on the ramp would possibly contaminate the entire data set, and thus understanding the detection area for the equipment to becomes important.

While it was possible to estimate a Bluetooth sampling rate by comparing the number of Bluetooth signals received during a period to a separately determined number of vehicles counted during the same period, this did not implicitly correspond to a maximum theoretical sampling rate from all possibly available sources in the traffic stream. This research shows that in a typical roadside setup with a standard antenna, the Bluetooth data logger was able to capture around 95 percent of the available data. When one changes the antenna used and its mounting location this sampling rate can be increased or decreased. This research demonstrated that when an antenna was elevated above ground level – even as little as three feet - detection rates could increase to 100 percent. This singular change of increasing the height, has implications for future studies, especially in areas where the overall availability of Bluetooth signals in the traffic stream is low. This also showed that the data captured included almost all of the possible data points and was not limited to only being able to capture a subset of the available data.

Noting that Bluetooth source placement in a vehicle did have a statistically significant impact on the detection reliability, this indicates that there could be a bias in the data toward drivers that either keep a phone on the dashboard or are talking while driving, as opposed to drivers that have their phone out-of-sight in the center console.

CHAPTER 4
URBAN CORRIDOR TRAVEL TIME

In the summer of 2010, the city of Lenexa, Kansas upgraded the traffic control hardware in use along their 95th Street corridor between Monrovia and Lackman Roads to hopefully improve traffic flow. This 95th Street study corridor functioned as an arterial route, serving between 20,000 - 30,000 vehicles per day. The study corridor also intersected Interstate 35, and served a preponderance of traffic flowing to/from the interstate. Located adjacent to the corridor were a number of strip shopping centers and business parks. However, going several blocks beyond the curb, there were a large number of single and multi-family residences as seen in Figure 16.

Figure 16 Residential housing along 95th Street corridor in Lenexa, Kansas.

Research Objective

The objective for the study was to quantitatively determine differences in travel time reported by means of a GPS equipped floating car and Bluetooth data for the same corridor. The null (H_o) and alternate hypotheses (H_a) were as follows:

- H_o: The average travel times resulting from the GPS floating car data were the same as the average travel times resulting from the Bluetooth data.
- H_a: The average travel times resulting from the GPS floating car data were not the same as the average travel times resulting from the Bluetooth data.

Work Plan

The work plan for the project consisted of four distinct phases. These included: data collection of the before state, data collection of the after state, and data analysis. Through discussions with the signal controller vendor that provided the hardware upgrades and the city, it was believed that since no physical changes to the 95th Street geometry or lane markings were being made that there would not need to be any extra time allotted for drivers to re-familiarize themselves with the corridor, thus the after data collection effort only needed to wait for the vendor to report that the signal controller upgrade was complete and active.

Field Data Collection

Field data were collected during one-week spans in July and August 2010. The data were collected for two days during each data collection week. Between the two data collection time periods no significant changes in the transportation network occurred other than the traffic signal controller hardware upgrades. Neither the local public school district nor a neighboring private school was in session during either data collection period. The field data collection was conducted on two standard data collection days (Wednesdays and Thursdays) and consisted of two parts: mainline travel times collected using GPS-equipped floating car runs, and Bluetooth-based mainline travel times.

GPS Floating Car Runs

Travel time measurements along 95th Street were one direct measurement of the performance of the signal system. Travel time typically varied inversely with the volume of traffic present on 95th Street, and fluctuated throughout the day with peaks during the morning rush, lunch time, and the evening rush. The study corridor had two through lanes in each direction, and additional auxiliary lanes at several intersections. The travel time runs were conducted with the probe vehicle traveling at the prevailing average speed, but staying within a single lane. The probe vehicle alternated travel lanes between each travel time run. This allowed for a travel time average that was repeatable and not subject to a probe vehicle driver's passing aggressiveness. The travel time runs were conducted during six time periods during the day with the before data being collected on July 21-22 and the after data collected on August 11-12. The hourly periods that data collection (travel time runs) were conducted are shown in Table 8 and were selected to match the observed peaks throughout the day.

The travel time runs were conducted with the assistance of a commercially-available GPS software system (PC-Travel). Using this GPS data collection software, other performance measures in addition to travel time were obtained for the number of stops, average speed, average delay, average fuel consumption, average hydrocarbon emissions, average carbon monoxide emissions, and average nitrous oxide emissions. Calculations for these performance metrics were based on the vehicular trajectories recorded in real-time by the GPS component of the software and processed using default parameters.

Table 8 Probe Vehicle Data Collection Hours

Time Period	Traffic Condition
7:00 – 8:30 a.m.	Morning Peak
9:00 – 11:00 a.m.	Morning Off-Peak
12:00 – 1:00 p.m.	Noon Peak
2:00 – 3:00 p.m.	Afternoon Off-Peak
4:00 – 6:00 p.m.	Evening Peak
7:00 – 9:00 p.m.	Evening Off-Peak

Bluetooth Data Collection

The Bluetooth data loggers were deployed on Tuesday and retrieved on Friday of each test week, thus a full 48 hours of data were available on the test days and the Bluetooth system had the potential to include data outside of the probe vehicle data collection hours shown in

Table 8.

The deployment of Bluetooth data loggers for the study consisted of nine units. On the south side of 95th Street a unit was placed approximately one-half block from each end of the corridor, and an additional unit was placed on the north side of the road to maximize the likelihood of detecting passing Bluetooth signals. An example data logger placement is shown in Figure 17. Additionally, due to the importance of access to I-35 and the regional and national mobility that it provided, units were placed along 95th Street near each of the two ingresses and two egresses to the interstate. Thus, it would be possible to capture travel times for traffic traveling to/from I-35 to each extent of the corridor, along with travel times across the interchange for through traffic on 95th Street. The deployment of detectors on each side of 95th Street was to ensure that there would be a maximum likelihood of detecting Bluetooth signals emanating from all the lanes of the traffic stream.

Figure 17 Bluetooth data logger at the northwest corner of I-35 and 95th Street in Lenexa, Kansas.

Analysis

After the data were collected in the field, the data were analyzed and separated into the two types of data collected: GPS travel time runs and Bluetooth data. Travel time data were then subdivided into four segments for further investigation: one being the entire corridor, and the other three were as shown in Figure 18.


95th Street from Lackman Road to West of I-35

95th Street across I-35 interchange

95th Street from East of I-35 to Monrovia Street

Figure 18 Travel time segments along 95th Street in Lenexa, Kansas and Bluetooth data logger placements (*18*).

GPS Travel Time Runs

Travel time runs were conducted using a floating probe vehicle as previously described. Inside the probe vehicle, there was a driver and a researcher as a passenger. The research passenger managed a laptop computer that was connected to an external GPS receiver and used in conjunction with PC-Travel software to capture each travel time run. The research passenger ensured the driver traversed the study corridor in alternate lanes during each pass. When the probe vehicle was in the middle of each signalized intersection, the research passenger noted it in the GPS data. The tasks of the research passenger and driver were separately staffed; the City of Lenexa provided the probe vehicle and driver, the University of Kansas provided the research passenger.

Bluetooth Data Collection

The Bluetooth portion of the study could be broken down into four segments:

- traffic traveling the 95th Street along the entire corridor,
- traffic traveling on 95th Street between I-35 and Monrovia Street,
- traffic traveling on 95th Street between I-35 and Lackman Road, and
- traffic traveling on 95th Street across I-35.

For each segment, the traffic data were organized by direction and time of day. Each paired Bluetooth signal was assumed to represent a single independent vehicle. Data summaries for each direction are provided in Appendix A.

In an urban corridor such as 95th Street in Lenexa, the issue of travel time outliers was important. A travel time outlier for this study was based on percentile calculations and defined as any travel time observed that was in excess of three standard deviations above (or below) a moving average of thirty adjacent data points (*19*). This process was automated using software provided by the same vendor that supplied the Bluetooth data collection hardware, and was in accordance with their recommendations and research. All data presented in Appendices A and B have had the outlying data points scrubbed out of the data set; all calculations and statistical comparisons were also completed without regard to any outlying data points (travel times). Additionally, all data that were the result of the probe vehicle were also removed from the data set.

The advantage of the Bluetooth method could also be its weakest link, namely that data were only captured if a vehicle emitting one or more discoverable Bluetooth signals actually drove through each segment. Thus, for several hours of the day, no data were available to be collected, and thus no further analysis was possible (Appendix A). In total, when directionality of traffic was considered for each of the four segments, there were 192 hours with which hourly statistical comparisons could be made. Due to insufficient data during various time periods, 154 hours were left available for a before-after comparison. Considering the 154 available hours, 111 hours experienced a decrease in average travel time, while 43 hours experienced an increase in average travel time. However, 34 of the 111 decreases in travel time were deemed with 95 percent confidence to have a statistically significant difference from the travel time in the before case. Also of note is that 12 of the 43 increases in average travel time were also deemed with 95 percent confidence to have a statistically significant difference from the travel time in the before case. The p-values for each hourly two sample t-test can be found in Appendix A.

Table 9 Summary of Observed Bluetooth Based Travel Time Changes

	Total	Statistically Significant Hours
Hourly Time Periods for Comparison	154	46
Hourly Average Travel Time Reductions	111	34
Hourly Average Travel Time Increases	43	12

Findings and Discussion

Through the course of this research a number of findings were made:

Before-After Study

In several cases an increase in travel time along 95th street was observed in the Bluetooth data. The largest increase in travel time (1.6 minutes) was observed for eastbound 95th Street during the 2:00 p.m. hour. However, based on the data collected, with 95 percent confidence, it was not statistically possible to determine that the after travel time was actually larger than the before travel time. Several other hours/periods also indicated increased travel time; all but one were not statistically different from the before condition. The one hour that did have a travel time increase that was statistically different from the before condition was the 9:00 a.m. hour for eastbound traffic on 95th street (p-value 0.001). During this hour the travel time increased from 3.64 minutes to 4.44 minutes (48 seconds). For comparison, the GPS data for the overlapping time period also exhibited an increase in travel time from 4.15 to 4.76 minutes, although that increase was not statistically significant with 95 percent confidence (p-value 0.102). It was not known why this travel time increase occurred, but it was concurrently shown in both data sets. Results for the corridor are presented in full for Bluetooth data in Appendix A (hourly) and B (periodic), and hourly GPS data is presented in Appendix C (hourly) and D (periodic). Additional plots of the data are contained in Appendix E which shows before-and-after cumulative travel times collected using GPS data, and in Appendix F which shows the distributions of before-and-after average travel speeds collected using Bluetooth data.

Bluetooth Data to GPS Data Comparison

In comparing the Bluetooth data to GPS based data for the data collection time periods shown in

Table 8 for each direction in both the before and after cases 22 of 24 comparisons were possible. Two time periods in the eastbound after condition had no Bluetooth available for comparison. Among the 22 possible comparisons (Appendix G), five time periods had an average travel time that was determined to be with at least 95 percent confidence to be not the same between data collection methods. Focusing on these five time periods specifically, all but one of them indicated that the Bluetooth-based travel times were larger, implying slower mean travel times.

CHAPTER 5
URBAN FREEWAY TRAVEL TIME

Research Objective

While numerous algorithms exist to predict space mean speeds based on time mean speeds (spot speeds), none were without errors. Bluetooth technology presents, an opportunity was created to compare travel time predictions, and to show actual changes in travel time along a segment over time. Thus the null and alternate hypotheses were as follows:

- H_o: The travel times between the Kansas City Scout data and the Bluetooth data were not different.
- H_a: The travel times between the Kansas City Scout data and the Bluetooth data were different.

Work Plan

Working in concert with the Kansas City Scout Traffic Management Center, a plan was established to mirror existing monitored travel time segments. The Kansas City Scout Traffic Management Center was managed jointly by the Kansas Department of Transportation and the Missouri Department of Transportation and as such was able to have access to a vast array of in-pavement and roadside data collection sensors on major interstate routes in the Kansas City metropolitan area. Along a number of their routes, Scout would post travel times on dynamic message signs located adjacent to or overhead of the highway. Looking for an overlap of travel time segments a corridor stretching from just west of the K-10 and I-435 interchange and extending to the Kansas-Missouri border at State Line Road was selected as shown in Figure 19.

Five Bluetooth data loggers were deployed for eastbound and five data loggers were deployed for westbound traffic as shown in Figure 19 at the end points of the travel time segments.

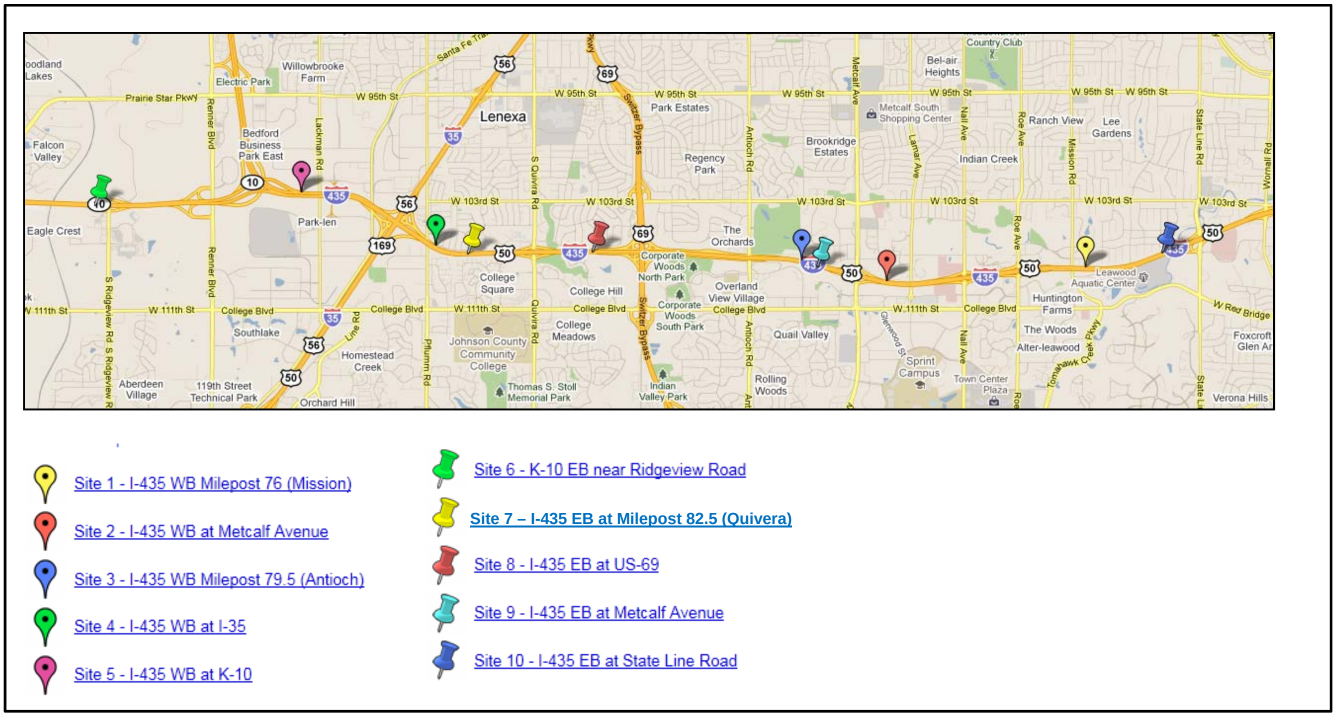


Figure 19 I-435/K-10 Bluetooth data logger placements along corridor.

Field Data Collection

The field data consisted of deploying the Bluetooth data loggers at the ten study sites for fifteen consecutive days. These study sites created eight travel time segments shown in Table 10 for analysis. However, the battery in the Bluetooth data logger at study Site 3 only lasted for 10.4 days, thus Routes 4 and 5 from Table 10 had slightly less data available than the other routes. The data from the Kansas City Scout Traffic Management Center did not require any fieldwork and was provided by e-mail correspondence from traffic operations engineer Mr. Jeremy Ball.

Table 10 K-10/I-435 Bluetooth Travel Time Segments

Route	Direction	Origin	Destination	Distance
1	Westbound	I-435 Milepost 76 (Site 1)	I-435 at Metcalf (Site 2)	1.9 miles
2	Westbound	I-435 Milepost 76 (Site 1)	I-435 at I-35 (Site 4)	6.2 miles
3	Westbound	I-435 Milepost 76 (Site 1)	I-435 at K-10 (Site 5)	7.5 miles
4	Westbound	I-435 Milepost 79.5 (Site 3)	I-435 at I-35 (Site 4)	3.4 miles
5	Westbound	I-435 Milepost 79.5 (Site 3)	I-435 at K-10 (Site 5)	5.0 miles
6	Eastbound	K-10 at Ridgeview Road (Site 6)	I-435 at US69 (Site 8)	4.8 miles
7	Eastbound	I-435 Milepost 82.5 (Site 7)	I-435 at Metcalf (Site 9)	3.3 miles
8	Eastbound	I-435 Milepost 82.5 (Site 7)	I-435 at State Line Road (Site 10)	6.5 miles

Analysis

The data recorded by the Bluetooth sensors required a filtering algorithm to be applied to separate statistical outliers from the rest of the travel time data points. An outlier could result from a vehicle not following the highway between the two Bluetooth data loggers that create each segment. For example, a driver might exit the highway to refuel his/her vehicle then return to the highway and continue along the segment. However this travel time, along the circuitous route, should not be considered alongside data from vehicles that did not make an intermediate stop.

The issue of outlier identification had been separately researched by the manufacturer of the Bluetooth data loggers. The firm found that the optimal means of identifying such data were to mark data points as outliers if they exceeded three standard deviations from the mean travel time of the thirty adjacent data points. The variation calculations required for outlier identification was computed using percentile difference instead of absolute differences (*19*). This same technique was also affirmed in the literature by Young (*5, 8*). The removal of the outliers then makes the resulting data less likely to include a circuitously routed vehicles, and thus more accurately reflected the actual mean travel time.

For each of the travel time routes in Table 10, the data were filtered for outliers and were summarized in fifteen-minute intervals over a two-week period of time. The mean travel time of each interval's Bluetooth data was paired to the reported travel time from the Kansas City Scout system data for the same interval, and a paired t-test was conducted between each pair of data. Due to the lack of available Bluetooth data, the lack of Scout data, or the lack of both data sets, not all intervals were available for comparison. Note that due to the detector at Site 3 shutting off early only 10.4 days of data were available for the two routes that utilized that data logger (Routes 4, 5) instead of 14 days for the rest of the routes.

