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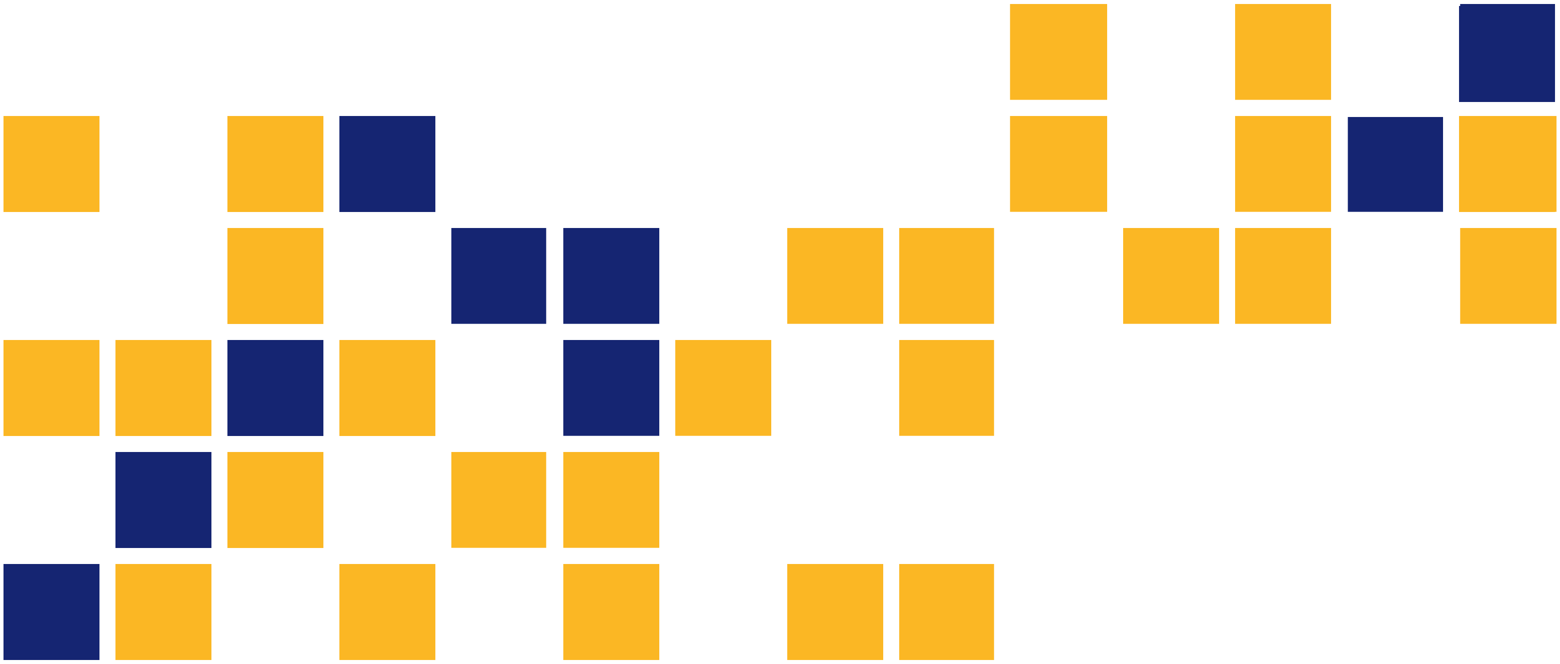
Feasibility of Bluetooth Data as a Surrogate Measure of Vehicle Operations

Robert A. Rescot, Ph.D.
Steven D. Schrock, Ph.D., P.E.
Eric J. Fitzsimmons, Ph.D.

The University of Kansas



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16 Abstract

This research was designed as proof-of-concept study to investigate how Bluetooth data loggers can be used to collect vehicle operational data over traditional vehicle counting methods. The reliability test included mapping areas for five antenna options and their detection reliabilities were investigated. Other tests were conducted to assess the impacts of roadside antenna placement, vehicular speeds and in-vehicle source placement. The feasibility of using data from Bluetooth enabled devices in vehicles as a surrogate for traditional traffic engineering data were investigated for several types of traffic studies. These studies included, urban corridor travel time monitoring, freeway travel time monitoring, origin-destination studies, estimating turning movements at roundabouts, and truck tracking across the state of Kansas. Each of these studies demonstrated how the same technology could be applied to different study objectives. While this technology was found to have enormous potential to collect vehicle operational data, it was not found to be completely stand-alone. An identified 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 for analysis due to low traffic volumes at some rural locations.

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Final Report

Prepared by

Robert A. Rescot, Ph.D.
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Executive Summary

The widespread use of portable electronic devices among consumers has allowed 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 is 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 when activated can be discovered electronically which unintentionally creates anonymous probes in the traffic stream.

Understanding the technology and potential uses for traffic data collection began by testing Bluetooth roadside data logger hardware configurations including the Bluetooth antenna selection and roadside placement options. Detection areas for five antenna options were mapped, and their detection reliabilities were investigated. Other tests were conducted to assess the impacts of roadside antenna placement, vehicular speeds and in-vehicle source placement. The feasibility of using data from Bluetooth enabled devices in vehicles as a surrogate for traditional traffic engineering data were investigated for several types of traffic studies. These studies included urban corridor travel time monitoring, freeway travel time monitoring, origin-destination studies, estimating turning movements at roundabouts, and truck tracking across the state of Kansas. Each of these studies demonstrated how the same technology could be applied to different study objectives.

The hardware evaluations showed that a dipole antenna placed 6 to 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. In the five study applications, four showed that the Bluetooth data were statistically comparable to data collected following traditional methodologies. The lone strategy that was found to be not comparable was when using Bluetooth data collection techniques at roundabouts. It is likely that some confounding issues arose at the selected locations (such as differences in trip type/purpose between short-range urban trips on city streets versus long-range intercity trips), and more study is needed to fully understand the differences between urban roundabouts and rural roundabouts

The data collected created an automated process for identifying and re-identifying vehicles along a corridor. This opened up new potential analyses of the data including being able to separate frequent (repeat) travelers from occasional travelers along a corridor.

While this technology was found to have enormous potential to collect vehicle operational data, it was not found to be completely stand-alone. An identified 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 for analysis at very low volume locations which can occur in some rural Kansas locations. This could be a particular issue when the data need to be separated into smaller hourly groups or if a long data collection period is not possible. 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.

Along with the need for calibration data to pair with the Bluetooth data, 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. The results of the study indicate that collecting vehicle operational data through the detection of a Bluetooth device in a vehicle to be adequate, given when the circumstances are correct.

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Chapter 1: Introduction

Modern traffic studies cover a wide range of needs including addressing roadway capacity, travel speeds, travel delay, origin-destination, and predicting future roadway utilization. For each study type an engineer selects a data collection methodology that suits each given purpose and need. These studies commonly rely on such data collection tools as pneumatic tube counters, video cameras, radar, inductive loops, microwave fields, or 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. These data loggers leverage the increasing presence of cellular phones and other devices among motorists. Many modern cellular phones often include a Bluetooth wireless radio that permits it to connect to other Bluetooth enabled devices in close proximity such as a headset. As part of the Bluetooth communications protocol, the Bluetooth wireless radio communicates a unique twelve character identification number (Media Access Control address; “MAC address”) when it is allowed to be discoverable. Enabling a Bluetooth device to be discoverable enables other Bluetooth devices to electronically ‘see’ the device and to possibly connect to it. In many cases in order to actually complete the device-to-device pairing a security pin code was needed (Bluetooth Special Interest Group, 2011).

In the context of collecting traffic data, the use of Bluetooth technology is similar to capturing license plate information. In both cases a unique identification number is recorded at one location and paired to itself at a second known location. A Bluetooth data logger is able to record the MAC addresses of nearby “electronically discoverable” devices along with a time stamp and stored in flash memory. At the time of this research study, there were two principal vendors of Bluetooth data collection equipment intended for roadside usage. The products from both vendors were compared and their specifications were similar. The criteria for equipment selected for this research was that it had to be self-contained portable units with interchangeable parts and include an on-board Global Positioning System (GPS) receiver. The Blue tooth data logger used for this research is illustrated in Figure 1.

FIGURE 1
Bluetooth Data Logger Used in the Research Studies

Chapter 2: Background

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 provided a medium for multiple agencies to discuss Bluetooth-based data collection including researchers from the California Department of Transportation, Houston-Galveston Area Council, Texas Transportation Institute, University of California Berkeley, University of Kansas, University of Maryland, and University of Virginia. The Bluetooth summit showcased several on-going tests and implementations around the country, along with discussions of current research needs in the field.

Researcher Stan Young from the University of Maryland noted advantages of Bluetooth technology, and that it represented a significant advancement over four other similar technologies. Table 1 provides other technologies Bluetooth traffic data could be compared with including: passive loop detectors, Global Positioning System data from fleet vehicles, cellular phone locations, and automated toll tag readers.

TABLE 1
University of Maryland Slide Comparing Traffic Study Technologies (Young, 2007)

Technology	Costs	Privacy	Travel Time Accuracy	Coverage	
				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		✓✓✓✓	✓✓✓	✓✓✓

As shown in Table 1, each of these competing technologies was considered by Young to have a number of disadvantages as compared to Bluetooth based technologies. Conventional loop detectors do not permit the ability to calculate travel times (only spot speeds). Data from GPS units in fleet vehicles are 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 (American Transportation Research Institute, 2007). The detection of electronic toll road tags is only practical in areas where toll roads were present. For example, the use of toll tag readers in Garden City, Kansas would not be practical as a way to collect vehicle operational data as the nearest toll road is over 200 miles away (Young, 2007).

The other technology mentioned by Young that lent itself for comparison was geolocated cell phone data. The significant shortcoming of this technology includes that is not possible to only collect data along a specific corridor. Such data are customarily available as a blanket data set across a specific geographical area. The implication of this technology is the ability 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 are possible using this data collection methodology, assignment of trips to a specific route was not possible. As shown in Figure 2 Geolocated cell phone travel data for trips to/from FedEx Field in Landover, Maryland on September 15, 2009 that identified traveler origins (Young, 2007), exact driveways can be determined from geolocated cell phone data.

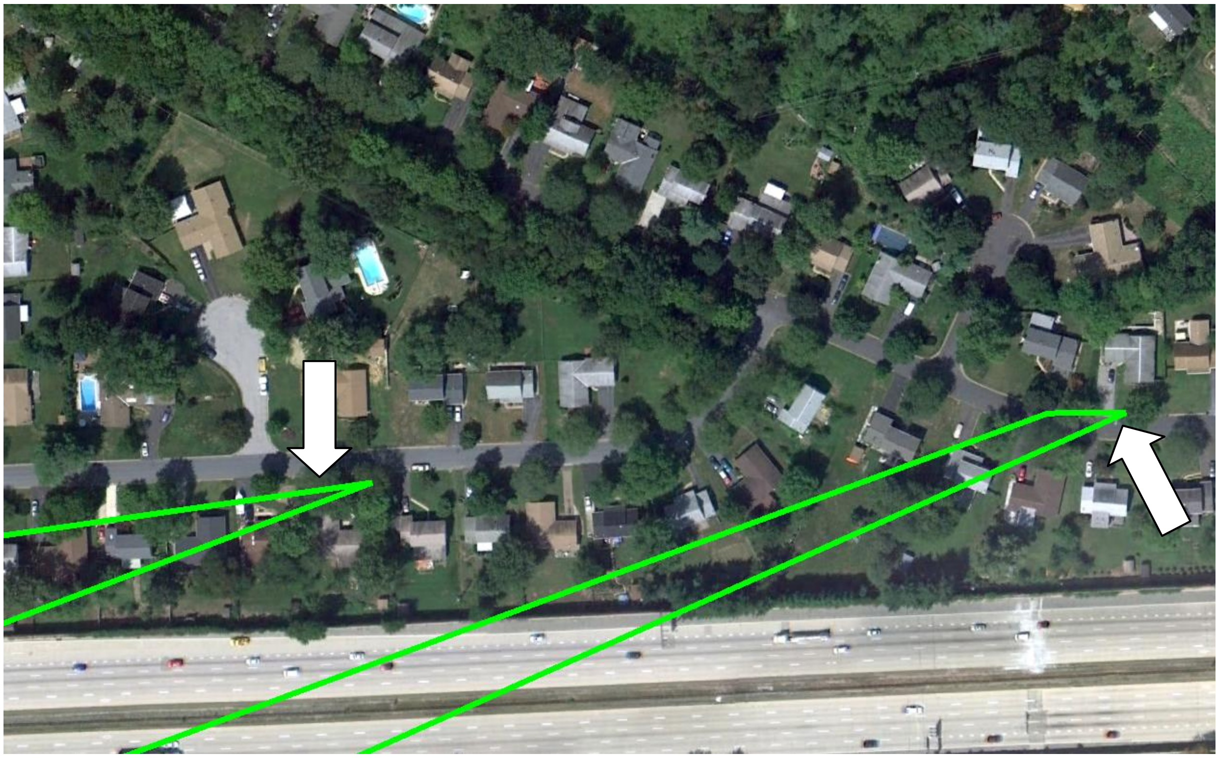

FIGURE 2
Geolocated Cell Phone Travel Data for Trips to/from FedEx Field in Landover, Maryland, on September 15, 2009, that Identified Traveler Origins (Young, 2007)

What set Bluetooth based detection apart from cellular phone technology was the low power strength of the radio signal and data could only be acquired at specific locations that would systematically prevent the identification of individuals. The Bluetooth technology 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.

Young (2007) experimented with repurposing Bluetooth technology for the acquisition of traffic data. The research found that a discoverable Bluetooth device publicly emits a unique MAC address, that when paired with a time stamp and was 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. The author 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”.

Wasson and Sturdevant of the Indiana Department of Transportation (2008) also looked at the use of acquiring Bluetooth MAC addresses for collecting transportation data. The authors deployed Bluetooth data loggers for six days along a 8.5 mile 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 analysis 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."

Bullock et al. of Purdue University (2010) also applied the technology to other scenarios in addition to the roadside acquisition of traffic data. The authors 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 radii that the authors estimated to be the range of a Class I receiver. The change in receiver class was due to the close proximity of the two detection stations inside of the airport terminal. Through their study they found that the number of Bluetooth sources recorded corresponded to a range between 5 to 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 passengers screened at the checkpoint. Shown in Figure 3 is a comparison between passenger counts and their respected security line travel times captured by the Bluetooth detectors.

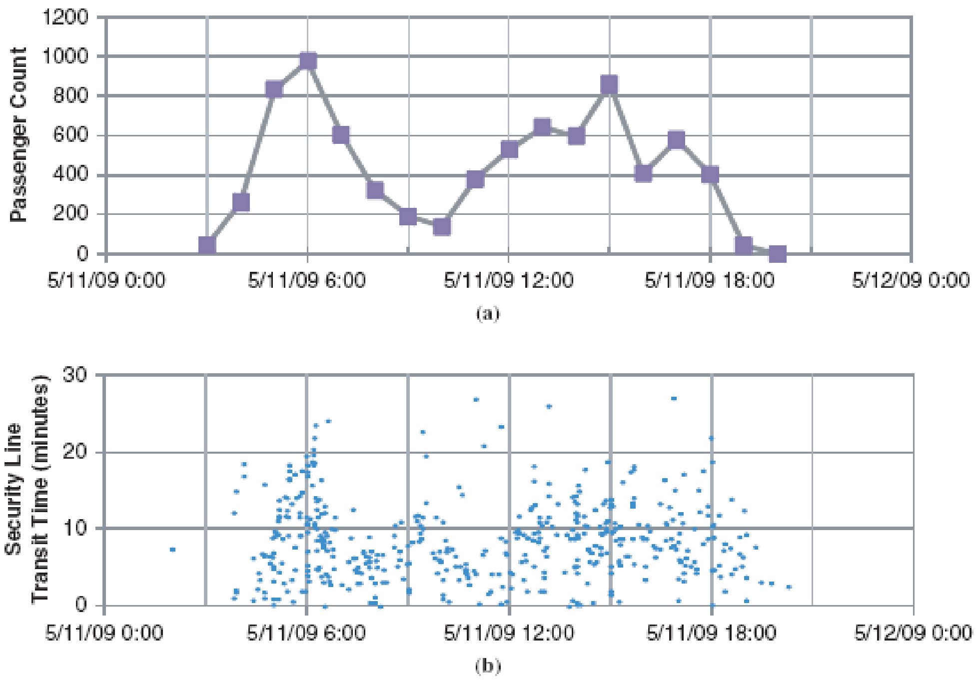

FIGURE 3
Comparison of Passenger Counts to Security Lane Travel Times (Bullock et al., 2010)

Also presented at the Bluetooth summit were several universities that were actively engaged in statistically validating third party data sources. Haghani and Hamedi of the University of Maryland together 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. Haghani and Hamedi (2010) noted a sampling rate between 2 to 3.4 percent if one assumed a sole Bluetooth source in each vehicle. Similarly, Schneider et al. (2011) of the University of Akron were also validating floating car run based travel time data from a vendor on behalf of the Ohio Department of Transportation (ODOT). The data prepared for ODOT included both arterial and freeway segments in and around Dayton, Ohio. The authors 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. They also felt that Bluetooth-based data provided greater data resolution than the floating car based data.

Focused on urban travel times, the City of Houston, Texas undertook several demonstration projects to find an alternative to the use of toll tag readers on urban streets were the prevalence of such toll tags was not able to capture a statistically significant sample size. Texas Transportation Institute researchers Puckett and Vickich (2011) found that Bluetooth-based traffic data collection technologies were viable for travel time data. 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 (2011) also showed that their Bluetooth travel time estimates comparably tracked with toll tag data as shown in Figure 4, 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.

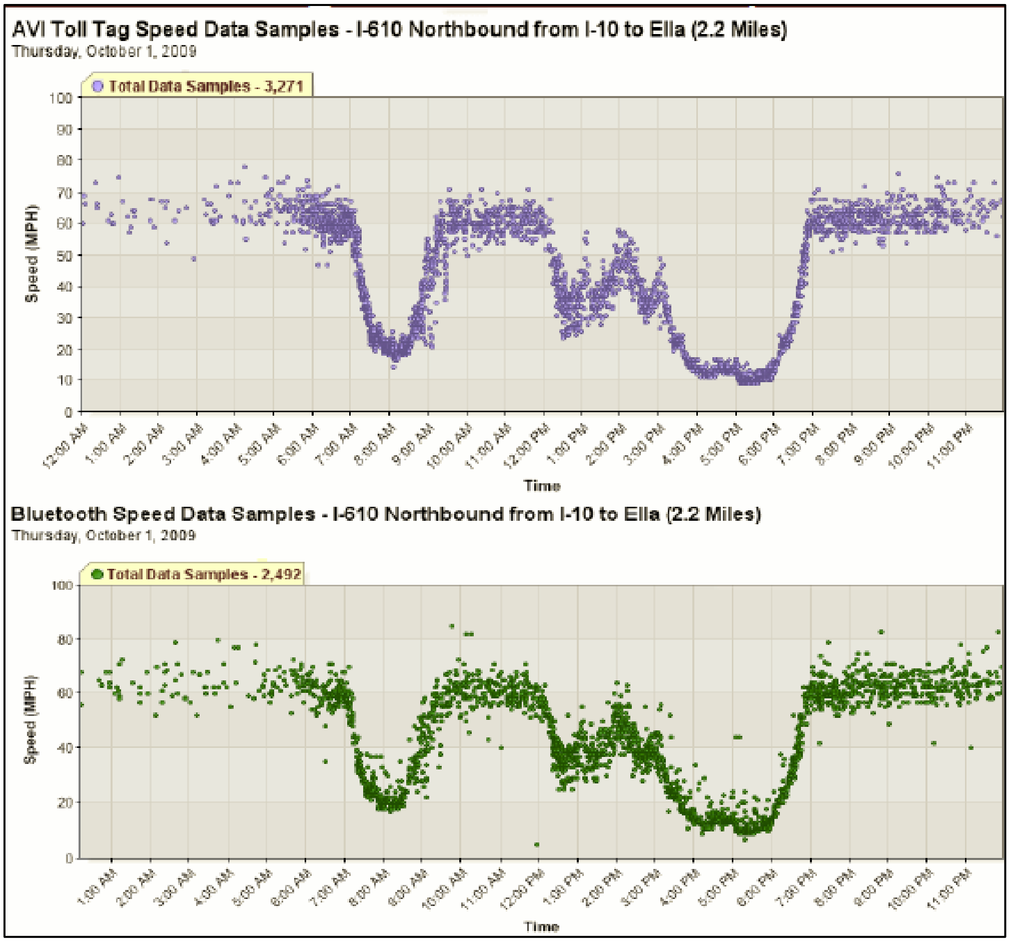

FIGURE 4
Comparison of Bluetooth and Toll Tag Travel Time Data in Houston, Texas (Puckett and Vickich, 2011)

Another related application was investigated by Rajbhandari of the Texas Transportation Institute (2010) which estimated border crossing times for vehicles entering the United States at several border crossings near El Paso, Texas. In addition to working across national borders the author 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.

Venkatanarayana et al. of the University of Virginia (2010) also experimented with Bluetooth based traffic data collection technologies. Their research was exploratory in nature as a proof-of-concept. The authors choose to conduct their testing for 70 hours along a four mile segment of Interstate 64 east of Charlottesville, Virginia. They 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 (2010) of the University of California Berkeley. 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 process of transmitting the data through cellular modems to a data processing center.

Recognizing that the specific antenna used by a Bluetooth data logger was a crucial variable, Brennan et al. (2010) set out to quantify this. As recognized previously by Bullock et al. (2010) which investigated the Indianapolis International Airport, closely spaced detection units need to have clearly delineated areas of detection. Brennan et al. (2010) focused specifically on vertical mounting height of a standardized antenna to determine any possible directional biases this could create in the data collected. The authors 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.

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 identified shortcomings and opportunities that merited further research. While several of the previously mentioned research studies were able to estimate a Bluetooth sampling rate, researchers still had limited knowledge of how accurate that rate was or how likely it was that they sampled all of the available Bluetooth signals without a closed-course study. This same sentiment was echoed by Kuhn (2010) and Venkatanarayana et al. (2011) 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 (Haghani and Hamedi, 2010; Schneider et al., 2011), 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.

Chapter 3: Report Organization

The objective of this research study was to evaluate the feasibility of using Bluetooth data as a surrogate analysis measure of traffic and 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 variables were tested in various combinations to establish performance metrics upon which the rest of the research could be built. Secondary objectives of the research study investigated common traffic engineering studies which relied on field data collection sharing the same 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).

These secondary objectives were carried out at various study sites in Kansas and Missouri including an urban corridor to evaluate travel time, a city with a special generator to determine vehicle movement and isolated roundabouts to verify turning movement volumes.

The final objective of the research study investigated how Bluetooth data collection could be utilized to track trucks and passenger cars across the State of Kansas. This proof of concept study would allow policy makers and planners to investigate major trucking routes from Southwest Kansas to the Kansas City, Missouri metropolitan area.

Chapter 4: Antenna Detection Area and Reliability

An understanding of the detection range (area) for various antenna options, as well as their detection reliability was sought after in addition to an understanding of other related variables such as phone (source) placement in a vehicle, vehicle speed, and Bluetooth data collection antenna mounting height. A thorough understanding of these variables was needed to optimize data collection equipment placement, as well as to provide a comprehensive analysis of the resulting data. Such research was intended to fill in a missing knowledge gap among the previous related studies.

One of the specific technical variables that had been previously overlooked was antenna selection. Antennas come in a variety of types that each correspond to variously shaped detection areas. 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 result in a circular radiation pattern emanating out from a circular antenna in all directions in the shape of a taurus as shown in Figure 5.

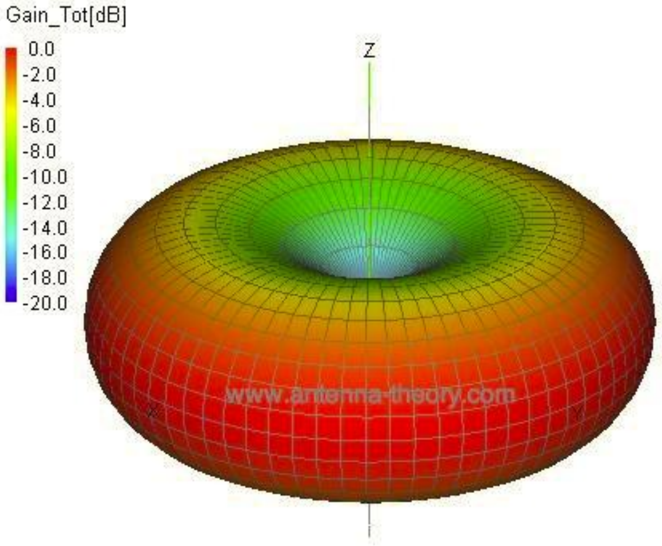

FIGURE 5
Normalized 3D Radiation Pattern for Diploe and Whip Antennas (Bevelacqua, 2011)

The size of the radius corresponds to the gain value. However a patch antenna operates from a flat plane as shown in Figure 6, making it directional in nature with a circular to conic looking radiation area in front of the plane.

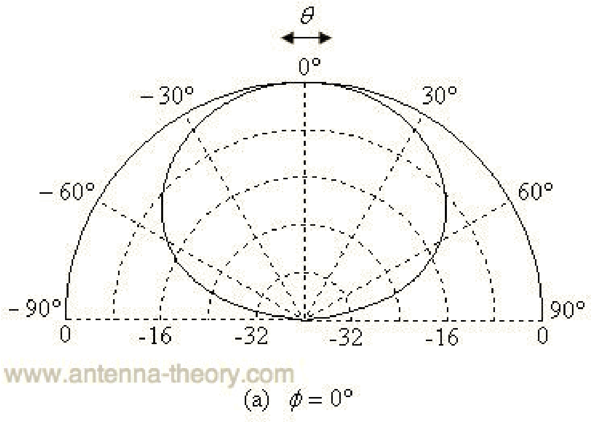

FIGURE 6
Normalized Radiation Pattern for a Patch Antenna (Bevelacqua, 2011)

Behind the plane, no communications are theoretically possible (Bevelacqua, 2011). 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.

4.1 Research Objectives

The first objective for this research 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
- 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 research studies that several variables would work together to affect the detection reliability. First, 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. Also, it was believed 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 level of confidence.

4.2 Work Plan

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

4.2.1 Equipment Selection

The Bluetooth data loggers chosen were commercially available at the time of the study. Each unit consisted of a weather-proof sealed case, on-board power source, a Bluetooth receiver with an interchangeable antenna, a Global Positioning System (GPS) receiver, and a small computer that stored the data onto a memory card. The equipment selected was shown previously in Figure 1.

4.2.2 Data Collection

The data collection plan consisted of several steps. The first data collection effort was accomplished by using: a flat, open field at 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 a researcher with a Bluetooth enabled mobile phone. The researcher would hold the phone at waist height (approximately 4 feet off the ground). The researcher 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 researcher 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 7.

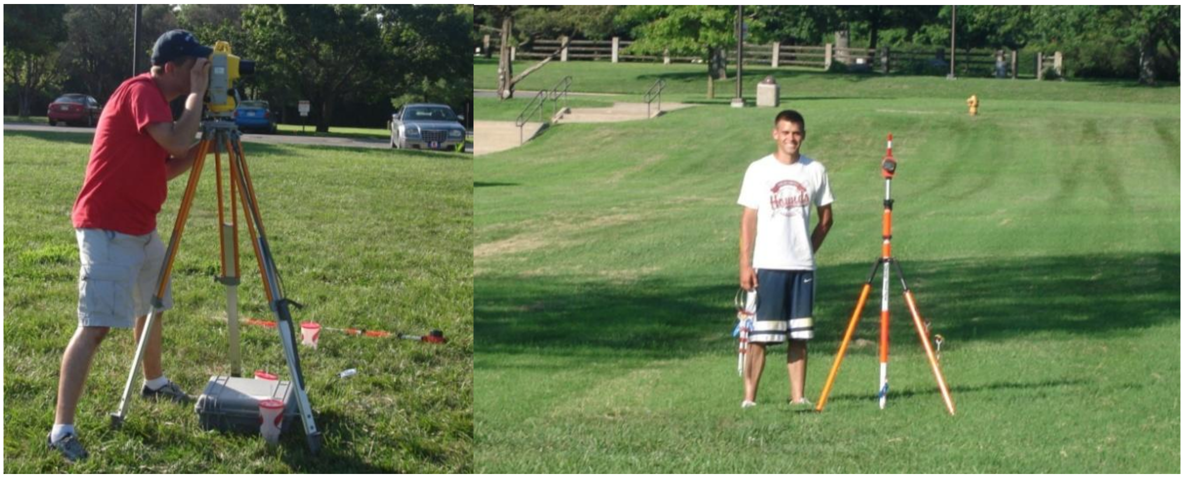

FIGURE 7
Researchers Surveying Bluetooth Detection Areas for Various Antenna Options

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.

To test the Bluetooth loggers in an open-course condition, data were collected at an off-campus location on a rural section of US 59 highway located in Jefferson County just south of of Oskaloosa, Kansas. This segment of roadway was selected for its low average annual daily traffic (AADT) volume of 2,760 vehicles per day, relatively high speed limits without a minimum speed limit (Brennan et al., 2010). It was important that the selected roadway segment be able to safely accommodate a range of test speeds, and be as free as possible of other competing Bluetooth signals. The data collection setup used is shown in Figure 8.