Table 11: Paired T-Test Comparison Between Bluetooth and Kansas City Scout Data

Route	15 Minute Interval Comparisons	Bluetooth Mean Travel Time (Minutes)	KC Scout Mean Travel Time (Minutes)	Travel Time Difference (Minutes)	Travel Time Percentage Difference (%)	P-Value	Reject H_o?
1	1,121	1.73	2.09	-21.6	-17.22	< 0.001	Yes
2	1,009	6.11	6.04	4.2	1.16	0.319	No
3	506	7.17	7	10.2	2.43	0.022	Yes
4	176	3.66	3.44	13.2	6.4	0.021	Yes
5	155	4.89	5.14	-15	-4.86	0.025	Yes
6	959	4.55	5.09	-32.4	-10.61	< 0.001	Yes
7	1,074	2.96	3.35	-23.4	-11.64	< 0.001	Yes
8	1,178	6.22	6.04	10.8	2.98	< 0.001	Yes

Findings and Discussion

The travel times reported in the Bluetooth data did permit a statistical rejection of the null hypothesis (H_o) with 95 percent confidence for seven of the eight segments using a paired t-test. While the rejection of the null hypothesis implied that the reported travel times between the two methodologies were not the same, the practical implications of this were limited. In the most extreme example, the difference in the mean travel times was 32.4 seconds for Route 6; this would not be a practically significant difference for a 6.5 mile route. Additionally, there was not any pattern observed of the Bluetooth data being either slower or faster than the Scout data. Four of the routes shown in Figure 20, were found to have Bluetooth travel time data that were faster than the Scout data (Routes 1, 5, 6, 7) and the other four routes showed the reverse result (Routes 2, 3, 4, 8) to be true. It was also important to note that since the Scout data was based on point speeds, it was not necessarily ground truth. Thus the indeterminate nature of the results were seen to affirm that the Bluetooth data was a practically equal performance measure.

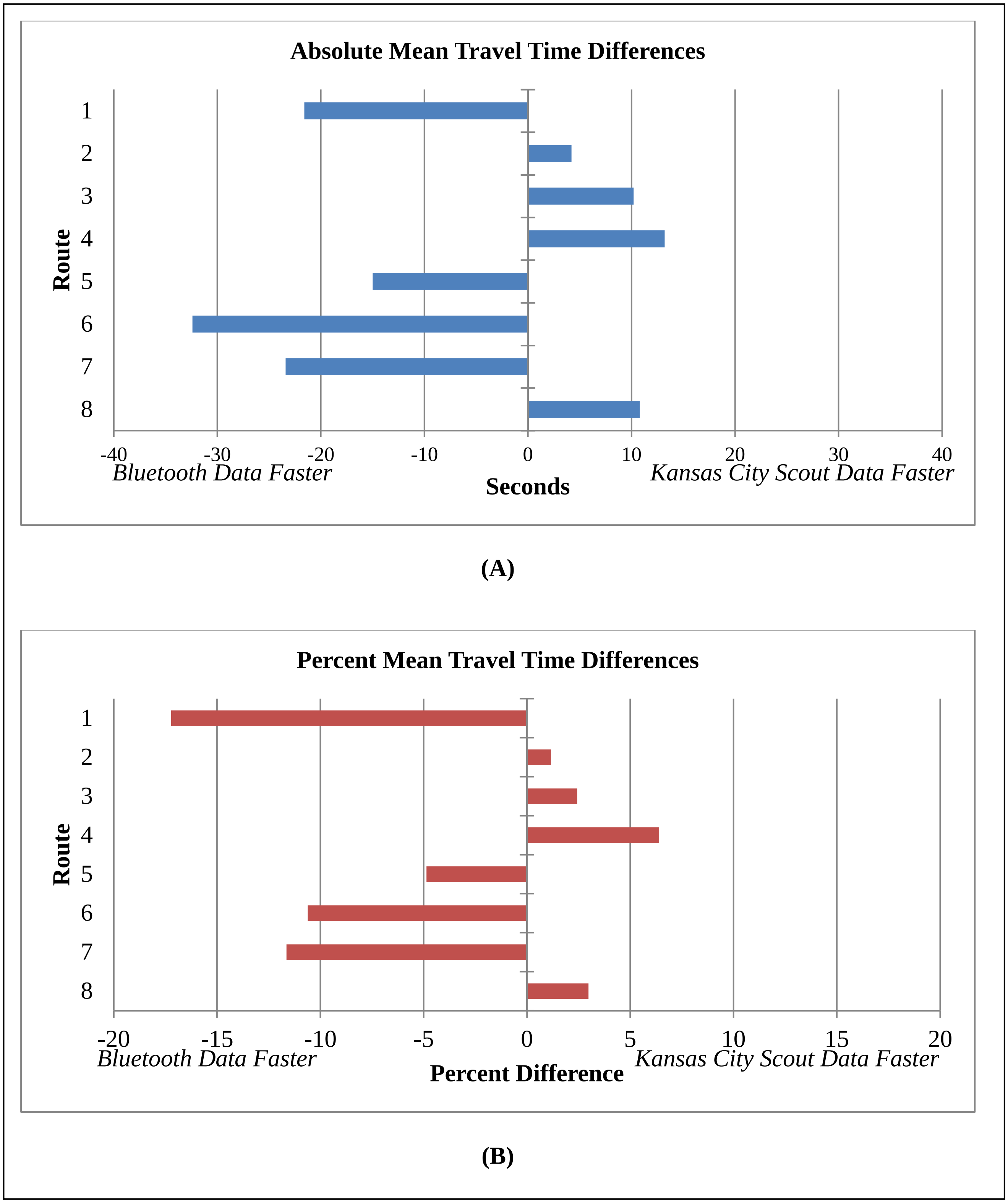


Figure 20 Mean Travel time differences of Bluetooth data less the Kansas City Scout data.

Limitations of Bluetooth Data Collection

The battery that failed in the Bluetooth data logger at Site 3 showcased one of the weakness of using portable Bluetooth data loggers to collect data. A critical part in the unit was the battery; this element determined how long each unit remained in operation. The data loggers used for the study utilized a rechargeable sealed gel battery. While the batteries were fully charged prior to the study, that does not preclude battery degradation after multiple charging cycles from affecting its performance in the field.

Additionally, the Bluetooth data once again showed that their chief weakness was not accuracy; it was their occasional lack of availability that formed the Achilles' heel of the technique. Considering the entire deployment time of the Bluetooth data loggers (including time before and after the 14 day study period) there were 11,171 fifteen minute study intervals possible among all the routes. However, 2,167 intervals (23 percent) had zero Bluetooth data available. While many of these vacant intervals were during off peak periods, some were during peaks in the traffic flow as this system relied on vehicle occupants to have active Bluetooth devices. As only a small fraction of vehicles were equipped with discoverable Bluetooth devices, one cannot guarantee that data will always be omnipresent.

If one were to take this study and integrate Bluetooth traffic monitoring into a comprehensive Intelligent Transportation System, the issues that occurred at Site 3 would not be an issue. In a permanent deployment, the units would be in a cabinet affixed to a signpost and would be hardwired to a power supply ensuring continuous electricity for the system to operate. As part of a system integration, the data would be fed in real-time to a computer for processing through a back haul channel to the traffic management center. Consideration would also have to be afforded to the issue of data availability. In a comprehensive system, the use of Bluetooth to measure travel times could be no more than a supplement to other data collection methods.

CHAPTER 6
ORIGIN-DESTINATION STUDY

Understanding that planning studies represented a key tool for city planners, and that the City of Columbia, Missouri's last origin-destination study was out of date, a research opportunity was born out of both need and research potential. Columbia, Missouri was a city of approximately 94,000 people spread throughout the city's 53 square mile area (*21*). Management of the city's road infrastructure was split between the city, and the state of Missouri. The state managed many of the arterials through the city as they were part of state route system; this was different than in Kansas where the state funds the various cities to perform maintenance on any state routes that pass through a city. Consequently, the Missouri Department of Transportation was also involved in supporting the study along with the metropolitan planning organization for the area (Columbia Area Transportation Study Organization, CATSO).

Research Objective

A study opportunity was assembled with several goals in mind. The primary objective for the study was to evaluate origin-destination patterns of basketball game-day traffic for the University of Missouri–Columbia, and to compare such perceived traffic surges to "normal" operations. As a member in a major athletic conference, the University of Missouri–Columbia regularly drew large crowds for both football and men's basketball home games. Many of these fans traveled to Columbia from out of town and were in addition to the many local fans. This combination caused the city to regularly alter signal phasings to disperse traffic following the event. The changes in traffic signal operations would cause disruptions to local drivers and those not associated with the game. Thus, an understanding of game day traffic flow patterns was deemed important to both the city and CATSO. This formed the basis for a pair of null and alternate hypotheses for this study which were as follows:

- Travel times:
    - H_{o1}: The travel times calculated by means of video re identification were not different than the travel times calculated using Bluetooth data.
    - H_{a1}: The travel times calculated by means of video re identification were different than the travel times calculated using Bluetooth data.
- Percent of through trips:
    - H_{o2}: The percentage of through trips from origin to destination, as documented through the video validation data and the Bluetooth data, were not different.
    - H_{a2}: The percentage of through trips from origin to destination, as documented through the video validation data and the Bluetooth data, were different.

Work Plan

In collaboration with the City of Columbia, Missouri and the University of Missouri–Columbia, a work plan was assembled to collect both Bluetooth data and other validation data to be able to extrapolate travel patterns. The study was organized around the men's basketball game of the on Saturday March 5, 2011 and featured an archrival school, which resulted in a sell-out crowd at the basketball arena. Three key corridors were identified for game day travel, all of which provided access to either an interstate highway (I-70) or a divided multilane highway (US-63), and are shown in Figure 21.

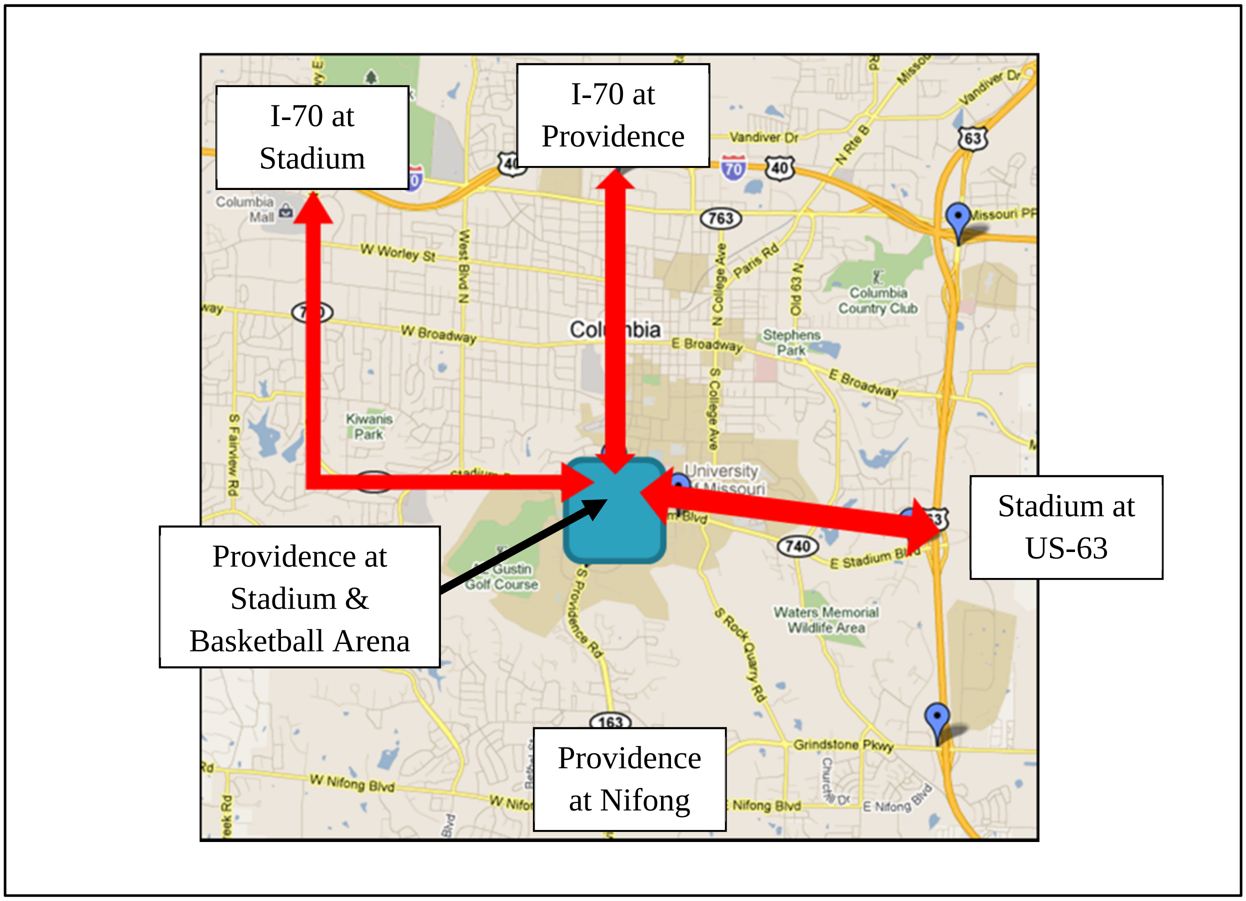


Figure 21 Primary origin-destination routes in Columbia, Missouri.

Field Data Collection

Field work consisted of collecting both Bluetooth data and video data to visually track vehicles through the study area.

Bluetooth Data

The Bluetooth data collection process required that ten data loggers be deployed throughout the City of Columbia. Many of these units were placed along the primary routes and around the basketball arena. Additionally two other units were deployed south of the area, and one northeast of the area. Each unit was affixed to a sign post or similar fixed object as shown in Figure 22 at the locations shown in Figure 23. Based on the recommendation of the city traffic engineer

Richard Stone, a detailed photographic log was created and distributed to university, city, county, and state law enforcement and to university facility operations staff. This log was created so that critical personnel would be able to easily identify the Bluetooth data loggers, and minimize any possible confusion that the units represented a threat to public security. These units were deployed for six complete days, March 3-8, 2011, for a total of 144 hours of data per unit; collectively 1,440 hours of data were collected in total.

Figure 22 Bluetooth data logger placement at Providence Road and Stadium Boulevard intersection.

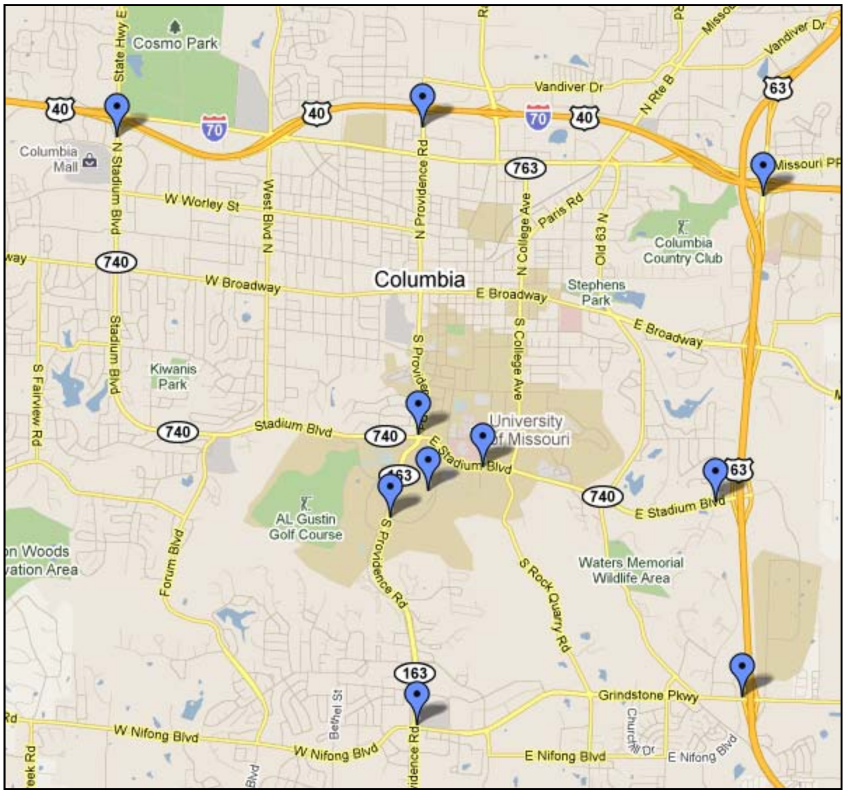


Figure 23 Location of Bluetooth data loggers in Columbia, Missouri.

Validation Data

In order to collect a complete dataset useful for generating and extrapolating origin-destination patterns, a secondary data source was needed. Such a data source needed to be able to positively identify and re-identify vehicles so that both travel time and origin-destination patterns could be derived. This was accomplished by means of using video cameras placed at the end points of the three primary routes (shown in Figure 21) along with a research assistant as shown in Figure 24. Due to logistical constraints and the enormous effort required to process such data, data were only collected on the basketball game day and only in one direction at a time. Prior to the game, data were collected along all three routes for traffic traveling toward the basketball arena, and following the game, data were collected for traffic traveling away from the area.

Figure 24 Video cameras set up east of the intersection of Providence Road and Stadium Boulevard.

Analysis

The data from the Bluetooth data loggers and video validation data were analyzed for results. The analysis was focused primarily around the events occurring before and after the basketball game on March 5, 2011. The analysis started with a breakdown of the video validation footage along with a comparison to Bluetooth data from the same time periods. Based on these results further analysis could be extrapolated.

The video validation data were processed to match vehicles at an upstream and downstream location together. This was accomplished by manually watching video footage, as shown in Figure 25, for surges and drop offs in peak traffic flow surrounding the basketball game. Once the time windows were set, vehicles were cataloged into a spreadsheet, as shown in Table 12, at the beginning and end of each segment, and then paired together to create trips and travel times.

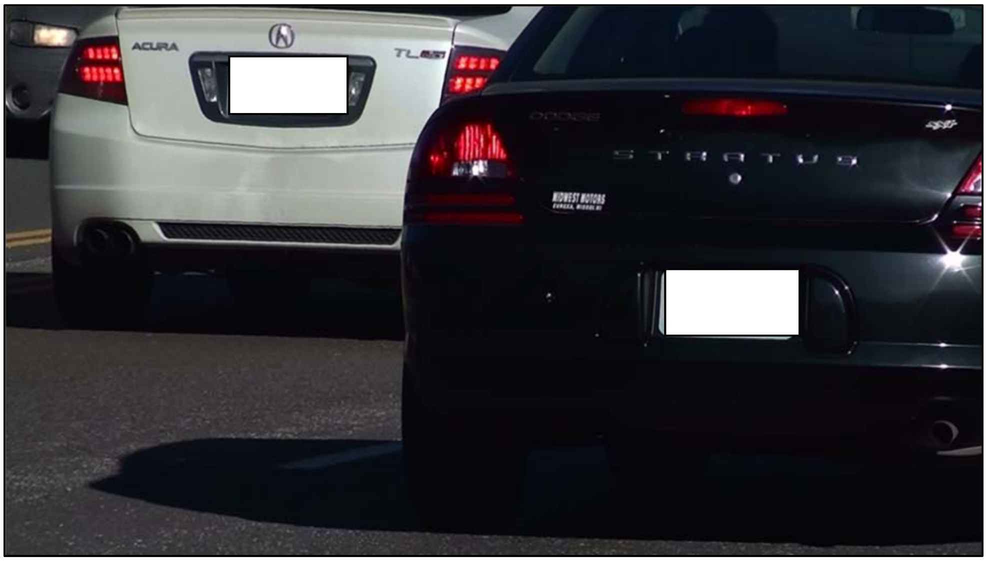


Figure 25 Example still frame of video re-identification footage (license plates redacted).