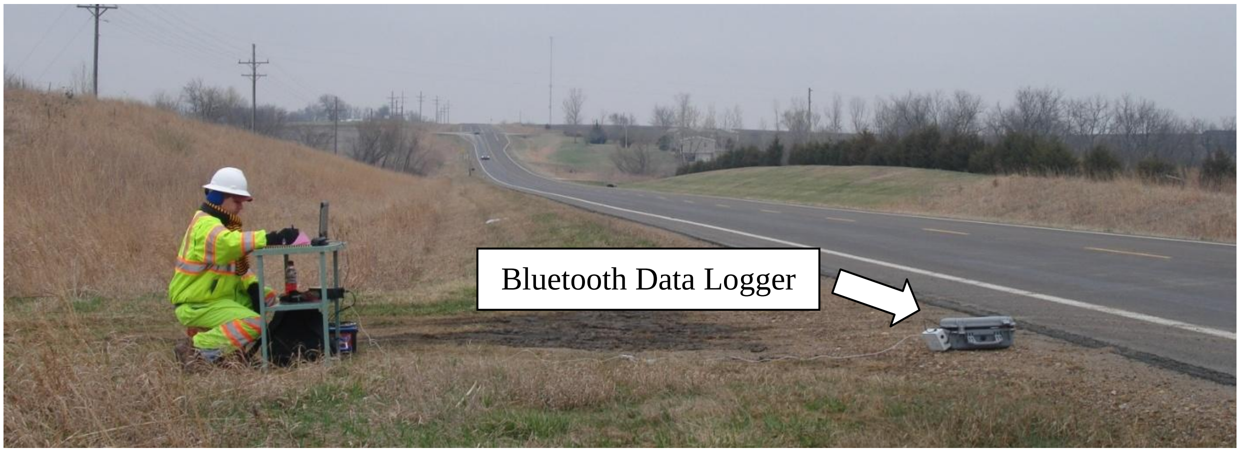

FIGURE 8
Researcher Conducting Bluetooth Detection Reliability Testing

At this location, three sites were selected each about 0.25 miles apart from each other so as to ensure 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 a Bluetooth enabled device. 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 between both test vehicles) at each of the testing speeds of 30, 45, and 60 mph. This process was repeated several times until all speed, antenna, and distance combinations were studied.

4.3 Field Data Collection

Field data were collected throughout the fall of 2010 and spring of 2011 and data were transcribed in 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 transferred from the log books to electronic form for aggregation. To establish consistency, standard testing phones were selected as shown in Figure 9. These phones were widely available at the time of the study which included both traditional cell and smart phones.

FIGURE 1
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

4.3.1 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 2, Test #1.

TABLE 2
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

The specific objective was to determine the detection range of several phones including the standard testing phone. All of the remaining tests in Table 2, (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 10. 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 11 shows the results of Test #1, Figure 12 shows the results of Tests #2-6, 8-11.

FIGURE 10
Testing Antennas, Left to Right: 5dB Dipole, Standard 3dB Dipole, 1dB Stub, 9dB Patch, 3.12 dB Whip, 6.12 dB Whip

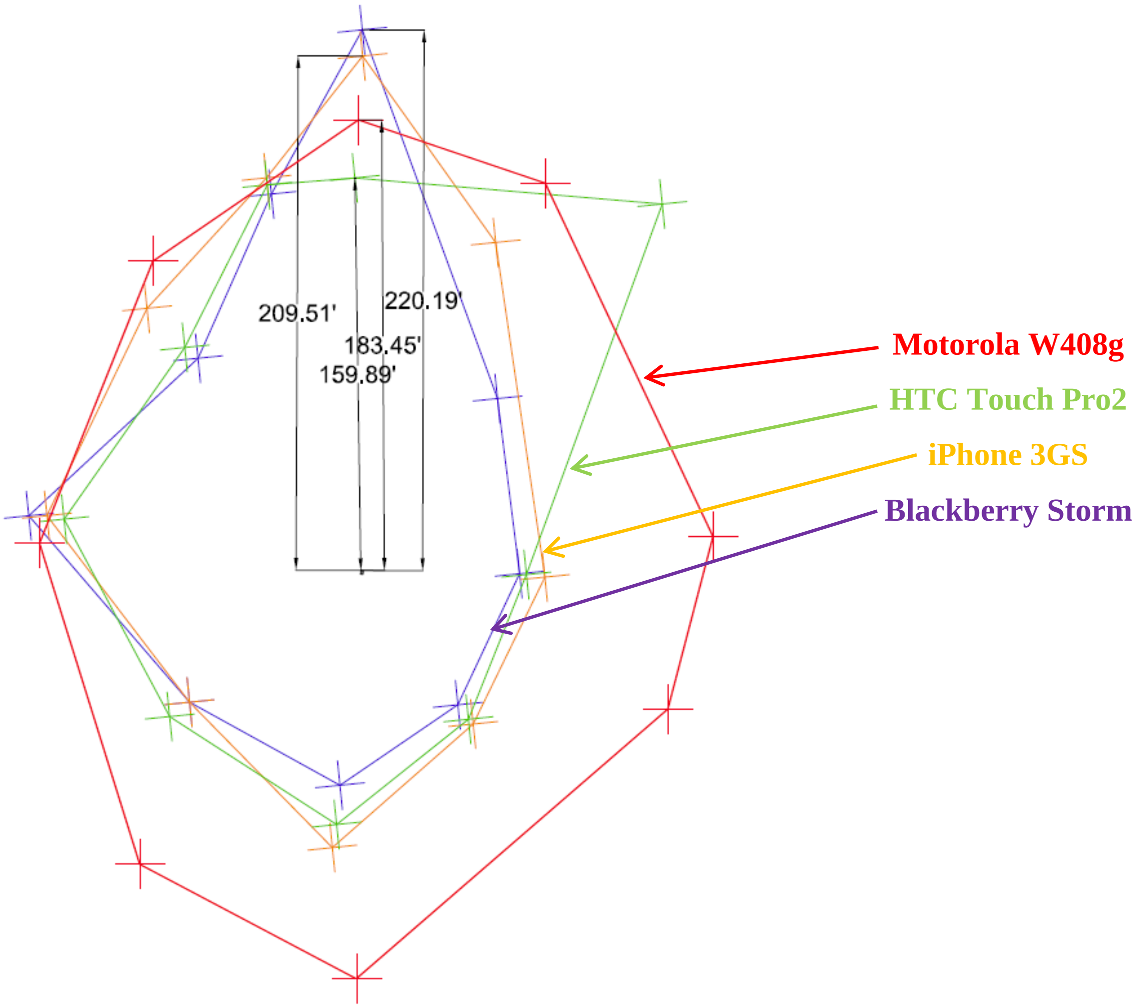

FIGURE 11
Bluetooth Detection Areas of Selected Cell Phones Used in Test #1

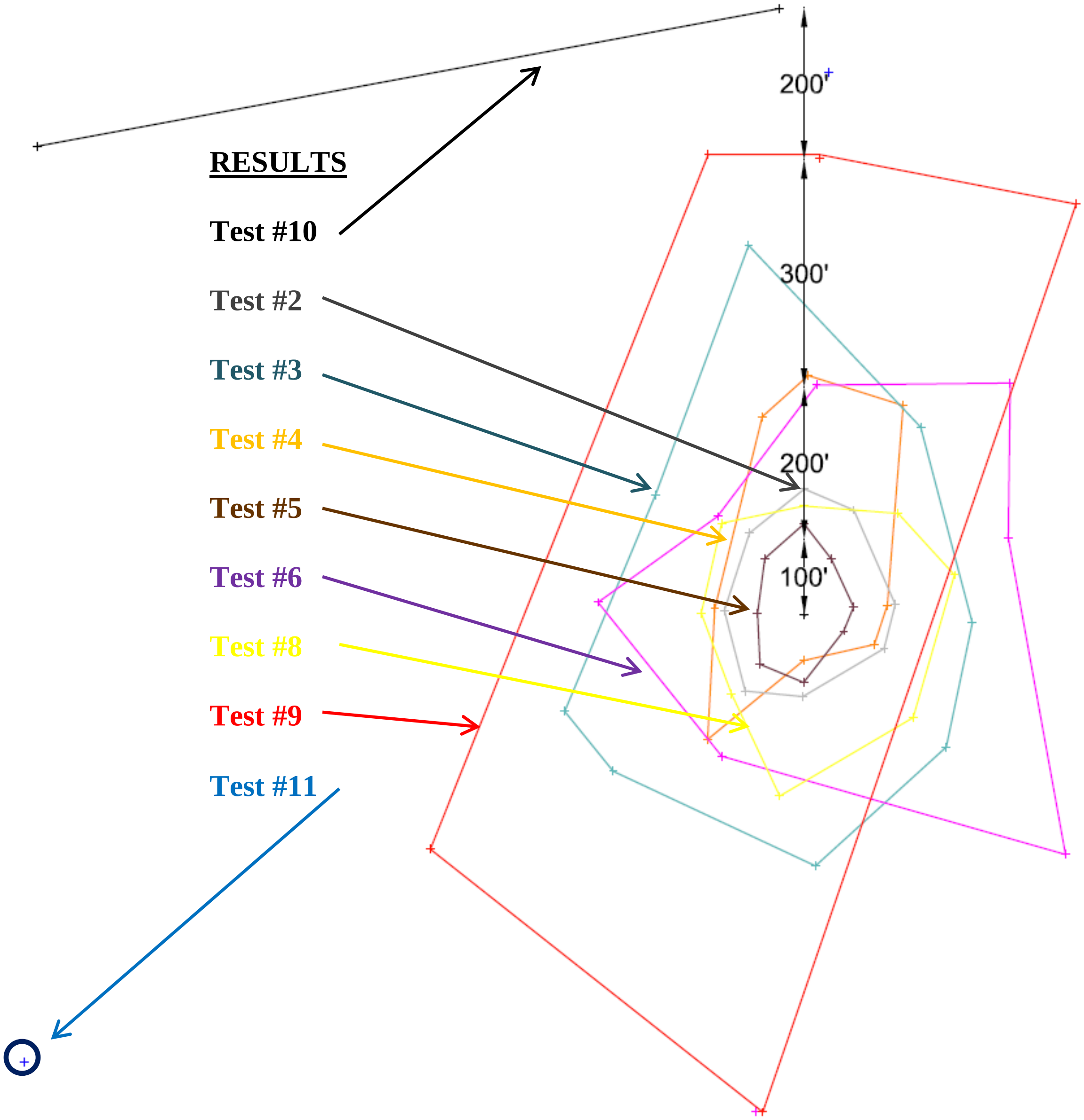

FIGURE 12
Bluetooth Detection Areas for Various Antenna Options Used with the Standardized Testing Cell Phone in Tests # 2-6 and 8-11

4.3.2 Bluetooth Detection Reliability

Each of the reliability testing scenarios shown in Table 3 was evaluated thirty times at each of three speeds: 30 mph, 45 mph, and 60 mph. The test vehicle drivers utilized the 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 13.

TABLE 3
Listing of Bluetooth Detection Reliability Tests and Results

Test #	Antenna	Mounting Height	Edge Line Setback Distance[a]	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.

[a] The smaller setback distance was for the near lane; the larger setback distance was for the far lane.

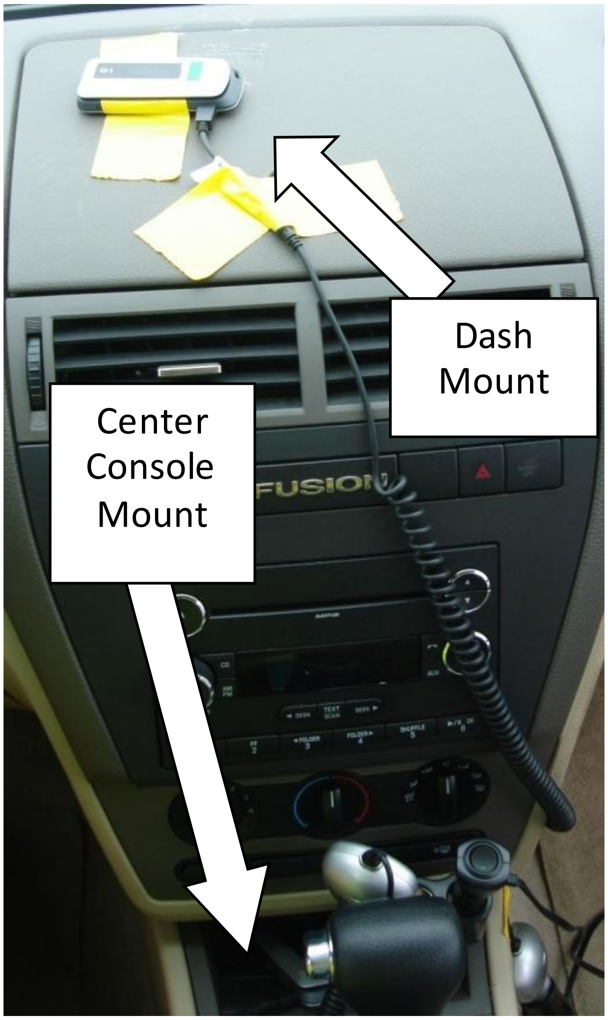

FIGURE 13
Bluetooth Source (Cellular Phone) Placements in Test Vehicle

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 testing structure required to achieve the 16 feet elevation was deemed to otherwise create a safety hazard and thus was required to be located at the edge of the roadside clear zone. This 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.

4.4 Analysis

4.4.1 Comparing Antennas

When conditions were standardized and differences between various antennas could be identified, the first null hypothesis was able to be 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 3, 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 4. 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 hypotheses H_{o1} was rejected.

TABLE 4
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

4.1.2 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 4, Test 2, a greatly increased setback distance, such as Test 8 in Table 4, 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.

4.1.3 Effects of Vertical Elevation on Antennas

The standard antenna above ground placement height was between three and sixteen feet (such as Tests 9-11 in Table 4), were shown to increase the detection rate. These elevation increases were statistically significant with 95 percent level of confidence when considered across all speed studied, set back distances, and source locations using a paired t-test (p-value 0.005). Thus the null hypothesis H_{o3} was rejected.

4.1.4 Effects of Vehicle Speeds

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 5.

TABLE 5
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

The research indicated that the detection rate drop-off occurred between 30 and 45 mph. A paired t-test with a 95 percent level of confidence was utilized, it was found to be 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.

4.1.5 Effects of In-Vehicle Bluetooth Source Location

Under standardized testing conditions, the results of the data collection effort showed the dash mounted mobile phone was detected 91 percent of the time as compared with a detection rate of 87 percent for the center console mounted mobile phone as seen in Table 6. Using a paired t-test with 95 percent level of confidence, the drop in detection rate was statistically significant (p-value <0.001). Thus the null hypothesis H_{o5} was rejected.

TABLE 6
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

4.1.6 Effects of Obstructions

The worst case scenario was tested in which a large object between the Bluetooth data logger and the Bluetooth source could obstruct the signals. This scenario was tested in Test #7 that utilized a shipping container as the obstruction as shown in Figure 14.

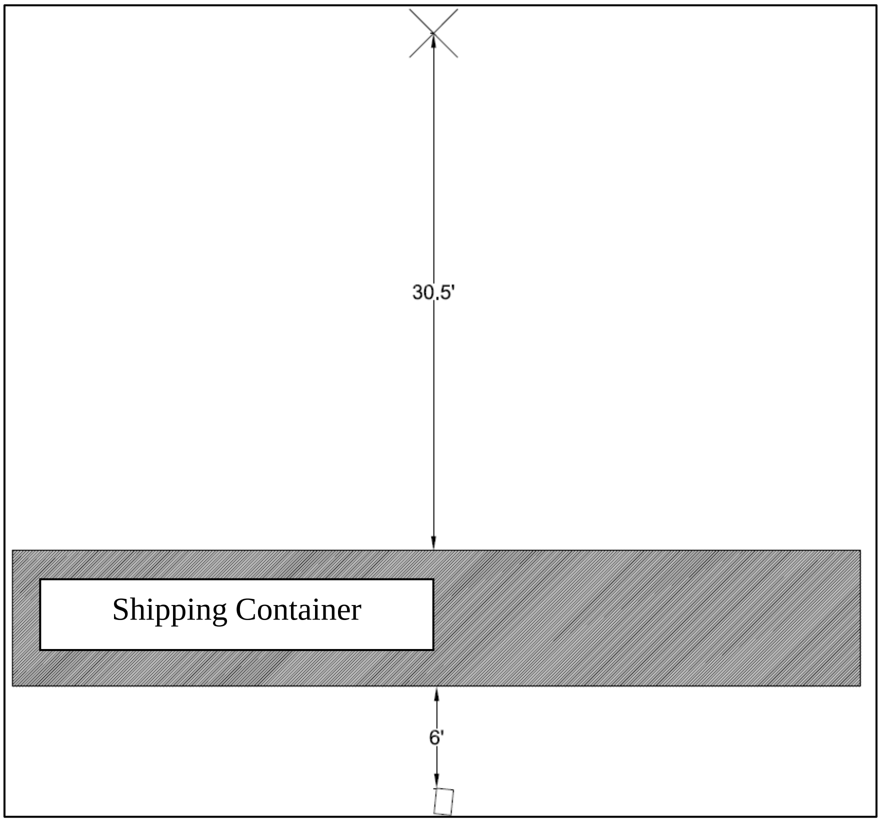

FIGURE 14
Bluetooth Detection Distance for Test #7

The detection area results indicated that the mobile phone signal was still robust enough to have over 30 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.

4.2 Findings and Discussion

Utilizing Bluetooth technology to perform a traffic study requires a thorough understanding of the limitations and potential use of the equipment and how to account for controllable variables that may impact the data collection effort. These variables include: antenna choice, equipment mounting height, roadside setback distance. Additionally, uncontrollable variables must be considered which may include: source traveling speed and source placement within the vehicle.

Antenna selection directly correlates to the quantity and quality of the data collected. 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 are present. For example, it would be beneficial 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 be utilized 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 manually 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 study showed that in a typical roadside setup with a standard antenna, the Bluetooth data logger was able to capture approximately 95 percent of the available data. When the antenna used changes and its mounting location the sampling rate can be increased or decreased. This research demonstrated that when an antenna was elevated above ground level, the sampling percentage increased to 100. 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.

Furthermore, Bluetooth source placement in a vehicle did have a statistically significant impact on the detection reliability, this serves as an indicator that there could be a bias in the data towards 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. The possible implications of this would be that the drivers’ speeds may be slightly slower than the rest of the traffic flow as they had to manage two mentally consuming tasks, talking and driving.

Chapter 5: Urban Corridor Travel Time

In the summer of 2010, the City of Lenexa, Kansas upgraded the traffic signal control hardware along the 95th street corridor between Monrovia and Lackman roads to improve traffic flow. This 95th Street study corridor functions as an arterial route, serving between 20,000 and 30,000 vehicles per day. This study corridor also intersects Interstate 35, and serves as a main route for traffic flowing to and from the interstate. Located adjacent to the corridor are a number of strip shopping centers and business parks. However, going several blocks beyond the corridor, there are a large number of single and multi-family residences as seen in Figure 15.

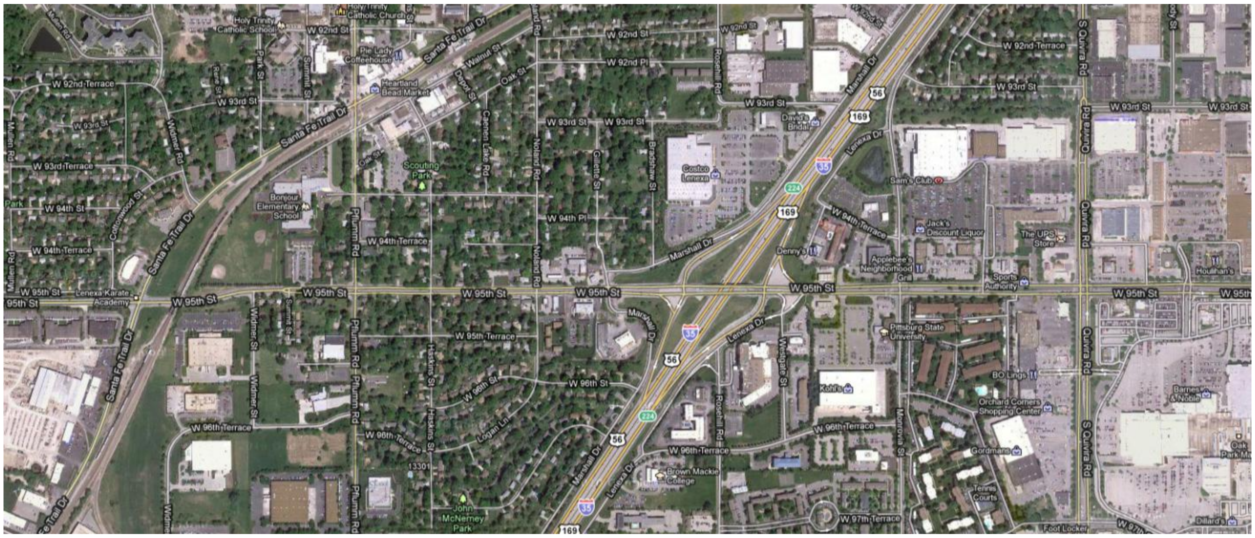

FIGURe 15
Residential Housing along 95th Street Corridor in Lenexa, Kansas

5.1 Research Objective

The research objective for this study was to quantitatively determine the differences in travel time using 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.

5.2 Work Plan

The work plan for the project consisted of three parts. 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.

5.3 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.

5.3.1 GPS Floating Car Runs

Travel time measurements along the 95th Street corridor were one direct measurement of the existing performance of the traffic signal system. Travel time typically varied inversely with the volume of traffic present on 95th Street. It also fluctuated throughout the day with peaks during the morning rush, lunch time, and the evening peak hours. 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 speed and kept 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 and 22 and the after data collected on August

11 and 12. The hours that data collection occurred are shown in Table 7 and were selected to match the observed peaks throughout the day.

TABLE 7
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

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 which included: 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 was based on the vehicular trajectories recorded in real-time by the GPS component of the software and processed using default parameters. Results for the corridor are presented in full in Appendix A.

5.3.2 Bluetooth Data Collection

The Bluetooth data loggers were deployed on Tuesday and retrieved on Friday of each test week. A total of 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 previously in Table 7. Nine Bluetooth data loggers were used for the study. On the south side of 95th street, a unit was placed approximately one-half block from each end of the corridor. 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 along the study corridor is shown in Figure 16.

FIGURE16
Bluetooth Data Logger at the Northwest Corner of I-35 and 95th Street in Lenexa, Kansas

Due to the importance for vehicles to access I-35, units were placed along 95th Street near each of the two ingresses and two egresses to the interstate. This allowed for travel time data of vehicle traveling to/from I-35 to each extent of the corridor to be captured, along with travel times across the interchange for through traffic on 95th Street. The deployment of detectors on both sides 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.

5.4 Analysis

After 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 17.

FIGURE 17
Travel Time Segments along 95th Street in Lenexa, Kansas and Bluetooth Data Logger Placements (Google, 2011)

5.4.1 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.

5.4.2 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. An assumption was made for the analysis that 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 (KDOT, 2011). 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 removed from the data set and subsequently all calculations and statistical comparisons were also completed without regard to any outlying data points (travel times). Additionally all data that was the result of the probe vehicle was also removed from the data set.

The advantage of the Bluetooth method can 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 direction 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 as shown in Table 8.

TABLE 8
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

However, 34 of the 111 decreases in travel time were deemed with 95 percent level of confidence to have a statistically significant difference from the travel time in the before case. Additionally, 12 of the 43 increases in average travel time were also deemed with 95 percent level of 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.

5.5 Findings and Discussion

Through the course of this research a number of findings were made and noted in the following sections.

5.5.1 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 2:00p.m. hour. However based on the data collected, with 95 percent level of 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 9:00a.m. hour for east bound 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 level confidence (p-value 0.102). It was not known why this travel time increase occurred, but it was shown in both data sets.

5.6.2 Bluetooth Data to GPS Data Comparison

In comparing the Bluetooth data to GPS based data for the data collection periods shown in Table 7, of the 22 comparisons, 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.

Chapter 6: Urban Freeway Travel Time

6.1 Research Objective

While numerous algorithms exist that attempt to predict space mean speeds based on time mean speeds (spot speeds), it was found that many included errors as they were estimators. Recognizing opportunities and limitations with the Bluetooth technology, the research team compared travel time predictions to demonstrate actual travel time changes along a segment over time. 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.

6.2 Work Plan

The research team worked with the Kansas City Scout Traffic Management Center (KC Scout) and a plan was established to mirror existing monitored travel time segments. KC Scout 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 near major interstate routes in the Kansas City metropolitan area. Along a number of their routes, KC Scout would post travel times on dynamic message signs located adjacent to or overhead of the highway. Investigating 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. Five Bluetooth data loggers were deployed for eastbound and five data loggers were deployed for westbound traffic as shown in Figure 18 at the end points of the travel time segments.

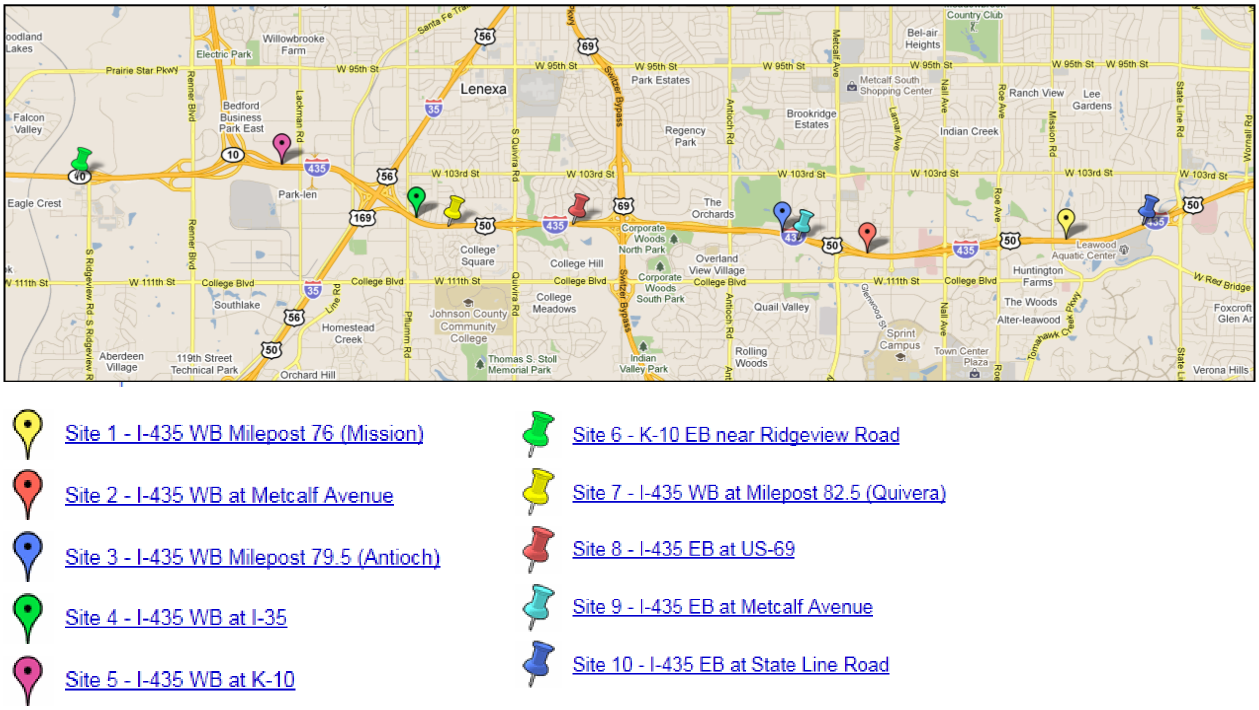

FIGURE 18
I-435/K-10 Bluetooth Data Logger Placements along Corridor

6.3 Field Data Collection

Field data collection consisted of deploying the Bluetooth data loggers at ten study sites for fifteen consecutive days. These study sites created eight travel time segments as shown in Table 9 for analysis.

TABLE 9
K-10/I-435 Bluetooth travel time segments

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

However, it was found the battery in the Bluetooth data logger at study Site 3 lasted only for 10.4 days. This resulted in Routes 4 and 5 shown in Table 9 to have slightly less data available than other routes. The data from the KC Scout did not require any fieldwork and was provided electronically.

6.4 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 vendor 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 recommended and computed using percentile difference instead of absolute differences (KDOT, 2011). This same technique was also affirmed in the literature by Young (2007, 2010). The removal of the outliers then makes the resulting data less likely to include a circuitously routed vehicle, and thus more likely to accurately reflect the actual travel time.

For each of the travel time routes shown 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 were paired to the reported travel time from the KC Scout system data for the same interval. A paired t-test was conducted between each pair of data as shown in Table 10.

TABLE 10 Paired T-Test Comparison between Bluetooth and KC Scout Data

Route	15 Minute Interval Comparisons	Bluetooth Mean Travel Time (Minutes)	KC Scout Mean Travel Time (Minutes)	p-value	Reject H_o?
1	1,121	1.73	2.09	< 0.001	Yes
2	1,009	6.11	6.04	0.319	No
3	506	7.17	7.00	0.022	Yes
4	176	3.66	3.44	0.021	Yes
5	155	4.89	5.14	0.025	Yes
6	959	4.55	5.09	< 0.001	Yes
7	1,074	2.96	3.35	< 0.001	Yes
8	1,178	6.22	6.04	< 0.001	Yes

As shown in Table 10, due to the lack of available Bluetooth data, the lack of KC 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.

6.5 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 level of confidence for seven of the eight segments using a paired t-test. While the rejection of the null hypothesis implies 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 8; this would not be a practically significant difference for a 6.5 mile route that a driver would notice. Additionally, there were no patterns observed of the Bluetooth data being either slower or faster than the KC Scout data. Four of the routes shown in Figure 19, were found to have the Bluetooth travel time data to be 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.