Table 12 Sample Validation Video Vehicular Re-Identification Data

ID	Clock	Make	Model	Color		Travel Time
142	10:18:04	Chevy	Tahoe	Black	[License Plate Numbers Redacted]	0:09:29
N/A	*10:18:05*	*Nissan*	*Altima*	*Black*		*N/A*
113	10:18:06	Ford	F150	Silver		0:10:52
158	10:18:08	Volvo	Sedan	Black		0:08:51
N/A	*10:18:08*	*Lexus*	*ES300*	*Black*		*N/A*
130	10:18:11	Infinity	Sports	Silver		0:10:10
159	10:18:11	Volvo	SW	Black		0:08:52
N/A	*10:18:13*	*Ford*	*Aerostar*	*Gray*		*N/A*
152	10:18:15	Chevy	MV	Red		0:09:29
143	10:18:17	Chevy	Monte Carlo	White		0:09:41
171	10:18:18	Cadillac	Escalade	Gray		0:08:26
169	10:18:18	Ford	Luxury	Black		0:08:27
N/A	*10:18:21*	*Jeep*	*Cherokee*	*White*		*N/A*
144	10:18:24	Impala	Sand			0:09:47
N/A	*10:18:27*	*Ford*	*F150*	*Black*		*N/A*
N/A	*10:18:28*	*Chevy*	*Sedan*	*Red*		*N/A*
N/A	*10:18:30*	*Ford*	*Contour*	*Green*		*N/A*
150	10:18:31	GMC	Yukon	Black		0:09:48
151	10:18:34	Hyundai	Sonata	Sand		0:09:49
168	10:18:56	Lexus	SUV	Gray		0:09:07
N/A	*10:18:56*	*Doritos*	*Truck*	*White*		*N/A*
N/A	*10:18:57*	*Toyota*	*Camry*	*Sand*		*N/A*
170	10:18:56	Honda	Accord	Black		0:09:05
N/A	*10:18:57*	*Geo*	*Prism*	*White*		*N/A*

Table 13 Origin-Destination Video Validation Data Processing Times for March 5, 2011

	Stadium (I-70 to Providence)	Stadium (Monk to US-63)	Providence (Stadium to I-70)	Providence (I-70 to Stadium.)	Combined
Time Periods Analyzed	10:07:08-10:11:19; 10:16:26-10:30:37; 10:47:05-10:51:58	13:30:14-13:54:14	13:30:14-13:32:28; 13:46:01-13:54:14	9:33:30-9:34:10; 10:45:52-10:48:48	
Total Time Analyzed	0:34:52	0:14:00	0:10:27	0:03:36	1:02:55
Total Vehicles	467	315	140	50	972
Flow Rate (vehicles/hour)	1120	1233	895	991	1100

Table 14 Comparison Between Bluetooth and Video Validation Data

Segment	Time Period	Video Based Vehicle Count	Video O/D Percentage	Video Average Travel Time (Minutes)	Video Standard Deviation of Travel Time	Bluetooth Based Vehicle Count	Bluetooth Average Travel Time (Minutes)	Bluetooth Standard Deviation of Travel Time	Bluetooth Penetration Rate (%)	Reject H_{o1}?	P-Value
Stadium (I-70 to Providence)	10:07:08-10:11:19	35	30.7	9.33	0.65	2	14.47	6.68	5.7	No	0.473
Stadium (I-70 to Providence)	10:16:26-10:30:37	55	21.0	7.35	0.68	0	-	-	-	-	-
Stadium (I-70 to Providence)	10:47:05-10:51:58	11	12.1	6.88	0.60	0	-	-	-	-	-
Stadium (Monk to US-63)	13:30:14-13:54:14	221	70.2	3.15	0.38	32	3.32	0.48	14.5	No	0.063
Providence (Stadium to I-70)	13:30:14-13:32:28	1	6.7	4.03	-	2	19.92	6.85	-	-	-
Providence (Stadium to I-70)	13:46:01-13:54:14	39	27.9	5.73	0.83	2	9.10	2.45	5.1	No	0.303
Providence (I-70 to Stadium)	9:33:30-9:34:10	3	21.4	5.92	0.22	0	-	-	-	-	-
Providence (I-70 to Stadium)	10:45:52-10:48:48	5	13.9	5.43	0.53	0	-	-	-	-	-

Using the eight time periods from Table 13, data values for number of vehicles, Bluetooth penetration rates, and origin-destination percentage were extracted and calculated for both of the methods to create Table 14. A two sample t-test with 95 percent confidence was used to test the null hypothesis. In the three cases where the test was possible, the first null hypothesis (H_{o1}) was not rejected.

While the validation data were limited by the labor required to capture and process the data, the Bluetooth data were not as constrained. Therefore, quite a bit more Bluetooth data were available for analysis. If one assumes the intersection of Providence Road and Stadium Boulevard was the center of the study and one ignores the other local streets in the area, other extrapolations were possible. The average daily traffic at that intersection was 60,000 vehicles per day; using that number a daily penetration rate (the ratio of Bluetooth sources to vehicles) could be estimated as shown in Table 15.

Table 15 Bluetooth Detections at Providence Road and Stadium Boulevard Intersection

Day	Bluetooth Detections	Penetration Rate (%)
March 3, 2011	4,849	8
March 4, 2011	4,762	8
March 5, 2011	3,867	6
March 6, 2011	3,411	6
March 7, 2011	4,425	7
March 8, 2011	4,295	7

Taking this study to its logical conclusion, based on the trips originating at the Providence Road and Stadium Boulevard intersection and terminating along each of the intersection’s four approaches, a preliminary destination matrix could be created as shown in Table 16. When one combines the data from Table 15 with the first six columns of Table 16, one could also estimate a percentage of all trips that follow through to each destination. Recognizing that the data averaged a 6 percent Bluetooth penetration rate as shown in Table 15 which was not out of character compared to the validation data shown in Table 14, an extrapolated estimated origin-destination trip matrix could be created by dividing each of the cells in Table 16 by the average penetration rate (6 percent) to create Table 17. When the daily totals were broken down into proportions by destination, the result was Figure 26 which shows the estimated trip distribution based on the Bluetooth data.

Table 16 Preliminary Bluetooth Daily Directional Distributions for the Providence Road and Stadium Boulevard Intersection

Date	I-70 at Stadium	I-70 at Providence	US-63 at Stadium	Providence at Nifong	Total Trips	Percent of All Trips (%)
March 3, 2011	103	243	335	795	1,476	30
March 4, 2011	145	288	379	901	1,713	36
March 5, 2011	127	222	349	652	1,350	35
March 6, 2011	86	151	206	508	951	28
March 7, 2011	114	229	322	795	1,460	33
March 8, 2011	114	185	277	749	1,325	31
Total	689 (8%)	1,318 (16%)	1,868 (23%)	4,400 (53%)	8,275	32%

Table 17 Projected Number of Through Trips to Each Destination from the Providence Road and Stadium Boulevard Intersection

Date	I-70 at Stadium	I-70 at Providence	US-63 at Stadium	Providence at Nifong	Total
March 3, 2011	1,717	4,050	5,583	13,250	24,600
March 4, 2011	2,417	4,800	6,317	15,017	28,550
March 5, 2011	2,117	3,700	5,817	10,867	22,500
March 6, 2011	1,433	2,517	3,433	8,467	15,850
March 7, 2011	1,900	3,817	5,367	13,250	24,333
March 8, 2011	1,900	3,083	4,617	12,483	22,083
Total	11,483	21,967	31,133	73,333	

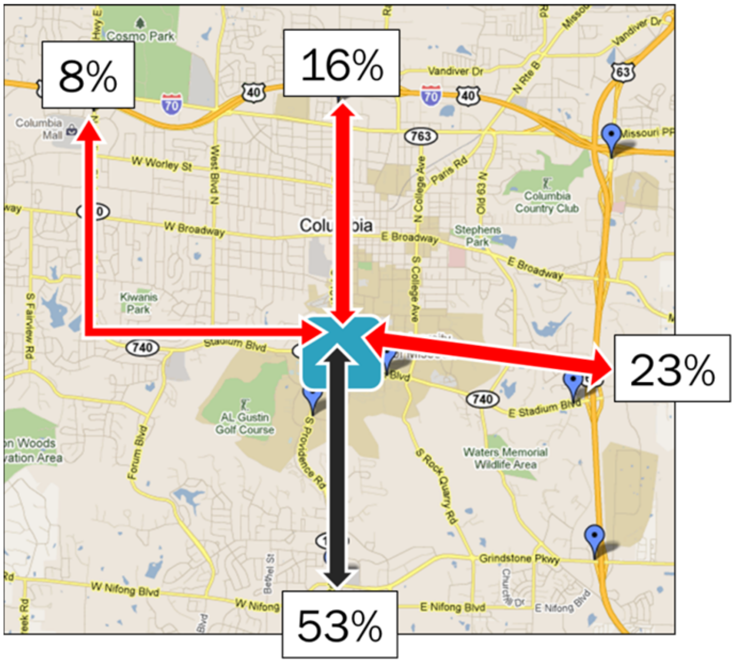


Figure 26 Destination percentages for through trips originating from the intersection of Providence Road and Stadium Boulevard estimated using Bluetooth data.

The ground truth data could be used to validate the Bluetooth data. Focusing on the comparable segment in Table 14, "Providence (Stadium to I-70)," if one takes a weighted average of the video-based origin-destination percentage, the result is 23 percent. This means that 23 percent of all traffic cataloged as originating from the intersection of Providence Road and Stadium Boulevard heading in the general direction of I-70 actually completed the study route. Unfortunately, a direct comparison to Bluetooth data was not possible, as the data logger located at the Providence Road and Stadium Boulevard Intersection was not able to distinguish a direction of travel; such directionality was only possible when the data were paired to downstream data. Thus the corresponding Bluetooth data would be the "Percent of All Trips" column from Table 16. The use of these data as a comparison to the validation data set required one to assume that the Bluetooth data did not suffer from disproportionate reduction in through trips as compared to the validation data. A z-test for two proportions with 95 percent confidence was conducted and the result was that one cannot reject the second null hypothesis (H_{o2}). The p-value for the z-test was 0.065.

Findings and Discussion

Bluetooth-based data for estimating origin-destination relationships were shown to not be statistically different from data collected using a conventional approach. While the data required multiplication factors to extrapolate estimated origin-destination patterns, the acquisition of point source volume data required far less effort than actual travel pattern data. As the Bluetooth data were recorded, roadway users were not in any way biased as they potentially could be in the case of travel diaries. The electronically-recorded MAC addresses in the Bluetooth data eliminated the tedious processing effort required to catalog license plates and vehicle descriptions for a video-based study. Thus the effort required to capture a single day’s worth of traffic was the same as that of several days’ worth of data.

The extended availability of the Bluetooth data opened up additional analysis possibilities that would otherwise have been logistically impossible to capture, such as being able to assess fluctuations in travel time over extended durations. Such analysis would not typically be possible if travel diaries were used and would represent a significant effort in the case of video data. As shown in Figure 27, if one was to remove the dates from the x-axis it would not be readily apparent on which day the basketball game occurred. In the context of several days of traffic, it was not an extraordinary event even when focused more specifically on March 5, 2011, and compared to a typical day as shown in

Figure 28. The only tell-tale sign of a difference was that the Tuesday traffic had more travel time outliers.

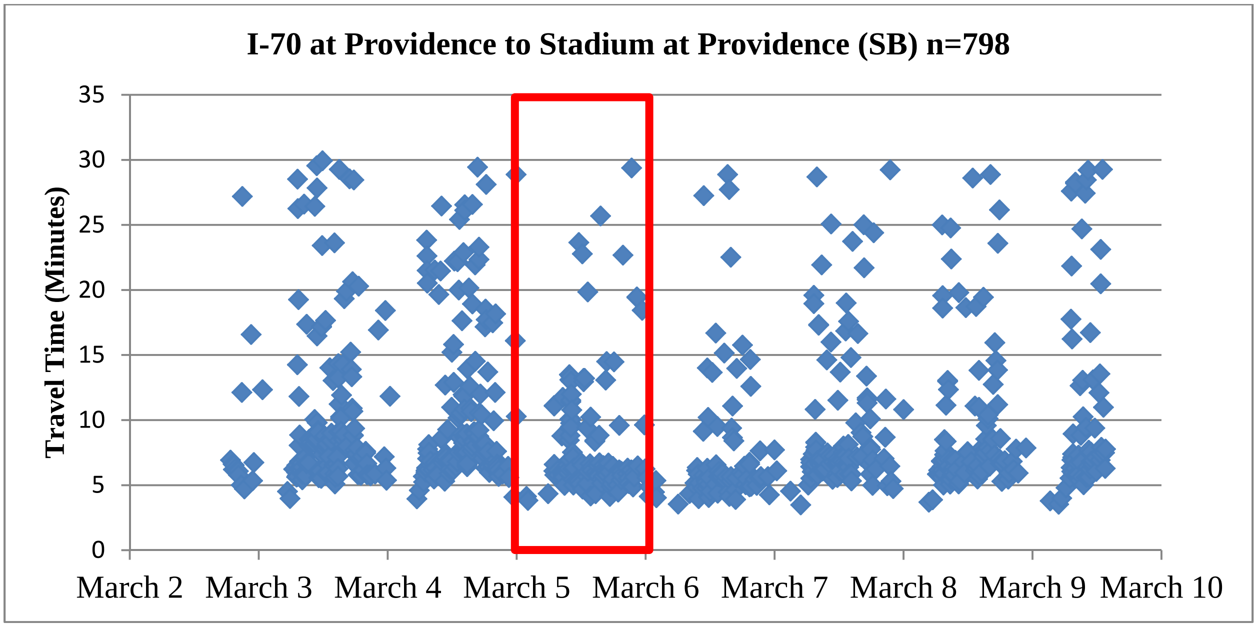
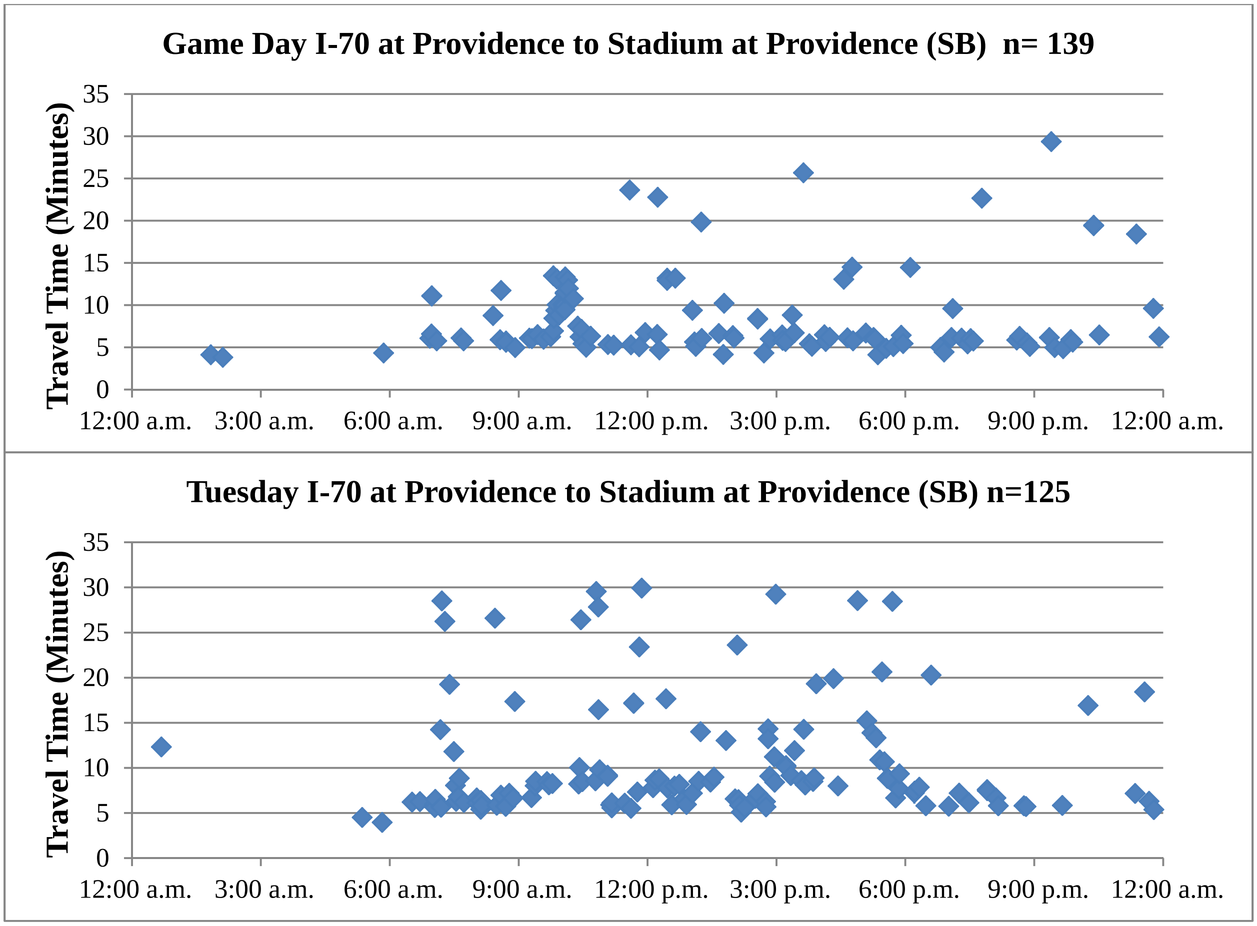


Figure 27 Bluetooth-based travel time fluctuations including outliers, with game day traffic emphasized.


Game Day I-70 at Providence to Stadium at Providence (SB) n= 139

Tuesday I-70 at Providence to Stadium at Providence (SB) n=125

Figure 28 Detailed travel time comparisons between game day and a typical day.

It was important to understand that the estimated trips were for through travel between each origin and destination. As shown in Table 16, these trips only accounted for 28-36 percent of all traffic. The remainder of the traffic originating at the intersection of Providence Road and Stadium Boulevard was presumed to have left the segment and continued along alternate roads to other destinations. Thus, the data in Table 17 were only valid for complete trips along each segment.