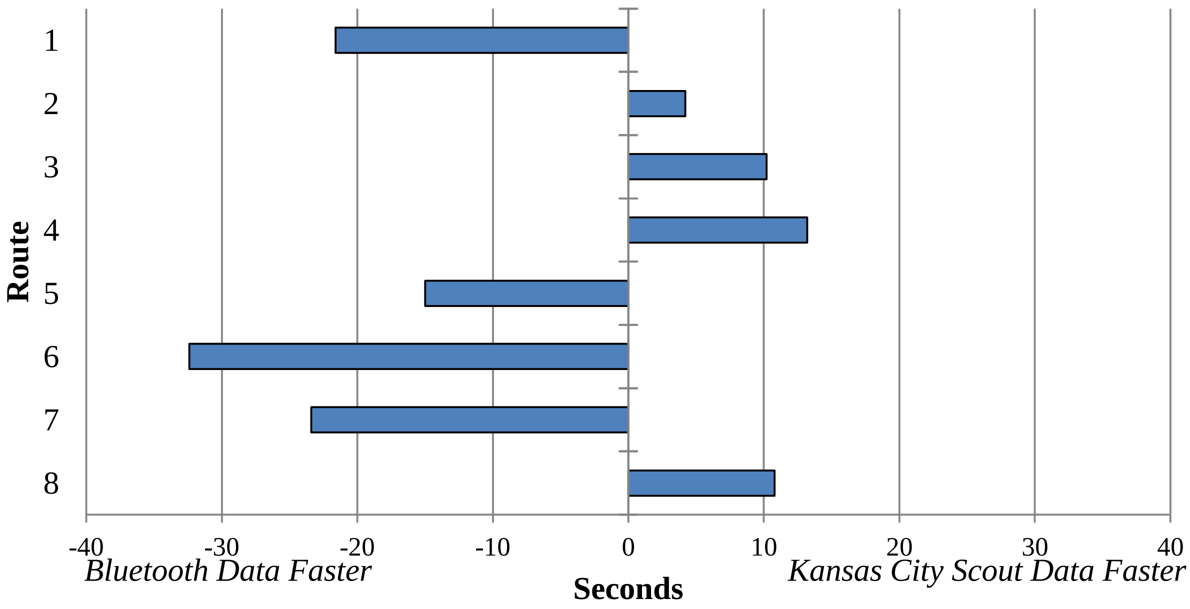

FIGURE 19
Travel Time Differences of Bluetooth Data Less the KC Scout Data

6.5.1 Limitations of Bluetooth Data Collection

The battery failure in the Bluetooth data logger at Site 3 is an example of one of the identified weakness of the Bluetooth data loggers to collect vehicle data. A critical part in the unit is 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.

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 vehicles are not required to be equipped with discoverable Bluetooth devices, there cannot be a guarantee that data will always be encountered.

If Bluetooth traffic monitoring was integrated into a comprehensive Intelligent Transportation System (ITS), the issues that occurred at Site 3 would not have be an issue. In a permanent deployment, the units would be located in a cabinet affixed to a signpost and hardwired to a power supply ensuring continuous electricity for the system to operate. Data would be fed in real-time to a computer for processing through a back haul channel to the traffic management center to prevent exceeding flash memory limits. However, 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 7: Origin-Destination Study

Planning studies are a key aspect for managing city growth and infrastructure development. The last origin-destination study the City of Columbia, Missouri conducted was found to be out of date. 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 (MoDOT) was also involved in supporting a study along with the metropolitan planning organization for the area, Columbia Area Transportation Study Organization (CATSO).

7.1 Research Objective

The primary objective for the study was to evaluate origin-destination patterns of basketball game-day traffic at the University of Missouri–Columbia, and to compare such perceived traffic surges to normal operations. The University of Missouri regularly draws large crowds for athletic events. Many fans travel to Columbia, Missouri from out of town and extended the existing city population. This combination caused the city to regularly alter signal phasing to disperse traffic following an event. Changes in traffic signal operations cause disruptions for local drivers and those not associated with the game. 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.

7.2 Work Plan

In collaboration with the City of Columbia, Missouri and the University of Missouri–Columbia, a research plan was assembled to collect both Bluetooth data and other validation data to be able to extrapolate travel patterns. The study was organized around a men’s basketball game on Saturday March 5, 2011. Three key corridors were identified for game day travel, all of which provided access to either Interstate 70 or the divided multilane State Highway 63 as shown in Figure 20.

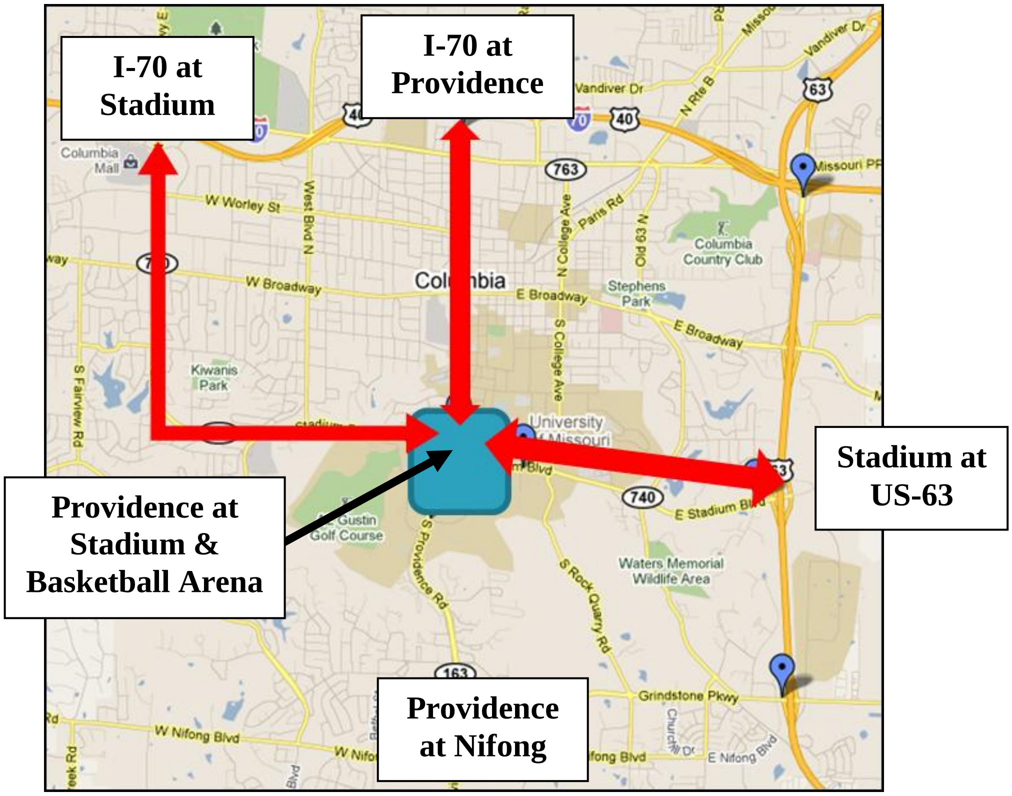

FIGURE 20
Primary Origin-Destination Routes in Columbia, Missouri

7.3 Field Data Collection

7.3.1 Bluetooth Data

The Bluetooth data collection protocol required that ten data loggers be deployed throughout the City of Columbia. Many of these units were placed along primary routes and around the basketball arena. Additionally, two 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 21 at the locations shown in Figure 22.

FIGURE 21
Bluetooth Data Logger Placement at Providence Road and Stadium Boulevard Intersection

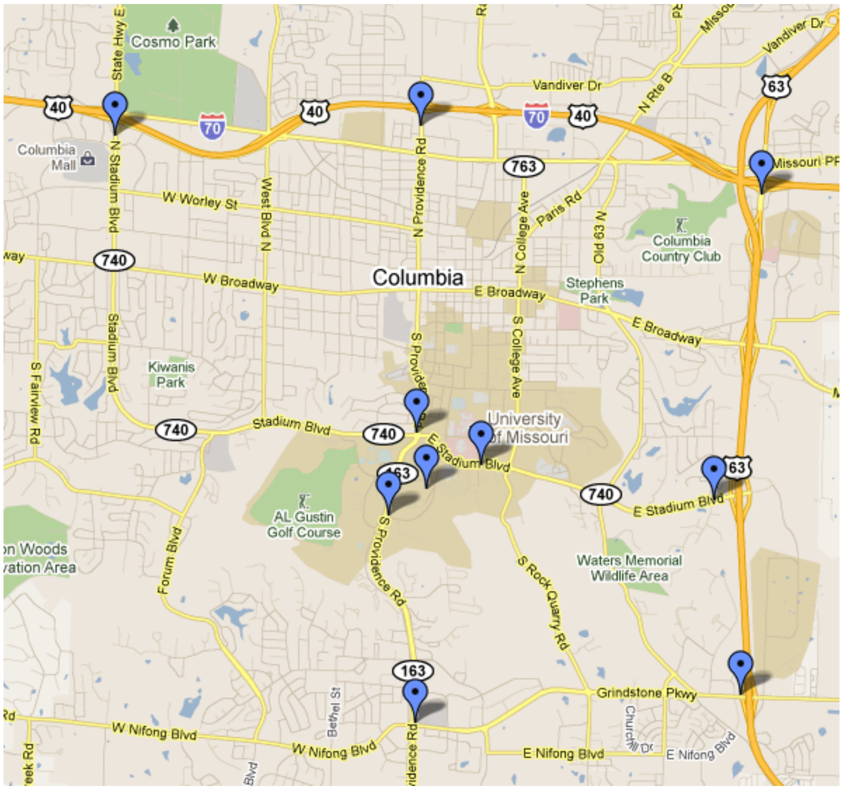

FIGURE 22
Location of Bluetooth Data Loggers in Columbia, Missouri

Based on the recommendations of the City of Columbia, Missouri traffic engineer, a detailed photographic log was created and distributed to state, country, city, and university law enforcement and to university facility operations staff. This log was created so that critical personal 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 to 8, 2011) for a total of 144 hours of data per unit. Collectively, approximately 1,440 hours of data were collected in total in the study area.

7.3.2 Validation Data

In order to have a complete dataset useful for generating and extrapolating origin-destination patterns, a secondary data source was needed to positively identify and re-identify vehicles so that both travel time and origin-destination patterns could be derived. This was accomplished by the use of video cameras placed at the end points of the three primary routes shown in Figure 23.

FIGURE 23
Video Cameras Set up East of the Intersection of Providence Road and Stadium Boulevard in Columbia, MO

Due to logistical constraints and the enormous effort required for data reduction, 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 arena.

7.4 Analysis

Data from the Bluetooth data loggers and video validation data were then 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 then processed to match vehicles at an upstream and downstream location together. This was accomplished by manually reducing the videos for surges and drop offs in peak traffic flow surrounding the basketball game. Once time windows were set as shown in Table 11, vehicles were cataloged at the beginning and end of each segment, then paired together to create trips and travel times as shown in Figure 24 and Table 12.

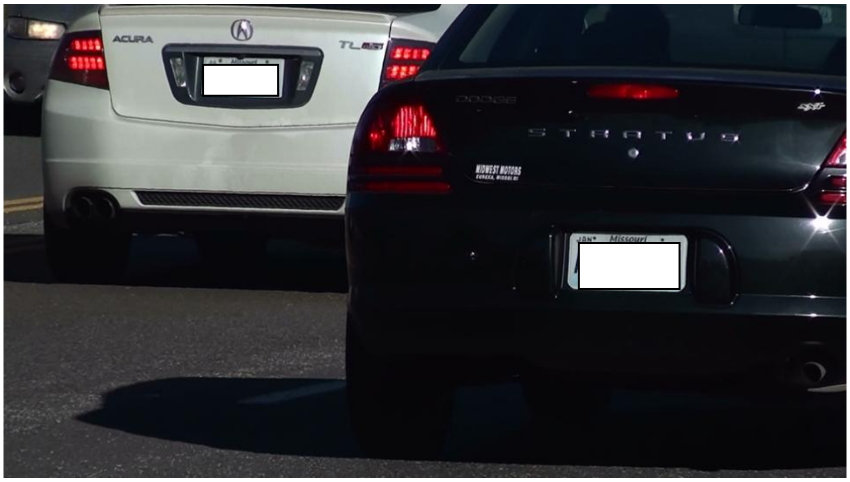

FIGURE 24
Example Still Frame of Video Re-Identification Footage (License Plates Redacted)

TABLE 11
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)	1,120	1,233	895	991	1,100

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*

Using the eight time periods from Table 11, data values for number of vehicles, Bluetooth penetration rates, and origin-destination percentage were extracted and calculated for both of the methods. A two sample t-test with 95 percent confidence was used to test the null hypothesis. In all cases where the test was possible, the first null hypothesis (H_{o1}) was not rejected as shown in Table 13.

TABLE 13
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	-	-	-	-	-

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, traffic on adjacent driveways, bicyclists and pedestrians, 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 14.

TABLE 14
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

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 was created as shown in Table 15.

TABLE 15
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%**

Combining Table 14 with the first six columns of Table 15, a percentage of all trips that follow through to each destination could be estimated. It was also found that the data averaged a 6 percent Bluetooth penetration rate as shown in Table 14. This was found to be a realistic result comparing to the validation data shown in Table 13. An extrapolated estimated origin-destination trip matrix was created by dividing each of the cells in Table 15 by the average penetration rate of 6 percent to develop Table 16. When the daily totals were broken down into proportions by destination, the result was Figure 25 which shows the estimated trip distribution based on the Bluetooth data.

TABLE 16
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**	

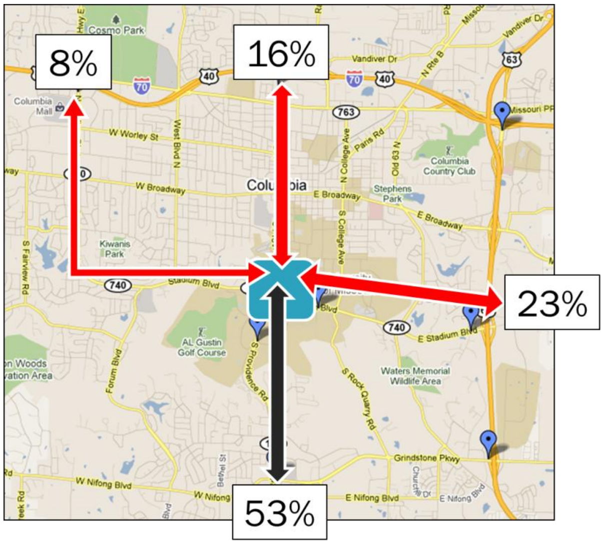

FIGURE 25
Destination Percentages for Through Trips Originating from the Intersection of Providence Road and Stadium Boulevard Estimated Using Bluetooth Data

The field data were used to validate the Bluetooth logger data. Focusing on the comparable segment in Table 13, “Providence (Stadium to I-70),” a weighted average of the video based origin-destination percentage resulted in 23 percent. This indicates that 23 percent of all traffic cataloged as originating from the intersection headed in the general direction of I-70 actually completed the study route. Unfortunately a direct comparison to Bluetooth data were not possible, as the data logger located at the Providence Road and Stadium Boulevard Intersection was not able to distinguish a direction of travel. This could only be accomplished if the data were paired to downstream data. Thus the corresponding Bluetooth data would be the “Percent of All Trips” column from Table 15.