The Bluetooth data enable additional possible analyses. One such analysis would be the separate identification of local traffic and visiting traffic. In the case of the basketball game, one could shift through the MAC addresses that formed Table 15 and tally how many unique MAC address were only recorded on game day that never appeared again in the other five days. In this case, a total of 6,584 unique Bluetooth MAC addresses passed through the intersection of Providence Road and Stadium Boulevard during the study period. However, out of the entire population of unique Bluetooth MAC addresses, 2,541 (39 percent) only appeared in the data for a single day. Not surprisingly, the day with the most unique Bluetooth MAC addresses, as shown in Table 18, recorded at the intersection was basketball game day, March 5, 2011.

Table 18 Daily Distribution of Unique Bluetooth MAC Addresses

Date	**MAC Addresses Appearing Only on Date**	**Percent of Unique MAC Address for Study Period (%)**
March 3, 2011	432	17
March 4, 2011	470	18
March 5, 2011	520	20
March 6, 2011	319	13
March 7, 2011	406	16
March 8, 2011	394	16
Total	***2,541***	***100%***

If one wanted to further extend the study methodology to estimate directional distributions in addition to origin-destination information, this might be possible. To do so, each line in Table 17 could be divided by the corresponding “Percent of All Trips” column in Table 16 to produce Table 19. However, validation data for this were not collected as part of the sturdy, and remains a subject for additional research.

Table 19 Estimated Directional Distributions at the Providence Road and Stadium Boulevard Intersection

Date	Westbound	Northbound	Eastbound	Southbound	Total
March 3, 2011	5,640	13,305	18,343	43,529	80,817
March 4, 2011	6,718	13,344	17,560	41,745	79,367
March 5, 2011	6,063	10,598	16,662	31,127	64,450
March 6, 2011	5,141	9,027	12,315	30,368	56,850
March 7, 2011	5,759	11,568	16,265	40,158	73,750
March 8, 2011	6,159	9,995	14,965	40,465	71,583
Total	35,479	67,836	96,109	227,392	

CHAPTER 7
ROUNDABOUT TURNING MOVEMENT ESTIMATION

Research Objective

An understanding of how motorists utilize an intersection was fundamental for engineers and planners alike to best manage operations. Traditional (signalized or all way stop control) intersections provide a temporal and spatial separation of turning movements that can be counted with relative ease compared to a roundabout. Roundabout intersections (particularly single lane roundabouts) offer no such separations; four vehicles that simultaneously approach from different directions all could enter at the same time and proceed to make any combination of movements. This path overlap has created a conundrum for traditional counting methodology, and, thus, typically requires a sophisticated video detection system, or, more commonly, labor-intensive manual observation.

One common mathematical solution for counting traffic at roundabouts was known as an algebraic solution. This solution, as published by the Federal Highway Administration, makes use of a series of simultaneous equations that can be solved for turning movements using matrix algebra (*22*). However, for this to work, one must:

- assume the volume of U-turns is negligible,
- have known entry, exit, and right turn volumes.

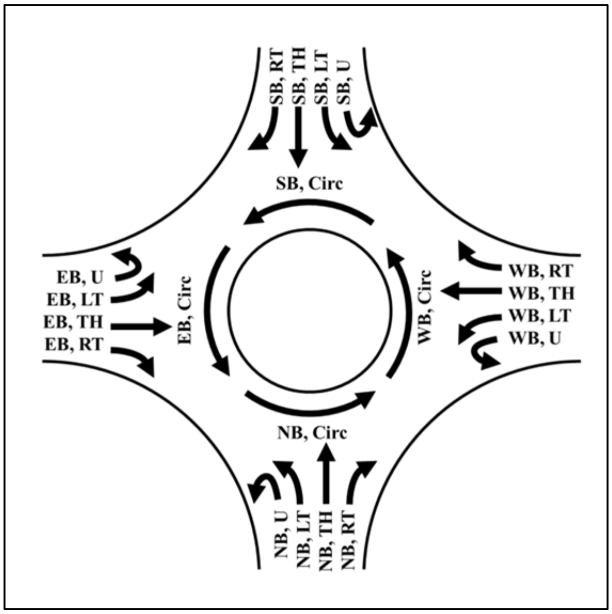


Figure 29 Roundabout turning movement diagram (*22*).

Each specific turning movement may be obtained by adding and subtracting various volumes. So for example, the equation to obtain the east bound through volume would be as follows.

$$V_{EB,TH} = V_{EB,Entry} + V_{WB,Exit} - V_{EB,RT} - V_{NB,RT} - V_{NB,Circ}$$

Where:

- volumes $V_{EB,TH}$ is eastbound through,
- $V_{EB,Entry}$ is eastbound entry,
- $V_{WB,Exit}$ is westbound exit,
- $V_{EB,RT}$ is eastbound right turn,
- $V_{NB,TH}$ is northbound through, and
- $V_{NB,circ}$ is the northbound circulating.

However, when the number of legs at a roundabout exceeds four, the resulting matrix becomes indeterminate and requires additional data for a solution to be possible. Such locations where there are more than four approach legs are also the same locations where the benefits of roundabouts are most apparent. An extension to this approach using video data and a processing algorithm was researched by Rescot in 2007. While Rescot showed in his research that one could obtain a 90 percent counting accuracy or greater, his video processing methodologies broke down if there were more than one circulating lane, or more than four approaches. For example, a five legged roundabout would have 25 possible turning movements or 20 movements if u-turns were excluded (an increase over the 16 possible movements for a four legged roundabout or 12 movements if u-turns were excluded), and in order for the matrix algebra to be determinate, an equal number of equations and unknown variables must be present. For the five legged roundabout, this would require the capture of several additional turning movements in addition to the right turns, which was beyond the scope the algorithm developed by the Federal Highway Administration (*23*).

At the core of solving the roundabout turning movement dilemma were several underlying philosophies. First, was to recognize that due to normal fluctuations in traffic, day to day, and month to month, there were diminishing rates of return for increasing the counting accuracy. Thus, a corollary to that would be that a count, to be useful, would not necessarily need to capture 100 percent of all turning movements, and that there could be some tolerance for error. Secondly, it was recognized that estimating turning movements at a roundabout was really a much smaller origin-destination study with each leg of the intersection both an origin and a destination for every other leg. Thus, the study segmentation possibilities were finite, and once a driver entered the study area there would be no other way out than to exit via a study route.

Considering the limitations and possibilities, the research hypotheses for comparing Bluetooth data to traditional traffic count data at roundabouts were as follows:

- H_o: The proportional variation between turning movements captured using manual traffic count data and Bluetooth data was not different.
- H_a: The proportional variation between turning movements captured using manual traffic count data and Bluetooth data was different.

Work Plan

Two sites were selected in Kansas for study. One was a urban four-legged roundabout located in Lawrence, Kansas on a principal collector road, and the other was a rural five-legged roundabout located near the City of Paola, Kansas in unincorporated Miami County on a state highway. For each roundabout, a Bluetooth data logger was deployed upstream of the central island on each leg and attached to the "Roundabout Ahead" advisory sign. To verify the validity of the data, two research assistants were deployed to manually count each turning movement, along with a video camera for verification purposes.

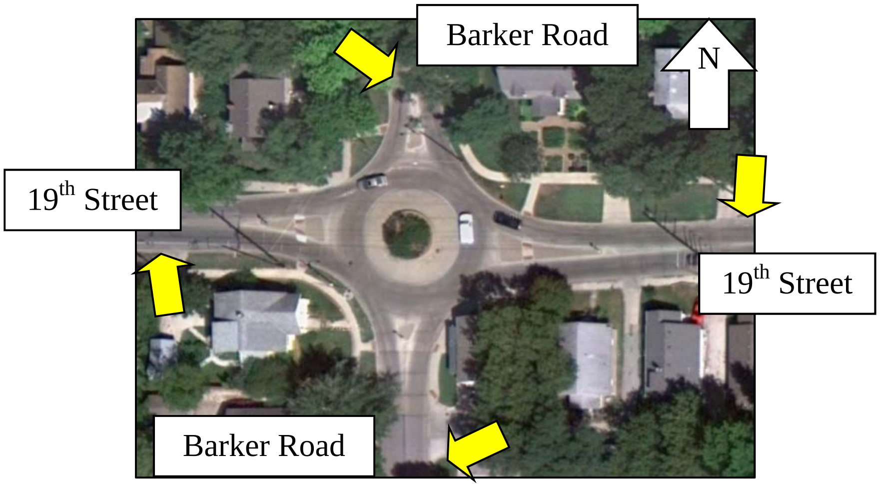


Figure 30 Lawrence, Kansas roundabout showing Bluetooth data logger placements (*18*).

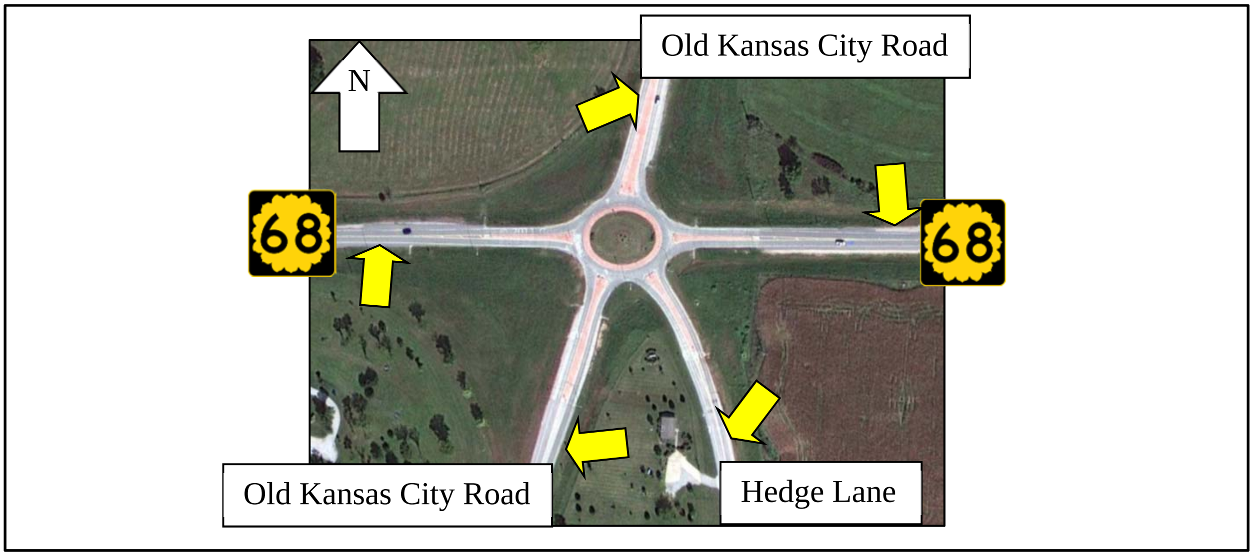


Figure 31 Paola, Kansas roundabout showing Bluetooth data logger placements (*18*).

Field Data Collection

Data collection for the project was twofold, collecting Bluetooth data, and collecting manually verified data. Manual data collection at each location was conducted over several days, 8.3 hours at the Paola, Kansas location, and 16 hours at the Lawrence, Kansas site for a total of 24.3 hours between both sites. As the Bluetooth data loggers could be left running from deployment to retrieval, there was a total of 99 hours of Bluetooth data for the Paola, Kansas roundabout and 51 hours for the Lawrence, Kansas roundabout. During all manual data collection times, a team of two research assistants were on-site to divide the counting duties so as to minimize the mental effort required to track traffic from the four or five approaches. The manual counts also served as a record of approach volumes during the count duration. Each research assistant used a digital handheld traffic counter that recorded time-stamped data for each movement. A video camera was also used to augment the manual counts, and was particularly useful at the Paola roundabout to capture the traffic on the fifth approach leg (Hedge Lane).

The choice of which Bluetooth antenna to use was based on location specific factors. Based on the data from

Table 8, along with Figure 12 and Figure 13, the standard antenna was utilized at the Paola, Kansas location. However, for the Lawrence, Kansas location, the stub antenna was selected due to the closer proximity of the sensors to each other. There was a concern that, if a more powerful antenna was used, traffic arriving on legs other than the one adjacent to the Bluetooth data collection unit might be inadvertently detected and contaminate the dataset.

The data collected at both roundabouts was tabulated for analysis. Data from the Paola, Kansas roundabout is presented in Table 20, and data for the Lawrence, Kansas roundabout is presented in Table 21. In each of the aforementioned tables, part A shows the manually counted data, part B shows the Bluetooth data for the same time periods, and part C shows the percentage movements captured by Bluetooth in comparison to part A.

Table 20 Paola, Kansas Roundabout Data

	Manual Count Data		Departure Leg				
		Volume	South Old KC Road	West K-68	North Old KC Road	East K-68	Hedge Lane
Origin Leg	**South Old KC Road**	285	-	79	72	132	2
	West K-68	340	80	-	13	204	43
	North Old KC Road	148	90	11	-	11	36
	East K-68	524	227	230	21	-	46
	Hedge Lane	95	3	26	37	29	-

n = 1,392 trips

(A)

	Study Period Bluetooth Data		Departure Leg				
		Volume	South Old KC Road	West K-68	North Old KC Road	East K-68	Hedge Lane
Origin Leg	**South Old KC Road**	285	-	5	1	5	1
	West K-68	340	4	-	0	13	5
	North Old KC Road	148	4	0	-	1	2
	East K-68	524	12	19	1	-	3
	Hedge Lane	95	1	4	3	0	-

n = 84 trips

(B)

	Study Period % Bluetooth Data		Departure Leg				
		Volume	South Old KC Road (%)	West K-68 (%)	North Old KC Road (%)	East K-68 (%)	Hedge Lane
Origin Leg	**South Old KC Road**	285	-	6	1	4	50
	West K-68	340	5	-	0	6	12
	North Old KC Road	148	4	0	-	9	6
	East K-68	524	5	8	5	-	7
	Hedge Lane	95	33	15	8	0	-

n = 84 trips

(C)

Table 21 Lawrence, Kansas Roundabout Data

			Departure Leg			
	Manual Count Data	Volume	South Barker Street	West 19th Street	North Barker Street	East 19th Street
Origin Leg	South Barker Street	1,075	5	113	666	291
	West 19th Street	4,790	199	4	251	4,336
	North Barker Street	1,960	544	572	0	844
	East 19th Street	4,543	121	3737	676	9

n = 12,368

(A)

			Departure Leg			
	Study Period Bluetooth Data	Volume	South Barker Street	West 19th Street	North Barker Street	East 19th Street
Origin Leg	South Barker Street	1,075	-	42	56	82
	West 19th Street	4,790	77	-	52	131
	North Barker Street	1,960	81	96	-	75
	East 19th Street	4,543	39	128	93	-

n = 952

(B)

			Departure Leg			
	Study Period % Bluetooth Data	Volume	South Barker Street (%)	West 19th Street (%)	North Barker Street (%)	East 19th Street (%)
Origin Leg	South Barker Street	1,075	-	37	8	28
	West 19th Street	4,790	39	-	21	3
	North Barker Street	1,960	15	17	-	9
	East 19th Street	4,543	32	3	14	-

n = 952

(C)

Table 22 Paola, Kansas Roundabout Turning Movement Distributions

		Departure Leg				
	Distribution of Manual Count Data	**South Old KC Road (%)**	**West K-68 (%)**	**North Old KC Road (%)**	**East K-68 (%)**	**Hedge Lane (%)**
Origin Leg	**South Old KC Road**	-	5.7	5.2	9.5	0.1
	West K-68	5.7	-	0.9	14.7	3.1
	North Old KC Road	6.5	0.8	-	0.8	2.6
	East K-68	16.3	16.5	1.5	-	3.3
	Hedge Lane	0.2	1.9	2.7	2.1	-

n = 1,392 trips

(A)

		Departure Leg				
	Distribution of Bluetooth Data	**South Old KC Road (%)**	**West K-68 (%)**	**North Old KC Road (%)**	**East K-68 (%)**	**Hedge Lane (%)**
Origin Leg	**South Old KC Road**	-	6.0	1.2	6.0	1.2
	West K-68	4.8	-	0.0	15.5	6.0
	North Old KC Road	4.8	0.0	-	1.2	2.4
	East K-68	14.3	22.6	1.2	-	3.6
	Hedge Lane	1.2	4.8	3.6	0.0	-

n = 84 trips

(B)

Table 23 Lawrence, Kansas Roundabout Turning Movement Distributions

		Departure Leg			
	Distribution of Manual Count Data	**South Barker Street (%)**	**West 19th Street (%)**	**North Barker Street (%)**	**East 19th Street (%)**
Origin Leg	**South Barker Street**	-	0.9	5.4	2.4
	West 19th Street	1.6	-	2.0	35.1
	North Barker Street	4.4	4.6	-	6.8
	East 19th Street	1.0	30.2	5.5	-

n = 12,368

(A)

		Departure Leg			
	Distribution of Bluetooth Data	**South Barker Street (%)**	**West 19th Street (%)**	**North Barker Street (%)**	**East 19th Street (%)**
Origin Leg	**South Barker Street**	-	4.4	5.9	8.6
	West 19th Street	8.1	-	5.5	13.8
	North Barker Street	8.5	10.1	-	7.9
	East 19th Street	4.1	13.4	9.8	-

n = 952

(B)

Analysis

The Bluetooth data captured by this technique represented a fraction of the total number of vehicles that used each roundabout. Assuming a single Bluetooth source per vehicle, the Paola, Kansas roundabout had a Bluetooth sampling rate of 6 percent (84 out of a possible 1.392 trips from Table 20), while the Lawrence, Kansas roundabout had a Bluetooth sampling rate of 8 percent (952 out of a possible 12,368 trips from Table 21) compared to manually counted data during the same time periods.

The Paola and Lawrence datasets both appear to have turning movement distributions by percentage of traffic in the manual count data that were related to the turning movement distributions in the Bluetooth data as shown in Table 22 and Table 23. This was important as any differences in the distributions could be reflected in the final output. When looking at an expanded Bluetooth dataset for Paola of 99 continuous hours, shown in Table 24, it was apparent that the Bluetooth data continued to regress toward the known manually counted distribution shown in Table 22a and Table 23a. An F-test for equal variations was used to test for changes in the overall variation of the turning movement distributions. It showed that one cannot reject with 95 percent confidence, a null hypothesis that the variation between the manual and Bluetooth data sets was not different for the Paola roundabout (p-value 0.924). However, using the same F-test on the Lawrence roundabout did permit one to reject the same null hypothesis for that location (p-value < 0.001). Upon further analysis of the data, the east-west directionality of the data stood out as a possible source of error. This was because the sum of the eastbound and westbound through movements represented 65 percent of the manually counted traffic volume, while the Bluetooth data only showed it to be 27 percent of the traffic volume, a 58 percent error.