The use of these data as a comparison to the validation data set required the assumption 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 level of confidence resulted that the null hypothesis could not be rejected (p-value = 0.065).

7.5 Findings and Discussion

The use of Bluetooth technology for estimating origin-destination relationships was shown through independent validation data 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 to obtain than actual travel pattern data. Due to the electronically recorded MAC addresses in the Bluetooth data, it eliminated the tedious processing effort required to catalog license plates and vehicle descriptions required for extracting the origin-destination data from the video. 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 using other methods, 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. The overall results of the travel time analysis are shown in Figure 26.

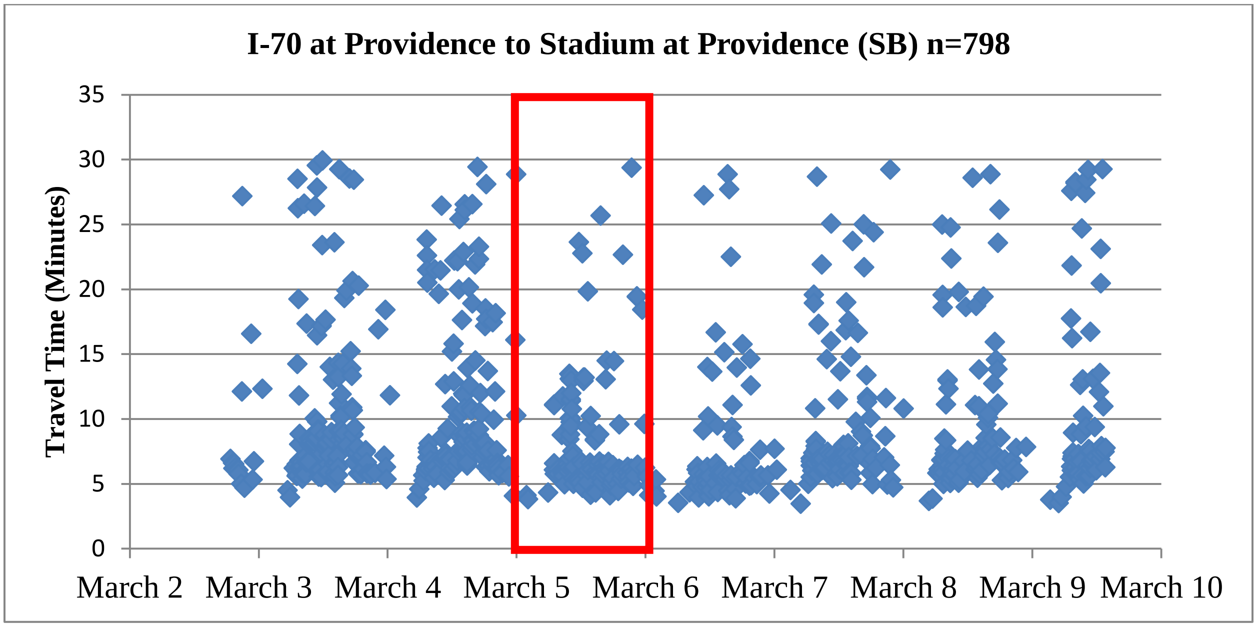

FIGURE 26
Bluetooth-Based Travel Time Fluctuations Including Outliers, with Game Day Traffic Emphasized

As shown in Figure 26, if the dates were remove 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 it to a typical day as shown in Figure 27. The only indication a difference existed was that the Tuesday traffic had more travel time outliers.

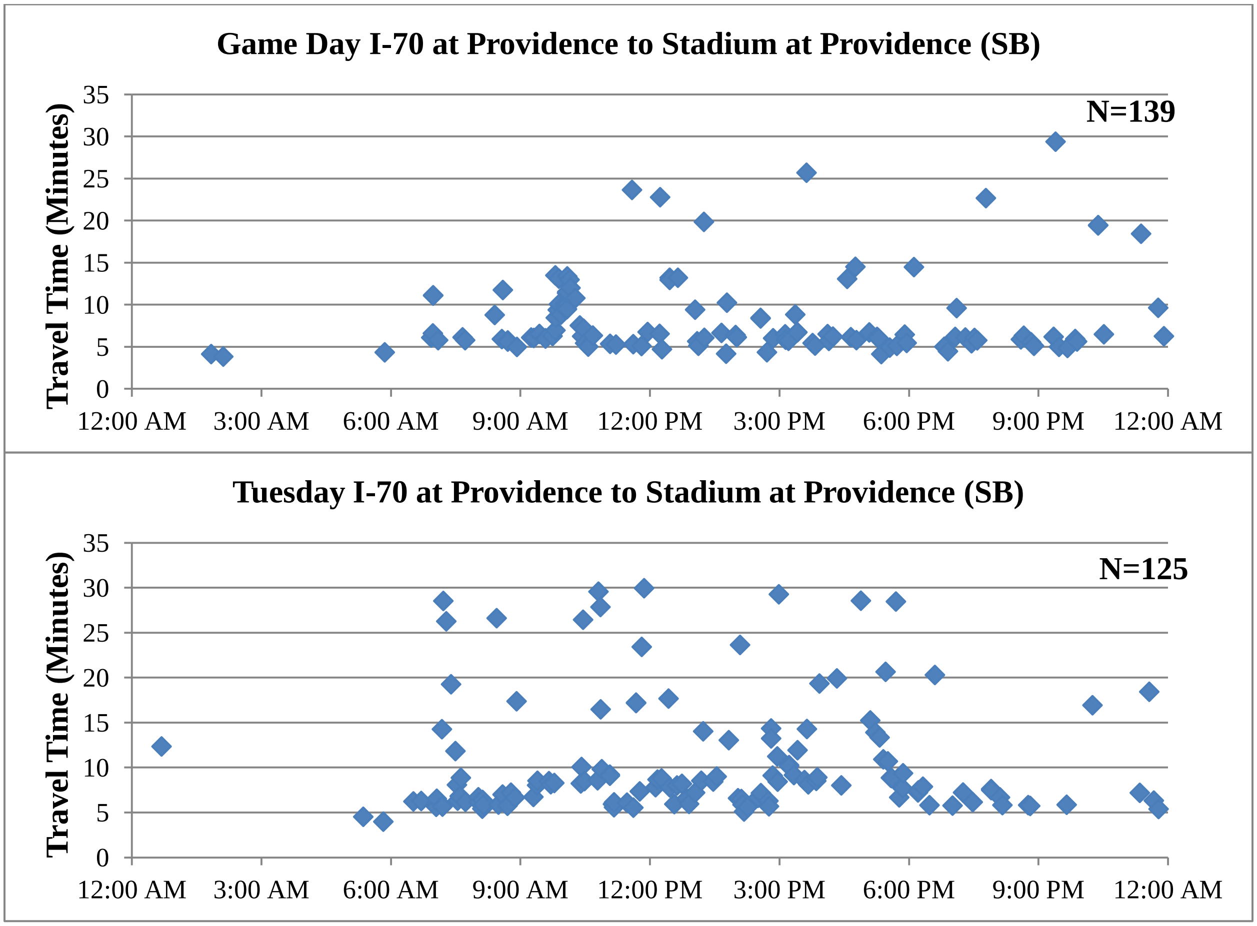

FIGURE 27
Detailed Travel Time Comparisons between Game Day and a Typical Day

It is important to understand that the estimated trips were for through travel between each origin and destination. As shown in Table 15, 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 16 were only valid for complete trips along each segment.

The Bluetooth data also presented the research team with additional possible analyses. One such possibility would be the separate identification of local traffic and visiting traffic. In the case of the basketball game, evaluation of the MAC addresses that formed Table 14 and tallying how many unique MAC address were only recorded on game day that never appeared again in the other five days of day. 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 (approximately 39 percent) only appeared in the data for a single day. The day with the most unique Bluetooth MAC addresses as shown in Table 17 recorded at the intersection was March 5, 2011 (basketball game day).

TABLE 17
Daily Distributions 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%**

Chapter 8: Roundabout Turning Movement Estimation

8.1 Research Objective

An understanding of how motorists utilize an intersection is fundamental for engineers and planners to best manage vehicular operations. Traditional intersections (signalized or all way stop control) 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. For example, four vehicles that simultaneously approach from different directions could all enter at the same time and proceed to make any combination of turning movements. This path overlap has created a challenge for traditional vehicle counting methodologies. Engineers have turned to either sophisticated video detection system, or more labor-intensive manual observation counting.

One common mathematical solution for counting traffic at roundabouts is known as an algebraic solution. This solution, as published by the Federal Highway Administration (FHWA), includes a series of simultaneous equations that can be solved for turning movements using matrix algebra (Robinson et al., 2000). However for this methodology to be utilized the following assumptions are made:

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

Illustrated in Figure 28 is typical turning movement label system for a single-lane roundabout.

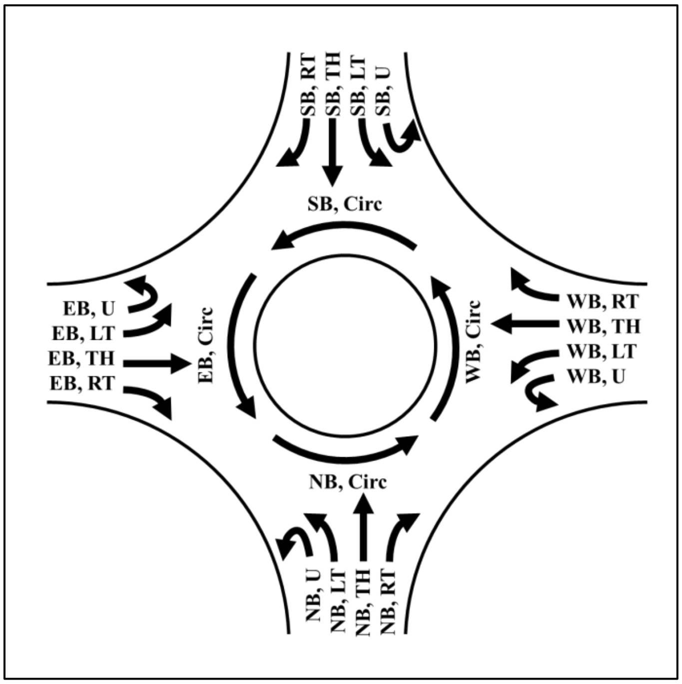

FIGURE 28
Roundabout Turning Movement Diagram
(Robinson et al., 2000)

Each specific turning movement may be calculated by adding and subtracting various turning movement volumes. As shown in Equation 1, the turning movement volume for the eastbound through movement is calculated.

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

Equation 1

Where:

- $V_{EB,TH}$ is the eastbound through movement volume;
- $V_{EB,Entry}$ is the eastbound entry volume;
- $V_{WB,Exit}$ is the westbound exit volume;
- $V_{EB,RT}$ is the eastbound right turning volume;
- $V_{NB,TH}$ is the northbound through movement volume; and
- $V_{NB,Circ}$ is the northbound circulating volume.

However, when the number of legs at a roundabout exceeds four, the resulting matrix becomes indeterminate and requires additional vehicular turning movement data. 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 data collection and reduction approach using video data and a processing algorithm was researched by Rescot (2007). While Rescot showed in his research that one could obtain 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). 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.

Solving the roundabout turning movement dilemma as explained previously are several underlying philosophies. First, to recognize that due to normal fluctuations in traffic, day by day, and month to month there are diminishing rates of return for increasing the counting accuracy. A vehicular 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 is a recognized that estimating turning movements at a roundabout is really a much smaller origin-destination study with each leg of the intersection both an origin and a destination for every other leg. Furthermore, 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

8.2 Work Plan

Two sites in Kansas were selected for this research study. One was an urban four-legged roundabout located in Lawrence, Kansas on a principal collector road. The second was a rural five-legged roundabout located near the city of Paola, Kansas in unincorporated Miami County on a state highway. Illustrated in Figures 29 and 30 are aerial views of the selected roundabout locations.

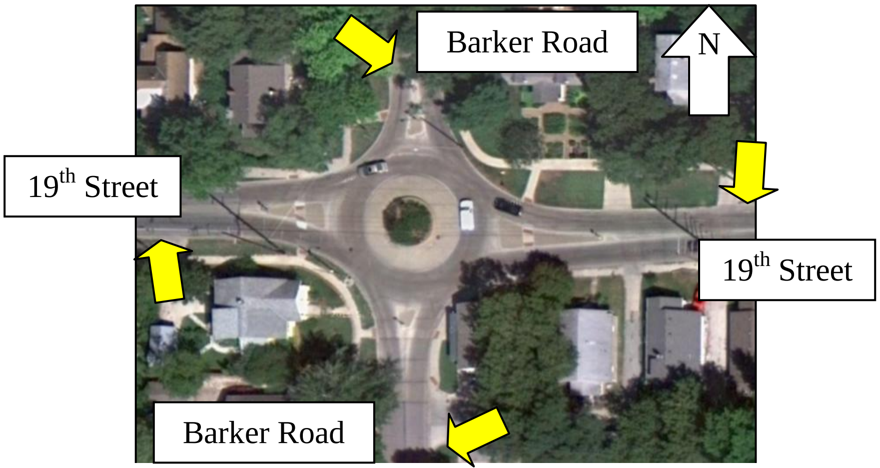

FIGURE 29
Lawrence, Kansas, Roundabout Showing Bluetooth Data Logger Placements (Google, 2011)

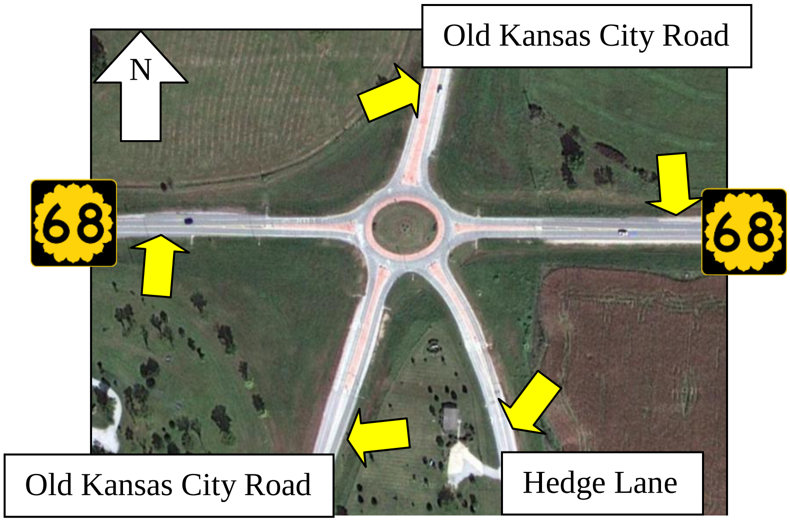

FIGURE 30
Paola, Kansas, Roundabout Showing Bluetooth Data Logger Placements (Google, 2011)

For each roundabout location, 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 manually counted each turning movement, along with collecting video data for verification purposes.