Table 24 Distribution of Paola, Kansas Bluetooth Roundabout Turning Movements Over 99 Hours

		Departure Leg				
	Distribution of Bluetooth Data	**South Old KC Road (%)**	**West K-68 (%)**	**North Old KC Road (%)**	**East K-68 (%)**	**Hedge Lane (%)**
Origin Leg	**South Old KC Road**	-	5.9	7.5	7.9	1.3
	West K-68	4.7	-	0.7	17.4	3.1
	North Old KC Road	5.1	0.7	-	0.6	2.7
	East K-68	10.0	19.9	1.7	-	2.5
	Hedge Lane	1.4	2.0	2.4	2.5	-

n = 708 trips

Table 25 Distribution of Lawrence, Kansas Roundabout Turning Movements Over 51 Hours

		Departure Leg			
	All Bluetooth Data Ratio	**South Barker Street (%)**	**West 19th Street (%)**	**North Barker Street (%)**	**East 19th Street (%)**
Origin Leg	**South Barker Street**	-	4.7	6.5	8.9
	West 19th Street	8.1	-	5.5	14.3
	North Barker Street	8.2	9.7	-	8.0
	East 19th Street	4.3	12.6	9.2	-

n = 2,795

Findings and Discussion

Based on the results demonstrated at the two test locations, this methodology demonstrated that the use of Bluetooth technology may be a cost-efficient alternative to other traffic counting techniques when approach volumes can be simultaneously captured. In this study, approach volumes were captured through the manual counts, but in other situations it could be captured using tube counters or basic video data extraction techniques. Recognizing that the Bluetooth data only detects a fraction of the overall number of turning movements, certain locations will require more time to collect sufficient data; the lower the volume of the roundabout, the longer the Bluetooth equipment would need to be in place.

Due to limitations in the Bluetooth data, U-turns were not considered for analysis. In the Bluetooth data stream, this would have appeared identical to a vehicle re-appearing out-of-sequence at the roundabout. This was because each data logger, on its own, was not able to determine the directionality of the signals detected, just that they were within range of the unit. Therefore, after one pairs the data from each leg to each of the other legs, the U-turns would be found within the un-paired data along with any other detections that were missed on the other trip end. A U-turn’s ‘signature’ would be its near sequential detection at the same station, being detected first on entrance to the roundabout and then again following its departure from the roundabout. However, this ‘signature’ could also be shared by anyone else hovering near the edge of the detection area where the detection area may be warped due to terrain. Thus, if a queue of vehicles extended backwards into the furthest extent of the detection area from the center of the roundabout, it could produce an identical ‘signature’ pattern in the data. If one has a significant number of U-turns, they would have to take care to place the data loggers in locations that would be beyond the lengths of any roundabout approach queues. In both the Lawrence and Paola, Kansas test locations, queues were observed to extend past the locations where the data loggers were placed. Research in the future may be able to create an additional algorithm in an attempt to quantify such movements.

A fundamental assumption to using Bluetooth as a substitute for traditional traffic studies is that a Bluetooth-enabled device was equally likely to appear in the normal traffic stream across all approaches and for all turning movements. This means that the movement of Bluetooth devices should be representative of the movement of the overall number of vehicles. If there were an imbalance between the two, any extrapolated data would show a bias both for and against specific movements that would likely erase any value the data otherwise would have. This assumption was tested for the Paola location by means of the F-test which resulted in not being able to reject the null hypothesis, however, at the Lawrence location it was more complicated.

The Lawrence, Kansas roundabout, comprised of two urban collectors, showed in the statistics that the eastbound and westbound through movements combined to form 65 percent of the manually counted traffic volume. This was in contrast to the Bluetooth data in which the same movements combined to form 27 percent of the overall volume. Given the differences in location, urban versus rural, and the functional classification of streets that the two roundabouts were on, urban collectors versus a rural highway, it was not possible to concretely determine a reason for this observed disparity. Additionally, there was also a potential for socio-economic demographic biases affecting travel patterns and driving behaviors in the vicinity of the roundabouts that were possibly also inseparably intertwined into the results. All of this combined to cause the null hypothesis to not be able to be rejected with 95 percent confidence with a F-test.

Based on the demonstrated distributions of Bluetooth based turning movement distributions at two sites and the combined 175 hours of data between Bluetooth and manual counting, there may be value in the use of Bluetooth data to conduct a turning movement study at a roundabout (or other intersection). However, as the two study locations ended with opposite results, it remained unclear what would be need to be changed in order to minimize the likelihood that the null hypothesis would not be rejected in a future study. Given the potential ability to automate such a study, and the time saving proposition that it would be compared to traditional techniques, one should not discard this methodology due to the conflicting results shown from this study.

CHAPTER 8
OVERALL FINDINGS AND DISCUSSION

Bluetooth based traffic data collection has been shown to be a possible source of data that when used in the right conditions was able to provide statistically reliable data for engineers. Like any other tool, engineering judgment should be utilized when considering the use of Bluetooth data, along with ascertaining an understanding of the purpose and need for any such traffic study. This is in addition to being able to recognize the limitations of the Bluetooth data. In the bigger picture, one must recognize several assumptions as being required for Bluetooth based traffic data to be useful.

- One must assume that all traffic is equally likely to be equipped with a discoverable Bluetooth device.
- Bluetooth equipped traffic behaves in a manor consistent with the rest of traffic .
- There are a minimal number of vehicles containing multiple Bluetooth sources, and are randomly distributed throughout the traffic stream.
- There are no traffic destinations in the vicinity of the study area that would cause a significant number of vehicles to follow a circuitous path between data loggers.
- There are a minimal number of pedestrians in the vicinity of the data loggers.
- The distribution of bicyclists is proportional to the rest of the traffic distribution.

Several examples where Bluetooth based traffic data collection might not be feasible include:

- near a fleet yard where many vehicles are equipped with Bluetooth and thus follow a specific path,
- near a heavily traveled bus route, and

- along a sidewalk on a college campus.

This is not a comprehensive list, as for certain purposes, bicyclist and pedestrians (if there are a sufficient number) would be readily identifiable due to multi-modal tendencies of their travel speeds over a distance.

Each Bluetooth data logger's detection area must be appropriately sized and placed for the specific requirements of each study. The overall size of the detection area at the time of initial detection, and re-identification contributes to travel time error. Since the detection occurs somewhere in the detection area this creates a margin of error equal to half of the width of the area perpendicular to the roadway. When the sum of both margins of error are disproportionally large compared to the length of the segment, this can create substantial errors that may undermine the process. Thus the selection of a proper antenna and mounting location becomes a controllable variable that an engineer can vary as needed based on site conditions and study objectives. If not considered, this potential error could have adverse consequences of data contamination. For example, if one was intending to separately capture each roundabout approach, but the antennas were powerful enough that they all capture all the traffic regardless of what movement is made, then the data would be indeterminate, and the effort wasted. Considering the possibilities and limitations, the following recommendations are made for hardware selection and placement.

- Ensure the power source will last the duration of the study by having fresh batteries or a hard-wired power source.
- Select antennas for each data collection site that adequately cover the intended study area and do not unnecessarily cover other roadways.

- Mount the antenna at least three feet above the surface of the roadway to ensure the largest possible sample size.

As seen in both the urban and freeway travel time studies, the availability of data was not assured. Bluetooth has shown itself to be most functionally useful where data can be aggregated together over long periods of time. This aggregation follows the premise of the Law of Large Numbers, but it also permits for gaps in the data to be filled. When this is not possible, and each time period is limited in scope, the probability that no Bluetooth data at all will be available increases dramatically. While higher volume roadways theoretically reduce this possibility, it still does not erase it as a factor. This is even truer for off-peak late night hours.

In Chapter 4 a statistically significant difference in travel times was observed that the Bluetooth data were more often slower than the GPS data which supports the rejection of H_{o5} from Chapter 3. In Chapter 3 the null hypothesis H_{o5}, was not rejected, thus meaning mobile phones placed above the center console were more likely to be detected than phones located lower in the vehicle. The slower travel times reported by the Bluetooth data were also consistent with the findings by Schneider et al. in the literature (*12*). To build upon this finding and the related finding in Chapter 3, a look into the literature on this found that according to University of Kansas researchers Dressel and Atchley, travel speeds for drivers simultaneously using a cell phone while driving resulted in slower travel speeds with greater variability than drivers focused solely on driving (*24*). This finding could imply that the Bluetooth data might be biased toward distracted drivers.

Ultimately, engineering judgment must prevail when designing a traffic study. Bluetooth technology, under the right circumstances, has proven that it should be included among other tools for an engineer to use as appropriate.

Contributions

Through the research in this dissertation and the results contained herein, several contributions were made to the field. The major contribution was toward the understanding the impacts that were associated with Bluetooth antenna selection. While a number of authors in this field had recognized that this was an issue, no one had conducted an in-depth controlled study and published on this topic. Furthermore, this principal contribution was extended into four traffic study applications including urban corridor travel times, urban freeway travel times, origin-destinations, and roundabout turning movement estimations. Each of the four applications then expanded on the pre-existing literature by adding additional robust statistical analysis, and broke ground on new applications that had not yet been investigated. All of this combines to advance the field of traffic engineering, and expands the body of knowledge. Using this new knowledge, researchers and practitioners alike, will be able to have a better understanding of the facets of the applications of Bluetooth technology to traffic studies. Having such understandings will empower them to better design traffic studies, and to better serve the public interest.

Future Research

Bluetooth based traffic data collection represents a repurposing of modern technology for a task that it was never intended to accomplish. Just as technology evolved to produce Bluetooth, it could very easily evolve beyond it to another similar technology. While the principles of these studies would likely hold true in the future, one cannot be certain how the specifics, along with changes in government regulations will interact to form future technological opportunities to usurp a technology and repackage it for conducting traffic studies.

Building upon the studies in this research, several opportunities exist to further this research. As addressed in Chapter 7, one opportunity would be to study more roundabout locations to determine with additional data, what circumstantial factors were likely to lead to turning movement percentages captured using Bluetooth to not be statistically different from ground-truthed data. Also another opportunity exists for creating either a different data collection plan, data processing algorithm, or a combination of both for the positive identification of u-turns at roundabouts. Several possible options for altering the data collection plan would be to add a data logger to the central island, and/or adding additional detectors along each leg to create trips along each route. However, the validation of these data would be complicated by the need to have a location with sufficient u-turn volumes.

Given that in most cases where travel time was calculated, the Bluetooth data were typically slower than comparable validation data, further research may be needed to understand the typical profile of vehicles and drivers captured using Bluetooth. This task would require combining Bluetooth data with other data sources to validate (or invalidate) assumptions that vehicles emitting a discoverable Bluetooth signal behave in the same manner as the rest of the traffic stream. One possibility would be to connect a digital camera to the Bluetooth data logger so that a photo of the roadway traffic would be captured whenever a Bluetooth signal is detected. A further extension of this would be to create location specific calibration factors that correct for the observed disparity between the Bluetooth and validation data.

The single key factor underpinning these studies were Bluetooth radios being set in “discovery mode.” A single update in the protocol by the SIG to set the maximum time a device can be locked in “discovery mode,” could eliminate this tool from the engineer’s tool box. Thus, future research into accessing non-discovery mode devices will be the next frontier in evolving this technological adaptation. Such research may also require legal opinions to address any questions about privacy issues.

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APPENDICES

Appendix A Hourly Bluetooth Data

Table A1 Eastbound 95th Street - Whole Corridor

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
12:00 a.m.	0	-	-	1	-	6.52	-	-
1:00 a.m.	0	-	-	0	-	-	-	-
2:00 a.m.	0	-	-	0	-	-	-	-
3:00 a.m.	0	-	-	0	-	-	-	-
4:00 a.m.	0	-	-	0	-	-	-	-
5:00 a.m.	0	-	-	0	-	-	-	-
6:00 a.m.	4	0.49	4.04	8	0.55	3.92	No	0.723
7:00 a.m.	3	0.30	4.54	3	0.54	4.84	No	0.455
8:00 a.m.	4	0.20	4.05	4	0.41	3.94	No	0.635
9:00 a.m.	3	0.20	3.64	11	0.51	4.44	Yes	0.001
10:00 a.m.	4	0.57	4.53	9	0.74	4.27	No	0.513
11:00 a.m.	7	0.53	5.12	7	0.76	5.20	No	0.816
12:00 p.m.	10	2.06	6.07	11	1.22	5.15	No	0.232
1:00 p.m.	8	1.66	5.26	6	0.53	4.16	No	0.105
2:00 p.m.	7	0.37	4.52	4	1.75	6.15	No	0.097
3:00 p.m.	5	4.28	6.04	10	1.39	5.54	No	0.801
4:00 p.m.	10	1.62	6.34	19	1.21	5.91	No	0.467
5:00 p.m.	8	0.42	4.62	12	0.89	4.83	No	0.477
6:00 p.m.	5	0.25	4.45	9	0.57	4.14	No	0.185
7:00 p.m.	3	0.54	4.37	9	1.09	3.73	No	0.211
8:00 p.m.	2	0.84	5.04	5	1.14	4.25	No	0.357
9:00 p.m.	1	-	3.67	0	-	-	-	-
10:00 p.m.	0	-	-	2	0.11	4.79	-	-
11:00 p.m.	1	-	3.40	0	-	-	-	-
Total	**85**	**-**	**-**	**130**	**-**	**-**	**-**	**-**
Unique	**77**	**-**	**-**	**117**	**-**	**-**	**-**	**-**

Table A2 Westbound 95th Street - Whole Corridor

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
12:00 a.m.	0	-	-	1	-	2.58	-	-
1:00 a.m.	0	-	-	0	-	-	-	-
2:00 a.m.	1	-	7.80	0	-	-	-	-
3:00 a.m.	0	-	-	0	-	-	-	-
4:00 a.m.	1	-	4.20	0	-	-	-	-
5:00 a.m.	0	-	-	3	1.76	4.69	-	-
6:00 a.m.	7	0.46	4.93	4	0.73	3.98	Yes	0.043
7:00 a.m.	4	0.57	4.12	4	0.77	4.10	No	0.967
8:00 a.m.	0	-	-	4	0.25	3.06	-	-
9:00 a.m.	4	1.72	4.58	5	0.78	4.35	No	0.811
10:00 a.m.	6	1.27	4.74	5	0.87	4.08	No	0.336
11:00 a.m.	9	0.91	4.69	10	1.10	4.78	No	0.853
12:00 p.m.	15	1.22	4.94	9	1.07	4.77	No	0.724
1:00 p.m.	10	0.79	4.71	8	0.76	4.58	No	0.735
2:00 p.m.	10	0.78	4.79	16	1.65	4.55	No	0.625
3:00 p.m.	20	1.47	5.66	23	0.82	4.75	Yes	0.018
4:00 p.m.	29	0.82	6.03	30	1.25	5.65	No	0.172
5:00 p.m.	13	0.66	4.37	10	0.80	4.31	No	0.849
6:00 p.m.	8	2.54	4.89	12	0.47	3.76	No	0.225
7:00 p.m.	10	0.76	4.34	13	0.41	3.37	Yes	0.001
8:00 p.m.	3	1.17	5.49	8	0.53	3.58	Yes	0.024
9:00 p.m.	0	-	-	0	-	-	-	-
10:00 p.m.	0	-	-	1	-	3.82	-	-
11:00 p.m.	0	-	-	0	-	-	-	-
Total	**150**	**-**	**-**	**166**	**-**	**-**	**-**	**-**
Unique	**140**	**-**	**-**	**155**	**-**	**-**	**-**	**-**

Table A3 Eastbound 95th Street: Lackman Road to I-35

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
12:00 a.m.	0	-	-	0	-	-	-	-
1:00 a.m.	0	-	-	0	-	-	-	-
2:00 a.m.	0	-	-	0	-	-	-	-
3:00 a.m.	0	-	-	1	-	2.80	-	-
4:00 a.m.	2	2.08	5.54	0	-	-	-	-
5:00 a.m.	0	-	-	2	1.19	5.38	-	-
6:00 a.m.	5	0.57	3.21	10	0.54	3.39	No	0.575
7:00 a.m.	10	0.75	3.52	5	0.93	3.68	No	0.754
8:00 a.m.	7	0.43	3.56	6	0.49	3.36	No	0.458
9:00 a.m.	7	0.70	3.49	16	0.49	3.43	No	0.829
10:00 a.m.	15	0.70	3.89	13	0.52	3.25	Yes	0.010
11:00 a.m.	13	0.74	4.16	9	0.45	3.73	No	0.103
12:00 p.m.	18	2.56	5.43	9	0.68	3.75	Yes	0.015
1:00 p.m.	20	0.83	3.65	11	0.42	3.30	No	0.137
2:00 p.m.	14	1.92	4.44	8	1.38	4.16	No	0.698
3:00 p.m.	21	2.48	4.73	11	1.07	3.99	No	0.250
4:00 p.m.	32	1.42	5.52	25	1.46	4.95	No	0.146
5:00 p.m.	13	1.95	4.14	15	0.68	3.67	No	0.415
6:00 p.m.	11	0.54	3.42	14	0.64	2.88	Yes	0.032
7:00 p.m.	8	3.30	5.41	11	0.98	2.94	No	0.056
8:00 p.m.	4	0.52	3.55	3	0.52	2.92	No	0.174
9:00 p.m.	6	0.47	2.81	2	0.08	3.08	No	0.236
10:00 p.m.	2	0.03	2.85	4	0.48	2.89	No	0.878
11:00 p.m.	2	0.00	2.78	2	0.80	3.22	No	0.524
Total	**210**	-	-	**177**	-	-	-	-
Unique	**189**	-	-	**161**	-	-	-	-

Table A4 Westbound 95th Street: I-35 to Lackman Road

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
12:00 a.m.	0	-	-	1	0.05	0.00	-	-
1:00 a.m.	3	0.01	2.63	1	-	2.72	-	-
2:00 a.m.	2	0.11	2.71	0	-	-	-	-
3:00 a.m.	2	0.14	2.93	1	-	2.15	-	-
4:00 a.m.	3	0.11	3.22	2	0.19	2.48	Yes	0.016
5:00 a.m.	3	0.43	3.53	5	0.91	3.41	No	0.799
6:00 a.m.	24	0.57	3.74	7	0.85	3.06	No	0.056
7:00 a.m.	13	0.82	3.49	8	0.51	2.99	No	0.103
8:00 a.m.	5	0.26	3.00	8	0.55	2.96	No	0.876
9:00 a.m.	12	0.78	3.57	10	2.94	4.32	No	0.443
10:00 a.m.	7	0.72	3.30	12	6.95	8.33	Yes	0.024
11:00 a.m.	14	0.36	3.61	19	6.38	7.56	Yes	0.011
12:00 p.m.	31	0.54	3.50	18	0.97	3.39	No	0.677
1:00 p.m.	24	1.38	3.85	14	3.57	4.69	No	0.404
2:00 p.m.	20	1.84	4.41	16	4.44	4.62	No	0.861
3:00 p.m.	30	0.70	4.09	34	0.75	3.28	Yes	<0.001
4:00 p.m.	43	0.96	4.63	44	0.97	3.56	Yes	<0.001
5:00 p.m.	15	0.79	3.58	24	0.67	3.34	No	0.342
6:00 p.m.	17	0.98	3.16	26	0.45	2.81	No	0.176
7:00 p.m.	14	0.72	3.32	18	0.31	2.66	Yes	0.003
8:00 p.m.	9	0.51	3.40	13	0.46	2.94	Yes	0.045
9:00 p.m.	3	0.21	3.34	8	0.54	2.71	Yes	0.021
10:00 p.m.	2	0.51	3.24	3	1.12	4.41	No	0.212
11:00 p.m.	3	0.12	3.17	3	0.52	2.28	Yes	0.046
Total	**299**	-	-	**295**	-	-	-	-
Unique	**267**	-	-	**259**	-	-	-	-