8.3 Field Data Collection

Data were collected at each location using two methods including Bluetooth data and manually. The choice of which antenna to use was based on location specific factors based on equipment testing previously described, a standard antenna was utilized at the Paola location and the stub antenna was used at the Lawrence site. The stub antenna at the Lawrence site was selected due to the closer proximity of the sensors to one another. There was also a concern that if a more powerful antenna was to be used, traffic arriving on legs other than the one adjacent to the Bluetooth data collection unit might be inadvertently be detected and give false-positive readings.

Manual data collection occurred over several days including 8.3 hours at the Paola site, and 16 hours at the Lawrence site for a total of 24.3 hours. Since the Bluetooth data loggers could be left running from deployment to retrieval, there were a total of 99 hours of Bluetooth data for the Paola roundabout and 51 hours for the Lawrence roundabout. During all manual data collection times, a team of two research assistants were on-site to divide the counting duties to minimize 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) as shown in Figure 30. Turning movement vehicle count and distributions for each leg of both roundabout study locations are shown in Tables 18 through 21.

TABLE 18
Paola, Kansas, Roundabout Data Summary

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

(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

(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

(C)

TABLE 19
Lawrence, Kansas, Roundabout Data Summary

	Manual Count Data	Departure Leg				
		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)

	Study Period Bluetooth Data	Departure Leg				
		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)

	Study Period % Bluetooth Data	Departure Leg				
		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 20
Paola, Kansas, Roundabout Turning Movement Distributions

Distribution of Manual Count Data		Departure Leg				
		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)

Distribution of Bluetooth Data		Departure Leg				
		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 21
Lawrence, Kansas, Roundabout Turning Movement Distributions

Distribution of Manual Count Data		Departure Leg			
		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)

Distribution of Bluetooth Data		Departure Leg			
		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)

8.4 Analysis

The Bluetooth data captured by the technique described was 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 penetration rate of 6 percent while the Lawrence, Kansas roundabout had a Bluetooth penetration rate of 8 percent.

Both study sites data sets indicated that the distributions by percentage of traffic in the manual count data compared to the Bluetooth data shown in Tables 20 and 21 were similar. This was important because any differences in distributions may be reflected in the final output. As shown in Table 22, it was apparent that the Bluetooth data continued to regress towards the known manually counted distribution shown in Table 20.

TABLE 22
Distribution of Paola, Kansas, Bluetooth Roundabout Turning Movements over 99 Hours

	Distribution of Bluetooth Data	South Old KC Road	West K-68	North Old KC Road	East K-68	Hedge Lane
		Departure Leg				
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

TABLE 23
Distribution of Lawrence, Kansas Roundabout Turning Movements over 51 Hours

	All Bluetooth Data Ratio	South Barker Street	West 19th Street	North Barker Street	East 19th Street
		Departure Leg			
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

F-tests for equal variations were performed to test for changes in the overall variation of the turning movement distributions shown in Tables 22 and 23. The null hypothesis was that the variation between the manual collected data and the Bluetooth collected data was not statistically different for the Paola roundabout study site. The results of the analysis indicated that the null hypothesis could not be rejected at the 95 percent level of confidence (p-value 0.924). However, a similar statistical test for the Lawrence roundabout site found enough evidence to reject the null hypothesis (p-value <0.001).

Upon further analysis of the data, the east-west directionality of the Lawrence roundabout 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.

8.5 Findings and Discussion

For this study, two roundabout sites were selected for analysis. Bluetooth loggers were used to capture vehicle turning movements and then compared to manual counts using statistical tests. One identified limitation of using Bluetooth loggers at a roundabout was 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 detection that was 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 adjacent to 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 a significant number of U-turns were identified at a roundabout, data loggers would need to be placed beyond the length of any roundabout approach queues. At both the Lawrence and Paola, Kansas test locations, queues were observed to extend past the locations where the data loggers were placed. Additional future research 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 was 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 was demonstrated at the Paola study location by means of using an F-test to test the data and not being able to reject the null hypothesis. The Lawrence study location analysis showed eastbound and westbound through movements were combined to form 65 percent of the manually counted traffic volume, while the Bluetooth data for the same movements represented 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 and also the antennas chosen for each location, it was not possible to concretely determine a reason for this observed disparity.

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. However, as the two study locations ended with opposite results, it remained unclear what additional criteria would be needed to minimize the likelihood that the null hypothesis would not be rejected in a future study unless more study sites were added. Given the potential ability to automate such a study, and the time saving proposition that it would be compared to traditional techniques, it was found that using Bluetooth loggers in this context would be viable for future data collection considerations.

Chapter 9: Truck Tracking Study across Kansas

9.1 Background

Engineers at KDOT have reason to believe that long-range freight movements from the Kansas City area to areas of the Southwestern United States (e.g., Albuquerque, New Mexico; Amarillo, Texas) were not following the Interstate Routes as expected (I-35 to I-40) but instead were traveling southwest across Kansas along a I-35/US-54 path to Liberal, Kansas. This study was an effort to determine if the Bluetooth data collection systems could determine if trucks were indeed taking this path, and if so, could the system estimate the magnitude of this freight movement.

It was expected that the system used would be able to track Bluetooth devices that moved in either direction between Liberal and Emporia, both as a total as well as a percentage of total traffic. While it was not expected that this relatively short-term study would provide a complete picture into the presence or absence of such freight movements, it was expected to prove the utility of using Bluetooth data loggers to answer practical questions about long-term movements across Kansas.

9.2 Data Collection

Vehicle data were collected along Kansas highways between August 29, 2011 to September 11, 2011 for approximately 320 hours using both pneumatic road tubes and Bluetooth data loggers. Data were collected at 10 locations in Kansas as illustrated by “A” through “J” as shown in Figure 31.

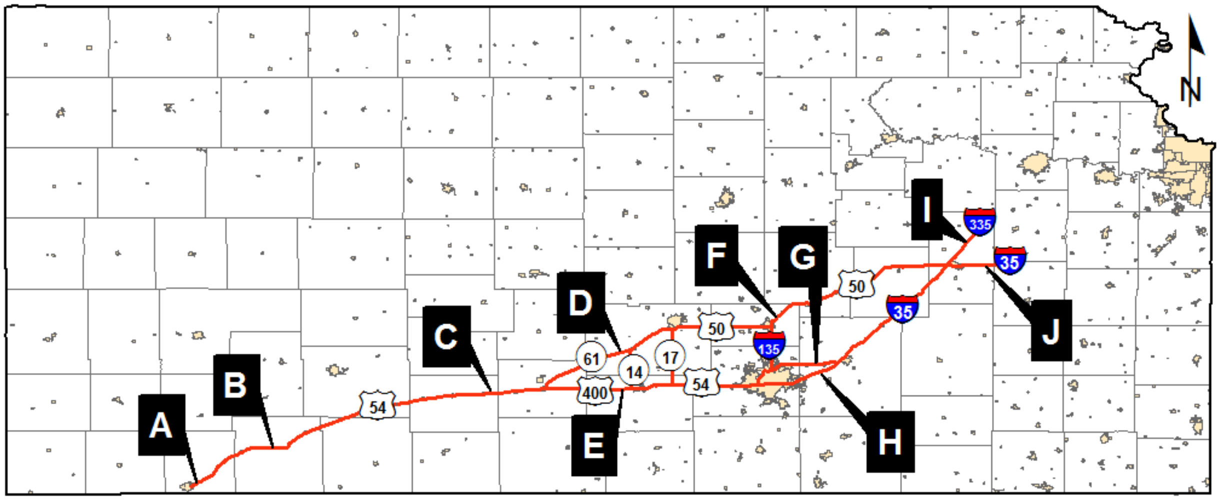

FIGURE 31
Locations of Data Collection within Kansas

The locations selected for this study were meant to provide coverage of the most expected routes from Liberal to Kansas City. In order to make maximum use of the ten units used in this study, the units were concentrated from Liberal to Emporia. Because there were several routes that truck drivers could take around Wichita, Bluetooth data loggers were concentrated around the Wichita area. Data collection locations were also placed near permanent automated traffic recording devices (ADT) so average annual daily traffic (AADT) could be used in the analysis.

In order to isolate truck observations and determine travel time across the state of Kansas using various routes, multiple steps were employed to clean and sort collected data including two and four lane roadways with posted speed limits between 55 and 75 mph. Location “A” as illustrated in Figure 31 was considered the point of entry and exit into and out of Kansas and pneumatic road tubes were installed only at this location along with a Bluetooth data logger. This area was located outside of the city of Liberal, Kansas near a heavy industrial area to potentially capture a high percentage of heavy vehicles. The equipment setup at this location is shown in Figure 32.

FIGURE 32
Pneumatic Road Tubes and Bluetooth Data Logger at Location "A"

Data from the pneumatic road tubes at location "A" were downloaded as basic data which included information for individual vehicle observations. Information for each vehicle observation included date, time, travel lane, number of axles, vehicle class (based of 14 possible classes), wheelbase length, speed, gap time and following time.

Similarly, the Bluetooth data logger provided the date, time, and number of hits and MAC id. The data logger records data for the same set of vehicle observations in which a Bluetooth enabled devices is activated when it passed the data collection point. Prior to deploying data collection devices in the field, the research team ensured the data loggers were working properly and internal clocks were synchronized between each device type. Equipment was deployed in the field and chained to a rigid object or structure (e.g. roadway signpost or fence) to ensure no vandalism occurred while data were being collected.

9.3 Data Reduction

Data were downloaded from the pneumatic road tube counter using Jamar Trax Pro software. The software uses time-stamped data to output operational variables. The overall data set were found to have less than a 10 percent error which indicates a valid data collection effort. Vehicle observations were sorted into three groups. This included passenger cars, trucks and unknown classification. Passenger car classification consisted of motorcycles, sedans, pickup trucks, vans and vehicles towing a small trailer. The truck classification consisted of two to multi-axle heavy vehicles. The classification "unknown" is an identified mechanical error or an unknown vehicle type as determined by the software based of the time-stamp data. Shown in Table 24 is a summary of the vehicle data collected at location "A" by the pneumatic road tubes.

TABLE 24
Pneumatic Tube Output for Location "A"

Total Observations	61,946 (100%)	
	Eastbound	**Westbound**
Total Observations	31,282 (50.4%)	30,664 (49.6%)
Passenger Cars	18,365	15,692
Trucks	11,140	13,908
Unknown Classification	1,777	1,064
85th Percentile Speed	64 mph	66 mph

As shown in Table 24, a balanced number of observations for all vehicle classes were recorded in each direction of travel. Westbound for this study was defined as the direction of travel leaving the State of Kansas towards the southwest. Also shown in Table 24, it was also found that the 85th percentile speed was higher than the posted speed of 55 mph at this location.

As stated previously, a Bluetooth logger was placed at the same location as the pneumatic road tubes. A total of 4,951 observations were captured by the Bluetooth data logger which was roughly 7.9 percent of the pneumatic road tube observations. It is speculated that the decrease in vehicle observations were due to a number of possible reasons. The research team believes this number in reality could be higher, but many drivers may elect to turn off the Bluetooth device in their cell/smart phones to conserve power if they do not own a hands free device.

Since the Bluetooth data logger cannot determine direction of travel or vehicle class, the two sets of data at location "A" were merged to identify large vehicles and passenger cars based on the pneumatic road tube data. To determine vehicle class, the time the Bluetooth logger captured a vehicle was compared to the pneumatic road tube time and a vehicle observation match was considered valid if the times were within 4 seconds of each other. Once a vehicle was identified using the two data sets, its class and direction of travel was determined using the pneumatic road tube data output. A summary of the analysis is shown in Table 25.

TABLE 25
Bluetooth Data Logger Vehicle Identification Based on the Pneumatic Road Tube Data

Total Pneumatic Road Tube Observations	61,949 *(100%)*	
Total Bluetooth data logger	4,951 *(7.9%)*	
Total Vehicle Identified	**1,629** ***(2.6%)***	
	Eastbound	**Westbound**
Total Observations	803	826
Passenger Cars	493	414
Trucks	289	399
Unknown Classification	21	13

As shown in Table 25, 2.6 percent of the total possible numbers of vehicles were identified based on the time stamp data from each device. Additionally, the numbers of vehicles identified in both directions of travel were balanced similar to the vehicle observations shown in Table 25. The research team speculated that the decrease in the number of identified vehicle observations could be from a mechanical error to the Bluetooth data logger detecting multiple Bluetooth devices or detecting Bluetooth devices not on the highway (e.g. minor roadway or adjacent parking lot). Once a passenger car and truck dataset were established at location “A” for both directions of travel, a further analysis was performed using multiple devices as explained in the following sections.

9.4 Statewide Analysis

9.4.1 Vehicle Travel Time and Speed Analysis

Each Bluetooth data logger shown in Figure 32 was equipped with a Global Positioning System (GPS) chip that allows the software program to determine the shortest path distance between each of the counters. Shown in Figure 33 is how the research team analyzed the data across the state of Kansas with location "A" located furthest west.

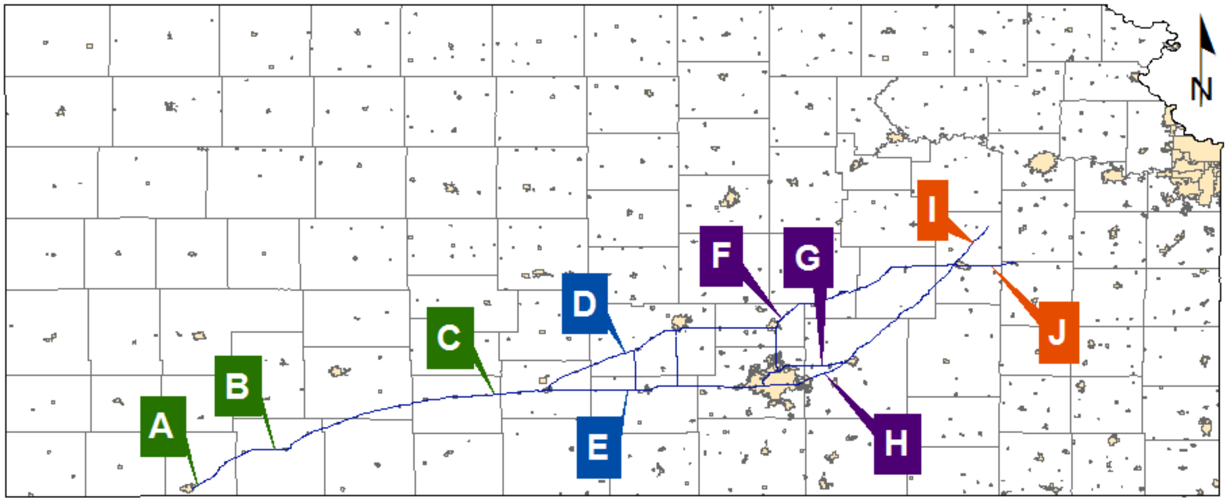

FIGURE 33
Analysis at Each Location

As shown in Figure 33, the data collections labeled in green are along a single route which was a two-lane highway. Locations in blue and purple are located on various state and federal highways and provide numerous routes a driver could take to get to the data collection locations in orange. The distance from location "A" to location "I" (furthest distance) was found to be approximately 287 miles.