Table A5 Eastbound 95th Street: I-35 to Monrovia Street

	Before			After				
Hour	N	Standard Deviation	Average Travel Time (Minutes)	N	Standard Deviation	Average Travel Time (Minutes)	Significant Difference	P-Value
12:00 a.m.	4	0.12	0.03	3	0.02	0.00	No	0.675
1:00 a.m.	4	0.19	0.52	2	0.06	0.34	No	0.160
2:00 a.m.	0	-	-	2	0.18	0.52	-	-
3:00 a.m.	6	0.53	0.59	2	0.27	0.50	No	0.776
4:00 a.m.	5	0.56	0.69	3	0.25	0.53	No	0.611
5:00 a.m.	13	0.35	0.64	6	0.16	0.61	No	0.788
6:00 a.m.	42	0.23	0.71	36	0.30	0.52	Yes	0.002
7:00 a.m.	54	0.40	0.75	18	0.45	0.69	No	0.617
8:00 a.m.	53	0.36	0.79	32	0.26	0.60	Yes	0.004
9:00 a.m.	69	0.28	0.69	37	0.27	0.67	No	0.736
10:00 a.m.	94	0.84	1.13	58	0.39	0.73	Yes	<0.001
11:00 a.m.	97	0.69	1.18	44	0.49	1.08	No	0.300
12:00 p.m.	195	0.45	0.91	0	-	-	-	-
1:00 p.m.	191	0.47	0.87	0	-	-	-	-
2:00 p.m.	181	0.46	0.86	0	-	-	-	-
3:00 p.m.	202	0.42	0.96	0	-	-	-	-
4:00 p.m.	203	0.56	1.15	29	0.46	0.88	Yes	0.004
5:00 p.m.	153	0.52	0.97	33	0.57	0.83	No	0.192
6:00 p.m.	98	0.43	0.88	29	0.40	0.79	No	0.329
7:00 p.m.	106	0.47	0.82	27	0.19	0.51	Yes	<0.001
8:00 p.m.	89	0.48	0.82	8	0.30	0.65	No	0.142
9:00 p.m.	32	0.71	0.83	6	0.08	0.47	Yes	0.008
10:00 p.m.	24	1.13	1.04	6	0.33	0.70	No	0.209
11:00 p.m.	19	1.11	0.70	2	0.24	0.53	No	0.569
Total	**1934**	-	-	**383**	-	-	-	-
Unique	**1677**	-	-	**370**	-	-	-	-

Table A6 Westbound 95th Street: Monrovia Street to I-35

	Before			After				
Hour	N	Standard Deviation	Average Travel Time (Minutes)	N	Standard Deviation	Average Travel Time (Minutes)	Significant Difference	P-Value
12:00 a.m.	6	0.05	0.01	10	0.09	0.01	No	0.811
1:00 a.m.	6	0.12	0.39	3	0.09	0.41	No	0.856
2:00 a.m.	4	0.07	0.36	3	0.13	0.36	No	0.967
3:00 a.m.	1	-	0.38	9	0.22	0.55	-	-
4:00 a.m.	4	0.83	1.00	6	0.14	0.41	No	0.197
5:00 a.m.	21	0.83	1.06	15	0.23	0.65	Yes	0.038
6:00 a.m.	40	0.26	0.48	61	0.40	0.70	Yes	0.002
7:00 a.m.	50	1.07	0.80	37	0.58	0.81	No	0.956
8:00 a.m.	47	0.96	0.85	49	0.65	0.79	No	0.743
9:00 a.m.	68	0.44	0.74	57	0.22	0.59	Yes	0.013
10:00 a.m.	91	0.91	1.10	92	0.45	0.71	Yes	<0.001
11:00 a.m.	77	0.41	0.96	112	0.61	1.05	No	0.249
12:00 p.m.	113	0.48	0.89	124	0.44	0.94	No	0.452
1:00 p.m.	118	0.64	0.97	121	0.55	0.96	No	0.949
2:00 p.m.	131	0.42	0.77	123	0.51	0.97	Yes	0.001
3:00 p.m.	122	0.58	0.94	207	0.67	1.26	Yes	<0.001
4:00 p.m.	174	0.48	0.89	170	0.69	1.26	Yes	<0.001
5:00 p.m.	111	0.60	0.96	106	0.53	0.90	No	0.437
6:00 p.m.	88	0.31	0.69	90	0.32	0.70	No	0.885
7:00 p.m.	59	0.40	0.83	98	0.17	0.52	Yes	<0.001
8:00 p.m.	29	0.52	0.88	64	0.16	0.49	Yes	<0.001
9:00 p.m.	21	0.68	0.73	17	0.45	0.63	No	0.561
10:00 p.m.	10	0.44	0.69	11	0.22	0.57	No	0.434
11:00 p.m.	6	0.13	0.40	9	0.24	0.51	No	0.271
Total	**1397**	-	-	**1594**	-	-	-	-
Unique	**1243**	-	-	**1412**	-	-	-	-

Table A7 Eastbound 95th Street: Across I-35 Interchange

	Before			After				
Hour	N	Standard Deviation	Average Travel Time (Minutes)	N	Standard Deviation	Average Travel Time (Minutes)	Significant Difference	P-Value
12:00 a.m.	4	0.05	0.00	5	0.02	0.00	No	0.925
1:00 a.m.	6	0.13	0.29	2	0.04	0.45	Yes	0.031
2:00 a.m.	5	0.15	0.50	3	0.12	0.47	No	0.779
3:00 a.m.	3	0.12	0.48	5	0.13	0.49	No	0.937
4:00 a.m.	9	0.16	0.46	6	0.36	0.63	No	0.298
5:00 a.m.	20	0.34	0.72	19	0.43	0.77	No	0.697
6:00 a.m.	44	0.44	0.74	43	0.31	0.50	Yes	0.005
7:00 a.m.	60	0.42	0.60	36	0.26	0.55	No	0.427
8:00 a.m.	41	0.42	0.65	42	0.37	0.66	No	0.900
9:00 a.m.	58	0.45	0.76	29	0.25	0.55	Yes	0.006
10:00 a.m.	95	0.44	0.73	40	0.20	0.52	Yes	<0.001
11:00 a.m.	83	0.42	0.73	27	0.28	0.66	No	0.368
12:00 p.m.	115	0.32	0.65	26	0.35	0.68	No	0.695
1:00 p.m.	119	0.48	0.77	33	0.40	0.70	No	0.374
2:00 p.m.	120	0.47	0.78	30	0.45	0.82	No	0.700
3:00 p.m.	136	0.49	0.79	35	0.47	0.64	No	0.114
4:00 p.m.	150	0.36	0.73	52	0.46	0.68	No	0.524
5:00 p.m.	82	0.33	0.63	44	0.45	0.62	No	0.865
6:00 p.m.	65	0.33	0.62	35	0.24	0.58	No	0.472
7:00 p.m.	53	0.34	0.68	31	0.37	0.68	No	0.981
8:00 p.m.	40	0.32	0.77	15	0.47	0.68	No	0.501
9:00 p.m.	20	0.25	0.58	13	0.22	0.61	No	0.723
10:00 p.m.	7	0.29	0.70	9	0.15	0.48	No	0.097
11:00 p.m.	11	0.12	0.42	8	0.19	0.49	No	0.411
Total	**1346**	-	-	**588**	-	-	-	-
Unique	**1090**	-	-	**532**	-	-	-	-

Table A8 Westbound 95th Street: Across I-35 Interchange

	Before			After				
Hour	N	Standard Deviation	Average Travel Time (Minutes)	N	Standard Deviation	Average Travel Time (Minutes)	Significant Difference	P-Value
12:00 a.m.	5	0.03	0.00	7	0.03	0.00	No	0.999
1:00 a.m.	5	0.16	0.41	4	0.08	0.41	No	0.997
2:00 a.m.	2	0.12	0.50	3	0.06	0.30	No	0.120
3:00 a.m.	12	0.10	0.50	11	0.13	0.45	No	0.351
4:00 a.m.	10	0.15	0.40	8	0.12	0.37	No	0.576
5:00 a.m.	16	0.26	0.66	19	0.24	0.54	No	0.176
6:00 a.m.	49	0.26	0.76	59	0.26	0.51	Yes	<0.001
7:00 a.m.	30	0.26	0.56	33	0.24	0.44	No	0.079
8:00 a.m.	34	0.28	0.61	39	0.17	0.41	Yes	0.001
9:00 a.m.	48	0.22	0.59	48	0.27	0.50	No	0.081
10:00 a.m.	56	0.17	0.49	64	0.22	0.44	No	0.220
11:00 a.m.	79	0.19	0.52	62	0.27	0.48	No	0.285
12:00 p.m.	98	0.22	0.52	66	0.31	0.44	No	0.066
1:00 p.m.	97	0.21	0.54	64	0.30	0.47	No	0.123
2:00 p.m.	78	0.34	0.67	70	0.31	0.53	Yes	0.009
3:00 p.m.	94	0.26	0.60	96	0.58	0.78	Yes	0.006
4:00 p.m.	96	0.33	0.67	110	0.58	0.80	Yes	0.043
5:00 p.m.	65	0.18	0.46	75	0.44	0.62	Yes	0.004
6:00 p.m.	57	0.14	0.42	75	0.29	0.53	Yes	0.007
7:00 p.m.	44	0.34	0.59	43	0.24	0.43	Yes	0.016
8:00 p.m.	33	0.24	0.62	39	0.20	0.42	Yes	<0.001
9:00 p.m.	14	0.21	0.51	15	0.13	0.38	No	0.068
10:00 p.m.	1	-	0.28	5	0.27	0.42	-	-
11:00 p.m.	9	0.14	0.45	7	0.11	0.26	Yes	0.009
Total	**1032**	**-**	**-**	**1022**	**-**	**-**	**-**	**-**
Unique	**897**	**-**	**-**	**840**	**-**	**-**	**-**	**-**

Appendix B Periodic Bluetooth Data

Table B1 Eastbound 95th Street - Whole Corridor

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	4	0.35	4.42	5	0.52	3.83	No	0.081
9:00-11:00 a.m.	7	0.63	4.15	8	0.72	4.76	No	0.102
12:00-1:00 p.m.	10	2.06	6.07	0	-	-	-	-
2:00-3:00 p.m.	7	0.37	4.52	0	-	-	-	-
4:00-6:00 p.m.	18	1.50	5.57	11	3.57	7.57	No	0.089
7:00-9:00 p.m.	5	0.67	4.64	4	0.15	3.75	Yes	0.025
Total	**51**	-	-	**28**	-	-	-	-
Unique	**44**	-	-	**28**	-	-	-	-

Table B2 Westbound 95th Street - Whole Corridor

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	4	0.57	4.12	6	0.76	3.81	No	0.478
9:00-11:00 a.m.	10	1.37	4.68	10	0.79	4.22	No	0.371
12:00-1:00 p.m.	16	1.23	4.86	9	1.07	4.77	No	0.858
2:00-3:00 p.m.	11	0.75	4.82	16	1.65	4.55	No	0.572
4:00-6:00 p.m.	42	1.09	5.51	40	1.28	5.31	No	0.451
7:00-9:00 p.m.	13	0.96	4.60	21	0.46	3.45	Yes	<0.001
Total	**96**	-	-	**102**	-	-	-	-
Unique	**91**	-	-	**93**	-	-	-	-

Table B3 Eastbound 95th Street: Lackman to I-35

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	12	0.69	3.47	9	0.75	3.45	No	0.950
9:00-11:00 a.m.	22	0.71	3.76	29	0.50	3.35	Yes	0.023
12:00-1:00 p.m.	18	2.56	5.43	10	0.67	3.69	Yes	0.011
2:00-3:00 p.m.	14	1.92	4.44	9	1.33	4.04	No	0.566
4:00-6:00 p.m.	45	1.69	5.12	40	1.37	4.47	No	0.054
7:00-9:00 p.m.	12	2.80	4.79	14	0.88	2.93	Yes	0.037
Total	**123**	-	-	**111**	-	-	-	-
Unique	**112**	-	-	**99**	-	-	-	-

Table B4 Westbound 95th Street: I-35 to Lackman

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	17	0.76	3.37	14	0.51	3.01	No	0.127
9:00-11:00 a.m.	20	0.73	3.47	22	5.76	6.51	Yes	0.019
12:00-1:00 p.m.	31	0.54	3.50	18	0.97	3.39	No	0.677
2:00-3:00 p.m.	20	1.84	4.41	17	4.33	4.50	No	0.942
4:00-6:00 p.m.	58	1.02	4.35	68	0.88	3.48	Yes	<0.001
7:00-9:00 p.m.	24	0.63	3.34	31	0.40	2.78	Yes	<0.001
Total	**170**	-	-	**170**	-	-	-	-
Unique	**157**	-	-	**154**	-	-	-	-

Table B4 Eastbound 95th Street: I-35 to Monrovia

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	49	0.43	0.84	38	0.36	0.63	Yes	0.016
9:00-11:00 a.m.	112	0.75	0.97	96	0.40	0.72	Yes	0.003
12:00-1:00 p.m.	138	0.45	0.92	0	-	-	-	-
2:00-3:00 p.m.	138	0.47	0.82	0	-	-	-	-
4:00-6:00 p.m.	245	0.53	1.05	63	0.51	0.86	Yes	0.010
7:00-9:00 p.m.	139	0.48	0.85	35	0.22	0.54	Yes	<0.001
Total	**821**	-	-	**232**	-	-	-	-
Unique	**712**	-	-	**230**	-	-	-	-

Table B5 Westbound 95th Street: Monrovia to I-35

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	64	1.21	0.84	52	0.66	0.88	No	0.831
9:00-11:00 a.m.	153	0.78	0.95	133	0.39	0.67	Yes	<0.001
12:00-1:00 p.m.	112	0.47	0.89	101	0.44	0.92	No	0.647
2:00-3:00 p.m.	129	0.41	0.76	106	0.51	0.96	Yes	0.002
4:00-6:00 p.m.	270	0.54	0.92	230	0.65	1.12	Yes	<0.001
7:00-9:00 p.m.	86	0.44	0.86	130	0.16	0.50	Yes	<0.001
Total	**814**	-	-	**752**	-	-	-	-
Unique	**726**	-	-	**671**	-	-	-	-

Table B6 Eastbound 95th Street: Across I-35

Hour	Before			After				
	N	Standard Deviation	Average Travel Time (Minutes)	N	Standard Deviation	Average Travel Time (Minutes)	Significant Difference	P-Value
7:00-8:30 a.m.	82	0.43	0.64	65	0.32	0.58	No	0.359
9:00-11:00 a.m.	156	0.44	0.73	69	0.22	0.53	Yes	<0.001
12:00-1:00 p.m.	115	0.32	0.65	26	0.35	0.68	No	0.695
2:00-3:00 p.m.	121	0.47	0.78	30	0.45	0.82	No	0.728
4:00-6:00 p.m.	232	0.35	0.69	96	0.45	0.65	No	0.435
7:00-9:00 p.m.	93	0.33	0.72	46	0.40	0.68	No	0.595
Total	**799**	-	-	**332**	-	-	-	-
Unique	**655**	-	-	**309**	-	-	-	-

Table B7 Westbound 95th Street: Across I-35

Hour	Before			After				
	N	Standard Deviation	Average Travel Time (Minutes)	N	Standard Deviation	Average Travel Time (Minutes)	Significant Difference	P-Value
7:00-8:30 a.m.	52	0.26	0.58	52	0.21	0.44	Yes	0.005
9:00-11:00 a.m.	104	0.20	0.53	113	0.24	0.47	Yes	0.024
12:00-1:00 p.m.	99	0.22	0.52	67	0.31	0.44	No	0.057
2:00-3:00 p.m.	79	0.34	0.67	71	0.31	0.53	Yes	0.007
4:00-6:00 p.m.	161	0.30	0.58	186	0.53	0.73	Yes	0.002
7:00-9:00 p.m.	78	0.30	0.60	82	0.22	0.43	Yes	<0.001
Total	**573**	-	-	**571**	-	-	-	-
Unique	**507**	-	-	**483**	-	-	-	-

Appendix C Hourly PC-Travel Data

Table C1 Eastbound 95th Street - Whole Corridor Travel Time

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
12:00 a.m.	0	-	-	0	-	-	-	-
1:00 a.m.	0	-	-	0	-	-	-	-
2:00 a.m.	0	-	-	0	-	-	-	-
3:00 a.m.	0	-	-	0	-	-	-	-
4:00 a.m.	0	-	-	0	-	-	-	-
5:00 a.m.	0	-	-	0	-	-	-	-
6:00 a.m.	2	0.75	5.02	0	-	-	-	-
7:00 a.m.	8	0.79	4.60	12	0.48	4.08	No	0.112
8:00 a.m.	5	0.60	4.15	6	0.52	3.69	No	0.209
9:00 a.m.	10	0.75	4.85	11	0.51	4.26	No	0.051
10:00 a.m.	10	0.57	4.82	10	0.45	4.24	Yes	0.022
11:00 a.m.	0	-	-	1	-	4.90	-	-
12:00 p.m.	6	1.57	6.21	8	0.80	4.97	No	0.102
1:00 p.m.	3	1.53	5.89	1	-	4.43	-	-
2:00 p.m.	9	0.34	5.00	9	0.54	4.17	Yes	0.001
3:00 p.m.	1	-	8.00	0	-	-	-	-
4:00 p.m.	8	0.70	5.30	8	1.60	5.58	No	0.658
5:00 p.m.	8	1.52	6.21	6	1.34	6.18	No	0.977
6:00 p.m.	0	-	-	0	-	-	-	-
7:00 p.m.	7	0.78	4.38	10	0.79	4.23	No	0.710
8:00 p.m.	9	0.93	5.25	11	0.59	3.92	Yes	0.002
9:00 p.m.	0	-	-	0	-	-	-	-
10:00 p.m.	0	-	-	0	-	-	-	-
11:00 p.m.	0	-	-	0	-	-	-	-
Total	**86**	**-**	**-**	**93**	**-**	**-**	**-**	**-**

Table C2 Westbound 95th Street - Whole Corridor Travel Time

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
12:00 a.m.	0	-	-	0	-	-	-	-
1:00 a.m.	0	-	-	0	-	-	-	-
2:00 a.m.	0	-	-	0	-	-	-	-
3:00 a.m.	0	-	-	0	-	-	-	-
4:00 a.m.	0	-	-	0	-	-	-	-
5:00 a.m.	0	-	-	0	-	-	-	-
6:00 a.m.	2	0.93	4.73	2	0.38	3.23	No	0.171
7:00 a.m.	8	0.97	5.32	10	0.47	3.75	Yes	0.001
8:00 a.m.	5	0.74	4.78	5	0.50	3.44	Yes	0.010
9:00 a.m.	10	0.49	4.54	11	0.39	3.47	Yes	<0.001
10:00 a.m.	10	0.53	4.57	10	0.37	3.59	Yes	<0.001
11:00 a.m.	0	-	-	1	-	5.28	-	-
12:00 p.m.	8	0.71	6.14	8	0.98	4.24	Yes	0.001
1:00 p.m.	2	0.35	5.07	1	-	6.80	-	-
2:00 p.m.	9	0.53	5.35	9	0.89	4.30	Yes	0.008
3:00 p.m.	1	-	6.50	1	-	4.33	-	-
4:00 p.m.	9	0.84	5.49	9	1.97	5.08	No	0.580
5:00 p.m.	6	1.36	6.38	7	0.93	5.59	No	0.251
6:00 p.m.	1	-	5.23	0	-	-	-	-
7:00 p.m.	7	0.39	4.22	10	0.59	3.85	No	0.139
8:00 p.m.	8	0.63	4.57	10	0.32	3.57	Yes	0.001
9:00 p.m.	0	-	-	0	-	-	-	-
10:00 p.m.	0	-	-	0	-	-	-	-
11:00 p.m.	0	-	-	0	-	-	-	-
Total	**86**	-	-	**94**	-	-	-	-

Appendix D Periodic PC-Travel Data

Table D1 Eastbound 95th Street - Whole Corridor Travel Time

	Before			After				
Observation Period	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	13	0.74	4.43	18	0.51	3.95	No	0.053
9:00-11:00 a.m.	20	0.65	4.84	21	0.47	4.25	Yes	0.002
12:00-1:00 p.m.	7	1.53	6.41	8	0.80	4.97	Yes	0.043
2:00-3:00 p.m.	9	0.34	5.00	9	0.54	4.17	Yes	0.001
4:00-6:00 p.m.	16	1.24	5.76	14	1.47	5.84	No	0.866
7:00-9:00 p.m.	16	0.95	4.87	21	0.70	4.07	Yes	0.008
Total	**81**	**-**	**-**	**91**	**-**	**-**	**-**	**-**

Table D2 Westbound 95th Street - Whole Corridor Travel Time

	Before			After				
Observation Period	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	13	0.90	5.11	15	0.49	3.65	Yes	<0.001
9:00-11:00 a.m.	20	0.50	4.55	21	0.38	3.53	Yes	<0.001
12:00-1:00 p.m.	8	0.71	6.14	8	0.98	4.24	Yes	0.001
2:00-3:00 p.m.	9	0.53	5.35	10	0.84	4.30	Yes	0.004
4:00-6:00 p.m.	15	1.13	5.84	16	1.58	5.30	No	0.278
7:00-9:00 p.m.	15	0.54	4.41	21	0.48	3.70	Yes	<0.001
Total	**80**	**-**	**-**	**91**	**-**	**-**	**-**	**-**

Appendix E 95th Street Cumulative GPS Based Travel Time Plots

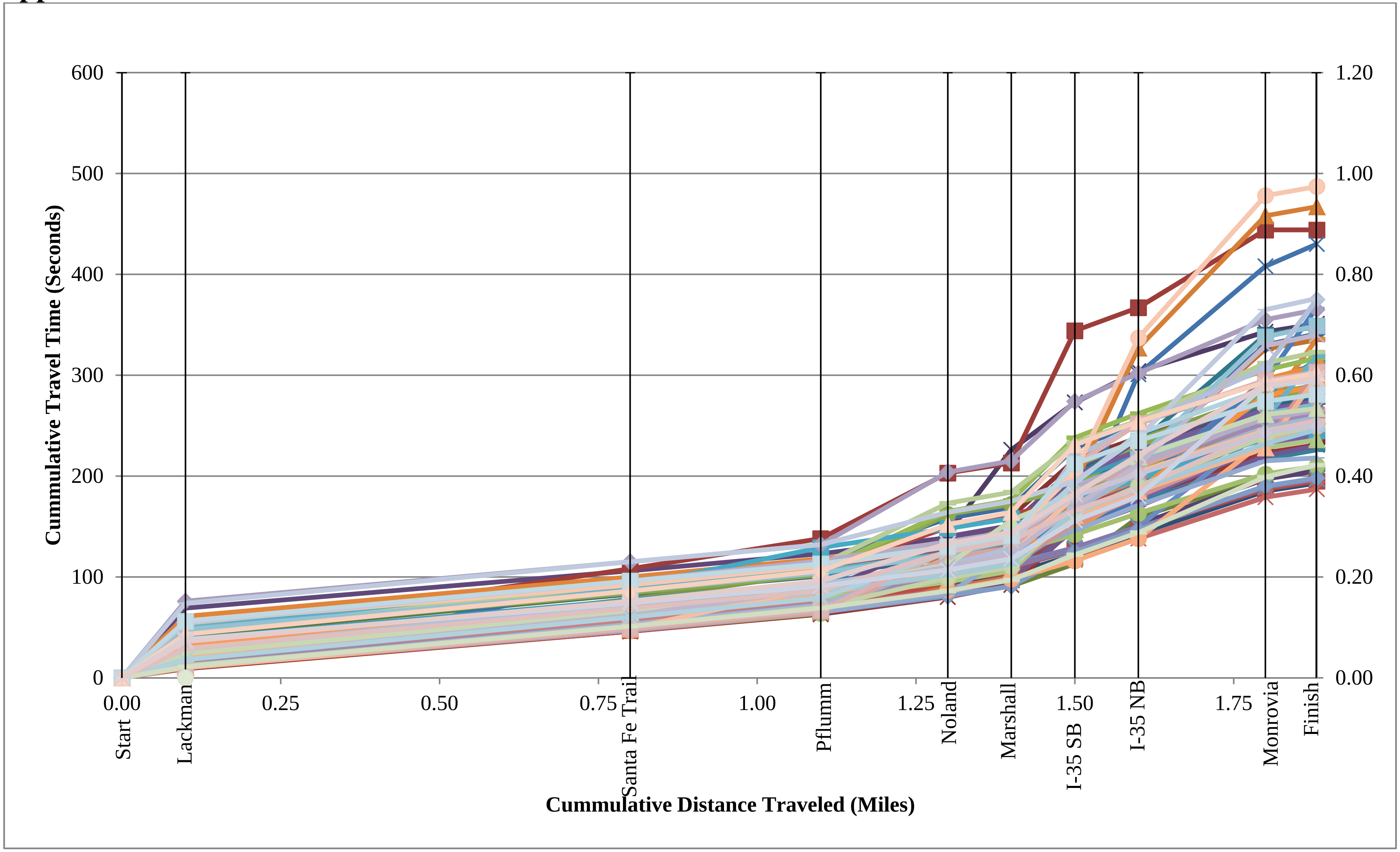

Figure E1 Eastbound 95th Street travel time plot (before).

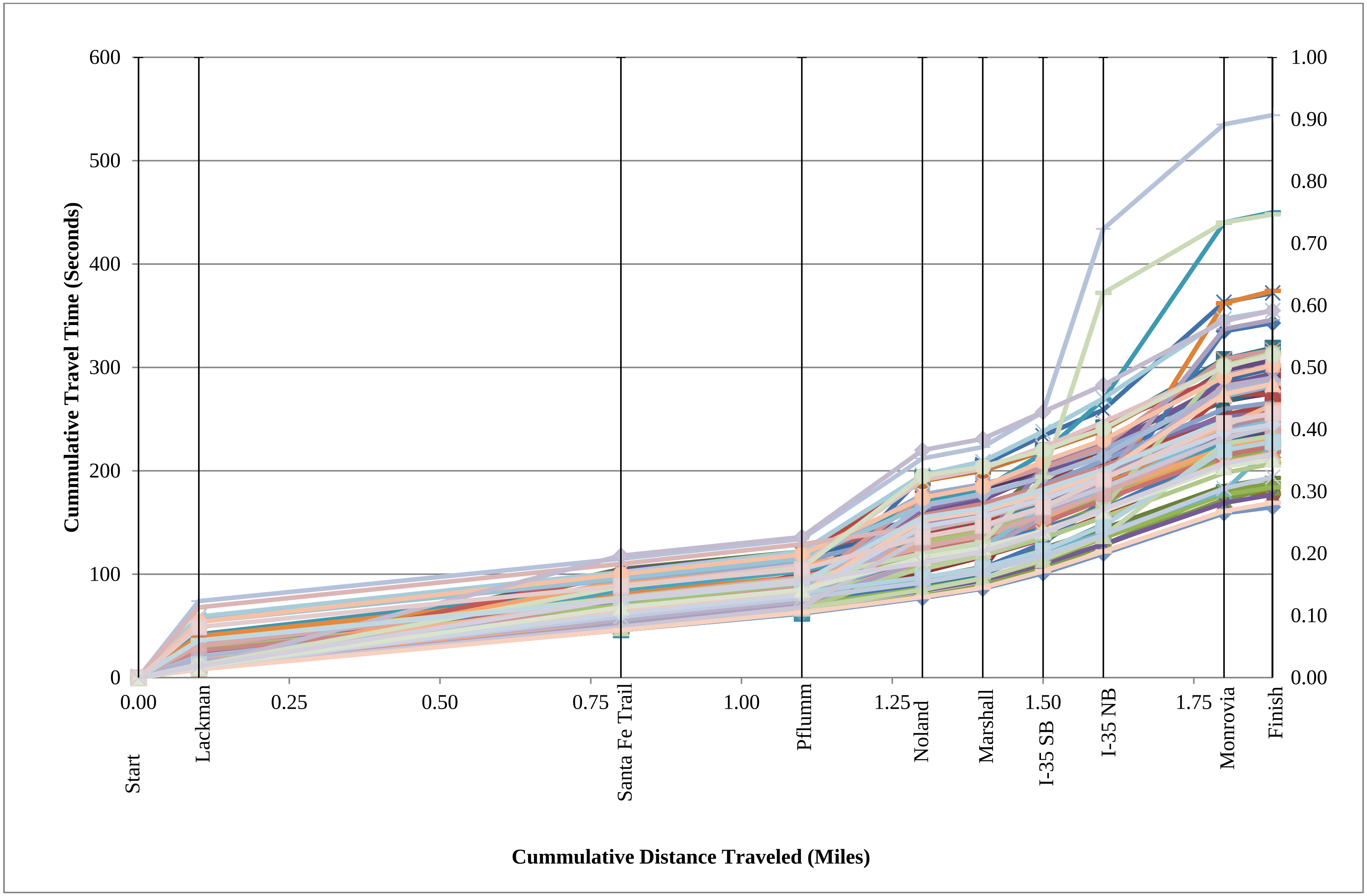

Figure E2 Eastbound 95th Street travel time plot (after).

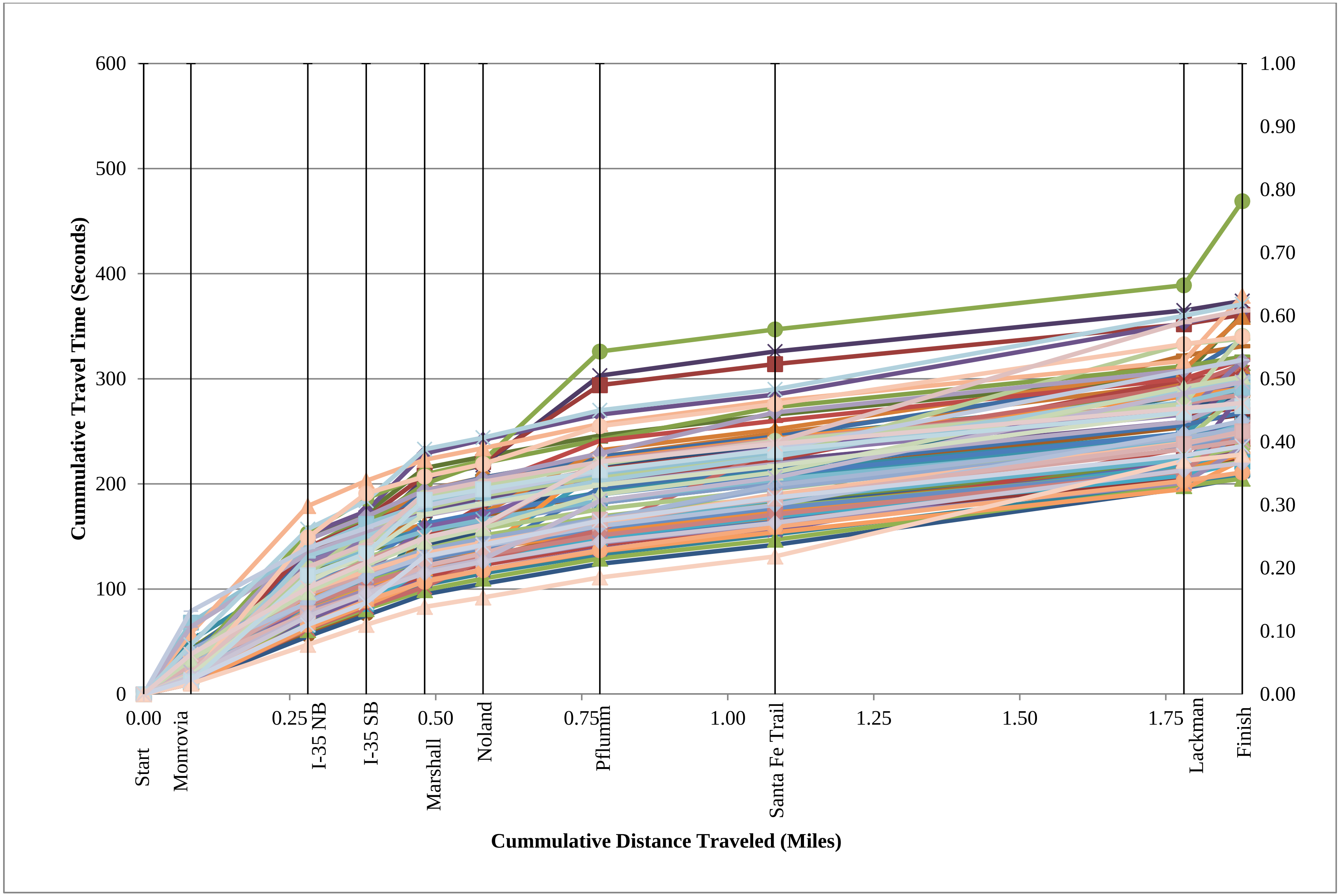

Figure E3 Eastbound 95th Street travel time plot (before).

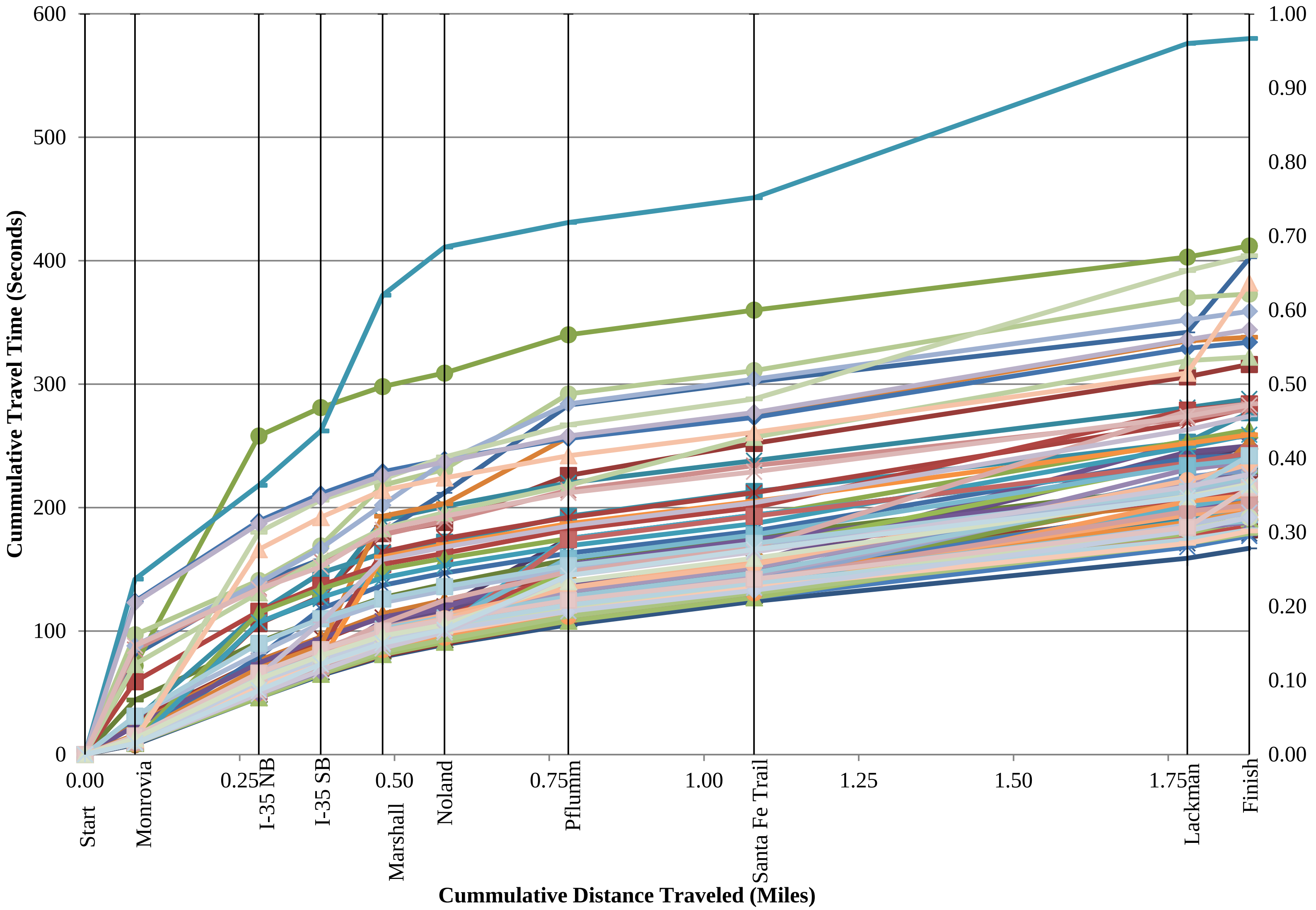

Figure E4 Westbound 95th Street travel time plot (after).

Appendix F 95th Street Bluetooth Speed Distributions

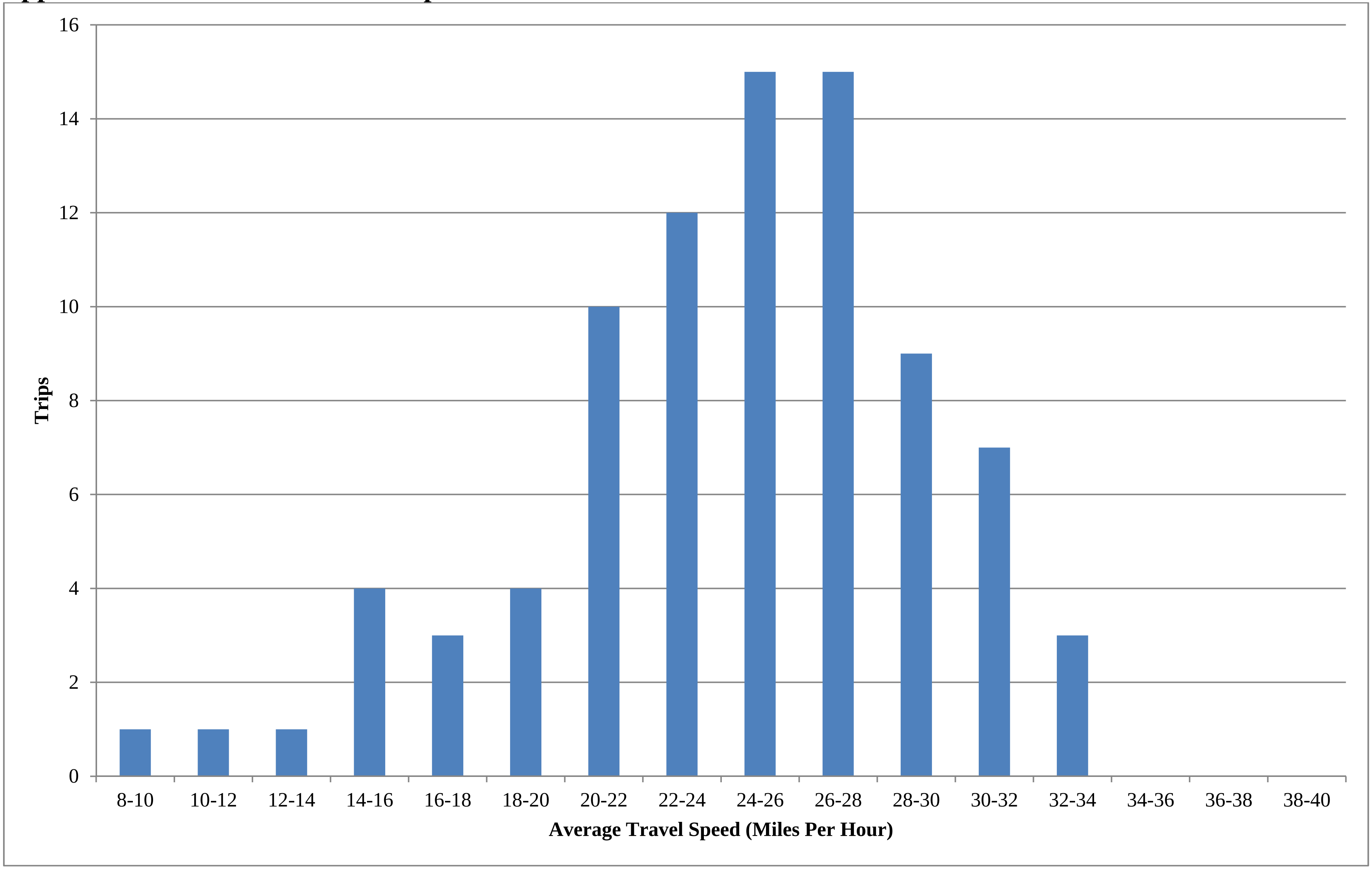

Figure F1 Eastbound 95th Street speed distribution for all time periods (before). n=86

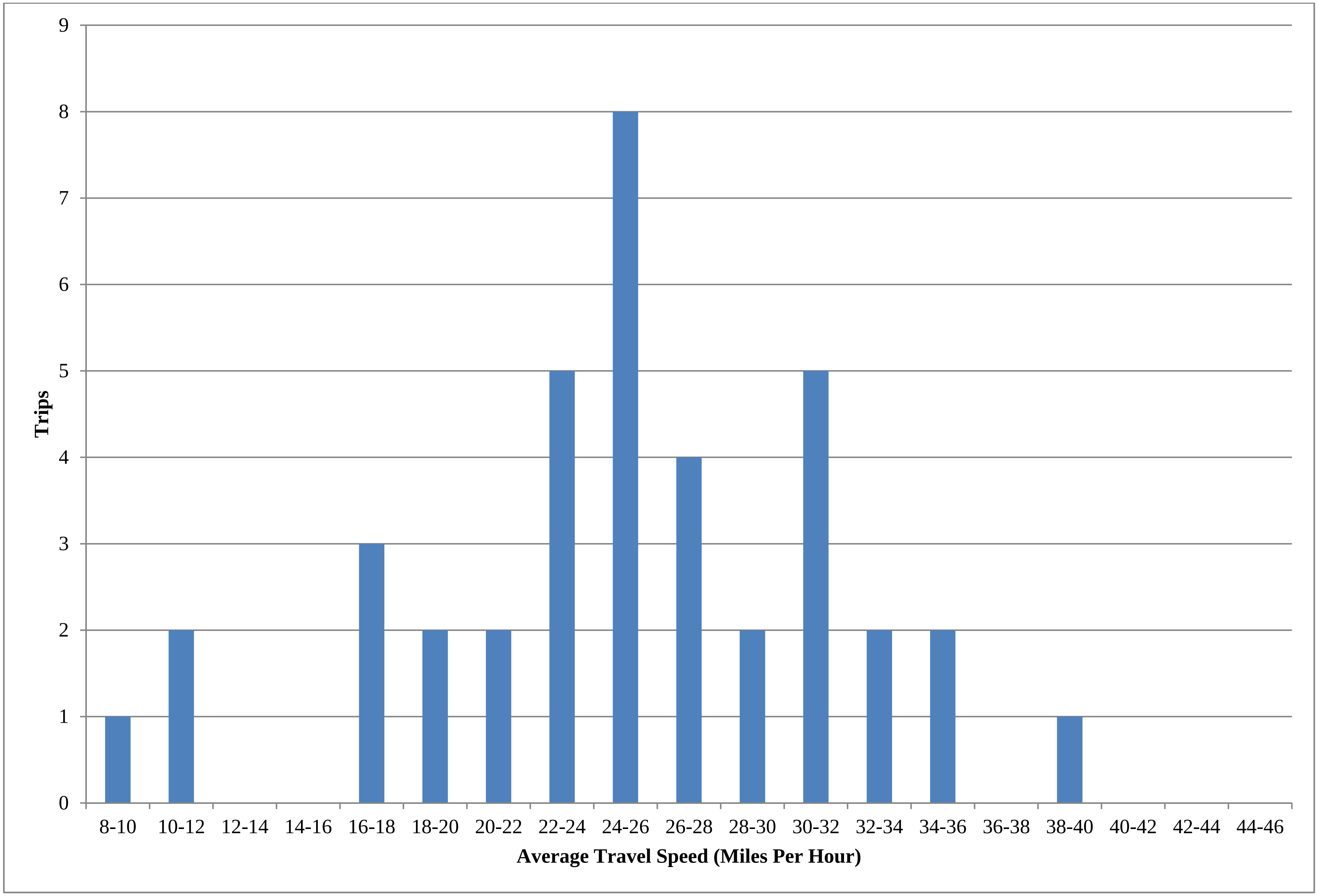

Figure F2 Eastbound 95th Street speed distribution for all time periods (after). n=41

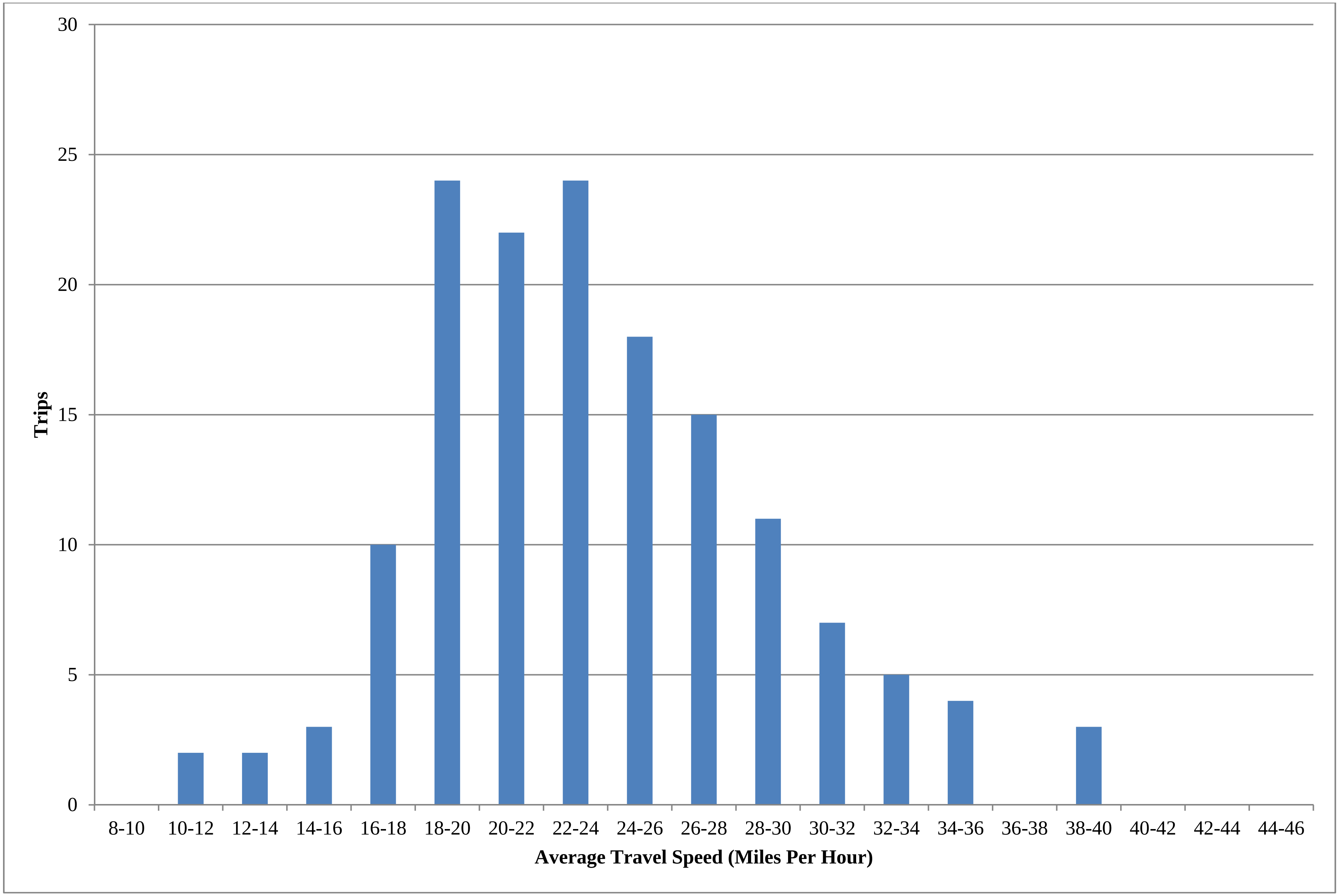

Figure F3 Westbound 95th Street speed distribution for all time periods (before). n=151

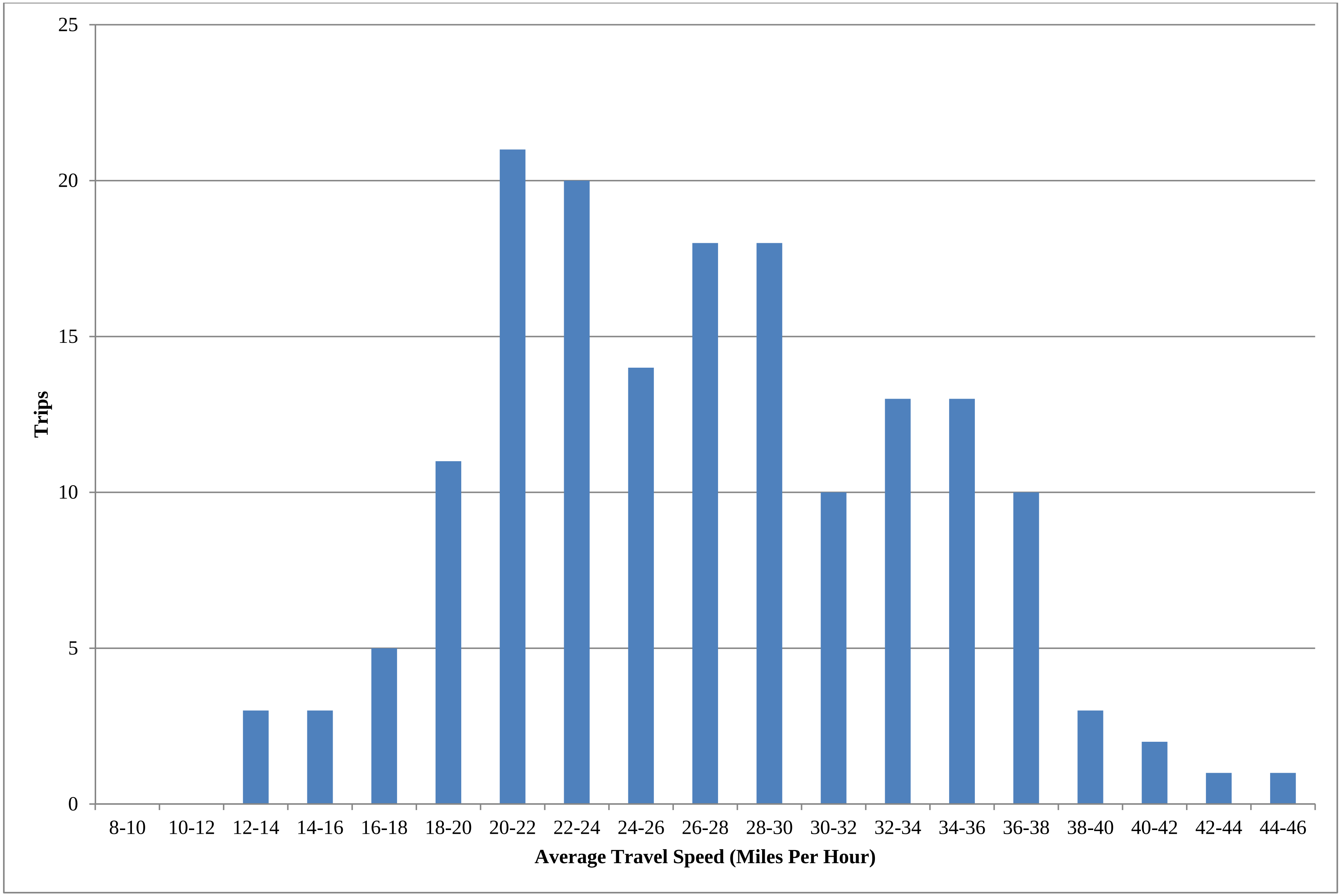

Figure F4 Westbound 95th Street speed distribution for all time periods (after). n=167

Appendix G Comparisons Between Bluetooth and GPS Based Travel Times

Table G1 Eastbound 95th Street - Whole Corridor (Before)

	Bluetooth			GPS				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	4	0.35	4.42	13	0.74	4.43	No	0.970
9:00-11:00 a.m.	7	0.63	4.15	20	0.65	4.84	Yes	0.021
12:00-1:00 p.m.	10	2.06	6.07	7	1.53	6.41	No	0.703
2:00-3:00 p.m.	7	0.37	4.52	9	0.34	5.00	Yes	0.018
4:00-6:00 p.m.	18	1.50	5.57	16	1.24	5.76	No	0.699
7:00-9:00 p.m.	5	0.67	4.64	16	0.95	4.87	No	0.551
Total	**51**	-	-	**81**	-	-	-	-
Unique	**44**	-	-	-	-	-	-	-

Table G2 Eastbound 95th Street - Whole Corridor (After)

	Bluetooth			GPS				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	5	0.52	3.83	18	0.51	3.95	No	0.642
9:00-11:00 a.m.	8	0.72	4.76	21	0.47	4.25	No	0.076
12:00-1:00 p.m.	0	-	-	8	0.80	4.97	-	-
2:00-3:00 p.m.	0	-	-	9	0.54	4.17	-	-
4:00-6:00 p.m.	11	3.57	7.57	14	1.47	5.84	No	0.145
7:00-9:00 p.m.	4	0.15	3.75	21	0.70	4.07	No	0.077
Total	**28**	-	-	**91**	-	-	-	-
Unique	**28**	-	-	-	-	-	-	-

Table G3 Westbound 95th Street - Whole Corridor (Before)

	Bluetooth			GPS				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	4	0.57	4.12	13	0.90	5.11	Yes	0.019
9:00-11:00 a.m.	10	1.37	4.68	20	0.50	4.55	No	0.787
12:00-1:00 p.m.	16	1.23	4.86	8	0.71	6.14	Yes	0.004
2:00-3:00 p.m.	11	0.75	4.82	9	0.53	5.35	No	0.083
4:00-6:00 p.m.	42	1.09	5.51	15	1.13	5.84	No	0.330
7:00-9:00 p.m.	13	0.96	4.60	15	0.54	4.41	No	0.517
Total	**96**	-	-	**80**	-	-	-	-
Unique	**91**	-	-	-	-	-	-	-

Table G4 Westbound 95th Street - Whole Corridor (After)

	Bluetooth			GPS				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30 a.m.	6	0.76	3.81	15	0.49	3.65	No	0.639
9:00-11:00 a.m.	10	0.79	4.22	21	0.38	3.53	Yes	0.014
12:00-1:00 p.m.	9	1.07	4.77	8	0.98	4.24	No	0.300
2:00-3:00 p.m.	16	1.65	4.55	10	0.84	4.30	No	0.611
4:00-6:00 p.m.	40	1.28	5.31	16	1.58	5.30	No	0.980
7:00-9:00 p.m.	21	0.46	3.45	21	0.48	3.70	No	0.090
Total	**102**	-	-	**91**	-	-	-	-
Unique	**93**	-	-	-	-	-	-	-