It should be noted that at locations "B" and "H" the Bluetooth data loggers experienced a mechanical failure and no data were collected at these locations. The research team found a battery failure in one device and an unknown failure in the other device. For this analysis, median travel time and speed were determined between location "A" and each of the subsequent locations in Figure 33. The Bluetooth data logger software identified repeating MAC id's between locations shown in Figure 33 and outputted information for these identified vehicles. Since a dataset was created earlier that identified trucks, passenger cars, and unknown vehicle classification, the outputted values by the software were compared against this database. If a vehicle was found by the software and also identified in the vehicle database, the vehicle was extrapolated for a summary analysis.

For the summary analysis, the median travel time was used to determine median speed. Using the median value of the data distribution accounted for outliers. Outliers for this study may have occurred if a vehicle stopped for extended period of time at one location instead of driving straight through the state of Kansas. Table 26 summarizes travel time, distance between data collection locations, and median speed for eastbound trucks from location "A".

TABLE 26
Eastbound Truck Analysis from Location "A"

Location	Trucks Identified	AADT	Median Travel Time from 'A' (min.)	Distance From 'A' (Miles)	Median Speed from 'A'(mph)
A	289	1,550	0	0	0
B	0[a]	1,460	-	-	-
C	43	1,730	114.9	105.5	55.1
D	11	730	175.6	154.8	52.9
E	35	980	167.1	152.4	54.7
F	14	1,630	259.8	210.2	48.5
G	4	1,180	239.9	210.8	52.7
H	0[a]	2,460	-	-	-
I	0	1,150	-	276.5	-
J	20	4,110	366.5	287.0	47.0

[a] Data logger mechanical failure identified

As shown in Table 26, 289 trucks were identified in the dataset as traveling eastbound. As expected the number of trucks decreased as data were collected further away from location "A." Average annual daily traffic (AADT) counts were based on the Kansas Department of Transportation's traffic count map. Shown in Table 27 is the same information as Table 26, however for passenger cars only.

TABLE 27
Eastbound Passenger Car Analysis from Location "A"

Location	Passenger Cars Identified	AADT	Median Travel Time from 'A' (min.)	Distance From 'A' (Miles)	Median Speed from 'A'(mph)
A	493	3,290	0	0	0
B	0[a]	2,710	-	-	-
C	77	3,450	112.8	105.5	56.1
D	26	2,050	165.8	154.8	56.0
E	37	3,930	172.9	152.4	52.9
F	24	4,490	235.4	210.2	53.6
G	0	10,620	-	210.8	-
H	0[a]	11,050	-	-	-
I	0	6,600	-	276.5	-
J	36	9,320	359.2	287.0	47.9

[a] Data logger mechanical failure identified

As shown in Table 27, similar results were found for passenger cars compared to trucks which indicate a similar percentage of vehicle mix follow similar routes across the state of Kansas. It was also found that both the median travel time and speed were lower for passenger cars than expected since cars will generally travel at a faster speed as compared to trucks.

A similar study was conducted for vehicles traveling westbound out of the State of Kansas. However, unlike the study conducted for eastbound traffic, pneumatic road tubes were unavailable at locations "I" and "J". For this analysis, data from each Bluetooth data logger were compared to location "A" where eastbound and westbound vehicle Bluetooth MAC id's were available. Shown in Table 28 are the results of westbound truck traffic.

TABLE 28
Westbound Truck Analysis to Location "A"

Location	Trucks Identified	AADT	Median Travel Time to 'A' (min.)	Distance to 'A' (Miles)	Median Speed to 'A' (mph)
A	398	1,550	0	0	0
B	0[a]	1,460	-	-	-
C	56	1,730	114.8	105.5	55.1
D	20	730	180.1	154.8	51.6
E	29	980	171.8	152.4	53.2
F	16	1,630	250.7	210.2	50.3
G	0	1,180	-	210.8	-
H	0[a]	2,460	-	-	-
I	0	1,150	-	276.5	-
J	8	4,110	560.9	287.0	30.7

[a] Data logger Mechanical Failure Identified

As shown in Table 28, only eight vehicles from location "J" were found to travel to location "A". It can also be seen that as data collection moved towards location "A", the number of trucks identified increased. This is also similar to the results indicated in Table 26. Finally, it was also found the median speed westbound was slightly higher than the median speeds between data collection locations for trucks traveling eastbound. A similar analysis was performed for westbound passenger cars shown in Table 29.

TABLE 29
Westbound Passenger Car Analysis to Location "A"

Location	Passenger Cars Identified	AADT	Median Travel Time to 'A' (min.)	Distance to 'A' (Miles)	Median Speed to 'A' (mph)
A	414	3,290	0	0	0
B	0[a]	2,710	-	-	-
C	47	3,450	116.7	105.5	54.2
D	20	2,050	171.4	154.8	54.2
E	29	3,930	173.7	152.4	52.6
F	15	4,490	245.5	210.2	51.4
G	0	10,620	-	210.8	-
H	0[a]	11,050	-	-	-
I	0	6,600	-	276.5	-
J	3	9,320	367.2	287.0	46.9

[a] Data logger Mechanical Failure Identified

As shown in Table 29, similar results were found as in Table 27 with passenger car median speeds being higher than truck median speed. It was also found that only three passenger cars traversed the entire length of the study section. It was also found that similar to all previous tables, the number of vehicles identified increased and data collection was captured closer to location “A”.

9.4.2 Bluetooth Device Analysis

In addition to investigating how well the Bluetooth data loggers performed at capturing travel time between data collection stations, the research team was also interested in determining what kind of Bluetooth devices truck drivers were using. As stated previously, the Bluetooth data loggers determined vehicle presence by a Bluetooth signal and recorded a searchable MAC id. Current websites allow inputted MAC addresses to determine such information as whether the Bluetooth chip was part of in-vehicle global positioning system, cell/smart phone, or fleet/logistics system.

The research team inputted the database of 907 truck MAC ids into a public MAC id search website which provided the manufacturer company of the Bluetooth device. Shown in Table 30 are the most common Bluetooth devices detected in the eastbound direction based on the MAC id search.

TABLE 30
Eastbound Top 10 Truck Bluetooth Devices Detected

Company	Description of Device Observed	Number Observed	Percent of Total Observations
Garmin	Global Positioning Unit	80	27.5%
Samsung	Smartphone / Cellular Technology	60	20.8%
Research in Motion	Blackberry Device	31	10.7%
Nokia Danmark	Smartphone / Cellular Technology	20	6.9%
Imarda Incorporated	Fleet Tracking & Telematics	17	5.9%
LG Electronics	Smartphone / Cellular Technology	14	4.8%
Parrot	Vehicle Hands-Free Music / Mobile Web Device	13	4.5%
Pantech	Hands-Free Bluetooth Headsets	11	3.8%
Alps Electric	Vehicle Audio / Visual Equipment	7	2.4%
Kyocera Corporation	Smartphone / Cellular Technology	7	2.4%

As shown in Table 30, Garmin in-vehicle global positioning systems were the most widely detected devices with 27.5 percent of the total number of Bluetooth devices detected. Cellular and smart phone manufacturers, fleet tracking/telematics, along with in-vehicle entertainments systems were also in the top 10. Similar results were also found for trucks traveling west bound as shown in Table 31.

TABLE 31
Westbound Top 10 Truck Bluetooth Devices Detected

Company	Description of Device Observed	Number Observed	Percent of Total Observations
Garmin	Global Positioning Unit	115	28.9%
Samsung	Smartphone / Cellular Technology	82	20.6%
Imarda Incorporated	Fleet Tracking & Telematics	29	7.3%
Research in Motion	Blackberry Device	26	7.0%
LG Electronics	Smartphone / Cellular Technology	26	6.5%
Nokia Danmark	Smartphone / Cellular Technology	20	5.0%
Parrot	Vehicle Hands-Free Music / Mobile Web Device	15	3.8%
Pantech	Hands-Free Bluetooth Headsets	13	3.3%
Kyocera Corporation	Smartphone / Cellular Technology	12	3.0%
Apple Inc.	iPhone / iPod	8	2.0%

As shown in Table 31, similar results were also found for trucks traveling westbound with Garmin global positioning systems accounting for 28.9 percent of the total number of Bluetooth devices detected. Similar to Table 30, cellular and smart phones accounted for a high percentage of devices detected.

9.5 Significant Findings

This research study was intended to be a proof-of-concept study to demonstrate how Bluetooth loggers can be used to track a certain type of vehicle class across long distances. The results of the study indicated that a truck can be tracked across Kansas. However due a large number of possible routes between the two furthest data collection points, it was found very few trucks were detected. Additionally, it was speculated that many trucks that entered the state of Kansas terminated at one of the larger cities within the data collection area. It was also found that matching Bluetooth data logger with pneumatic road tube data was complicated by not knowing if the Bluetooth data logger clock was in sync with the road tube counter clock.

It was also found through the Bluetooth MAC id search, that personal GPS systems were the predominate device detected by the logger. Furthermore, this research showed to be a viable way to collect data, however to investigate what percentage of trucks travel across the state of Kansas, and which routes they take, a significant amount of data beyond what was collected in this study would be needed.

Chapter 10: Discussion and Conclusions

Consistently shown in this research, Bluetooth-based traffic data collection has shown itself to be not only possible, but that it can provide statistically reliable data for traffic studies and subsequent data analyses.

This research effort resulted in the following significant conclusions.

1. In the antenna detection area and reliability study, the null hypothesis H_{o5}, was not rejected, indicating that there is a significant difference based on the placement of the Bluetooth device inside the vehicle. 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. (2011) in the literature.

2. In the urban corridor travel time study, a statistically significant difference in travel times was observed, indicating that the Bluetooth data were more often slower than the GPS data.

Taken together, there may be a concern that a small bias may be present in the Bluetooth data. A literature search indicated researchers Dressel and Atchley (2008) found vehicle travel speeds for drivers simultaneously using a cell phone and driving resulted in slower travel speeds with greater variability than drivers focused solely on driving. Dressel and Atchley's finding - coupled with the findings of this research could imply that the Bluetooth data might be biased toward distracted drivers in the following manner: drivers actually using their phones may be holding them higher in the vehicle (resulting in a higher likelihood of detection) and may be driving more slowly (as found in the urban corridor travel time study). The practical significance of this remains an open question, as the magnitude of the bias may not change the outcome of a KDOT planning study. However, it is hoped that future research in both wireless technologies and human factors will help researchers better understand this potential phenomenon.

3. Finally, the research team investigated the use of Bluetooth loggers as a way to determine truck routing through the State of Kansas. Trucks were identified using pneumatic road tube time-stamp data matched with Bluetooth logger data using a synchronized clock. This study showed promise in detecting and tracking truck traffic and determining significant routes and overall travel time. However, it was found that only a limited number of trucks were detected that traveled the entire study route; indicating that a significantly longer data collection study is needed to construct a meaningful travel time distribution.

The research team recognized that when Bluetooth-based counting is desired, the following assumptions are needed.

- Even though a portion of the traffic will actually have a Bluetooth device, all traffic is equally likely to be equipped with discoverable Bluetooth signal from one or more devices. Specifically, it is assumed that there is no bias in Bluetooth presence based on vehicle classification.
- Bluetooth equipped traffic makes turning movements in an equal proportion to the rest of traffic.
- A minimal number of vehicles containing multiple Bluetooth sources, and the distribution of multi-source vehicles are in proportion to the rest of traffic.
- 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 bus route, and
- along a sidewalk on a college campus.

It was also found in this study that a Bluetooth data logger's detection area must be appropriately sized and placed. The overall size of the clouds (section 4.1 of this report) 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, it can create substantial errors that undermine the process. Thus the selection of a proper antenna and mounting location becomes a controllable variable that can be varied as needed based on site conditions and study objectives. If not considered this potential error could have detrimental consequences of data contamination.

For example, if the data collection protocol was intended 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 Bluetooth logger 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 sample size.

As seen in the urban freeway study, urban corridor study, and state truck travel time studies, the availability of data was not consistent or assured. Bluetooth has shown itself to be most functionally useful where data can be aggregated together over considerably long periods of time, at least when traffic volumes are lower. 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. While higher volume roadways theoretically reduce this possibility, it still does not erase it as a factor. This is even more important for off-peak late night hours or if the study targets a certain vehicle class. This reinforces the importance of allowing for long data collection times when planning a data collection effort.

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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: INTERVAL 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**
7:00-8:30a.m.	4	0.35	4.42	5	0.52	3.83	No	0.081
9:00-11:00a.m.	7	0.63	4.15	8	0.72	4.76	No	0.102
12:00-1:00p.m.	10	2.06	6.07	0	-	-	-	-
2:00-3:00p.m.	7	0.37	4.52	0	-	-	-	-
4:00-6:00p.m.	18	1.50	5.57	11	3.57	7.57	No	0.089
7:00-9:00p.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**
7:00-8:30a.m.	4	0.57	4.12	6	0.76	3.81	No	0.478
9:00-11:00a.m.	10	1.37	4.68	10	0.79	4.22	No	0.371
12:00-1:00p.m.	16	1.23	4.86	9	1.07	4.77	No	0.858
2:00-3:00p.m.	11	0.75	4.82	16	1.65	4.55	No	0.572
4:00-6:00p.m.	42	1.09	5.51	40	1.28	5.31	No	0.451
7:00-9:00p.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**
7:00-8:30a.m.	12	0.69	3.47	9	0.75	3.45	No	0.950
9:00-11:00a.m.	22	0.71	3.76	29	0.50	3.35	Yes	0.023
12:00-1:00p.m.	18	2.56	5.43	10	0.67	3.69	Yes	0.011
2:00-3:00p.m.	14	1.92	4.44	9	1.33	4.04	No	0.566
4:00-6:00p.m.	45	1.69	5.12	40	1.37	4.47	No	0.054
7:00-9:00p.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**
7:00-8:30a.m.	17	0.76	3.37	14	0.51	3.01	No	0.127
9:00-11:00a.m.	20	0.73	3.47	22	5.76	6.51	Yes	0.019
12:00-1:00p.m.	31	0.54	3.50	18	0.97	3.39	No	0.677
2:00-3:00p.m.	20	1.84	4.41	17	4.33	4.50	No	0.942
4:00-6:00p.m.	58	1.02	4.35	68	0.88	3.48	Yes	<0.001
7:00-9:00p.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**
7:00-8:30a.m.	49	0.43	0.84	38	0.36	0.63	Yes	0.016
9:00-11:00a.m.	112	0.75	0.97	96	0.40	0.72	Yes	0.003
12:00-1:00p.m.	138	0.45	0.92	0	-	-	-	-
2:00-3:00p.m.	138	0.47	0.82	0	-	-	-	-
4:00-6:00p.m.	245	0.53	1.05	63	0.51	0.86	Yes	0.010
7:00-9:00p.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**
7:00-8:30a.m.	64	1.21	0.84	52	0.66	0.88	No	0.831
9:00-11:00a.m.	153	0.78	0.95	133	0.39	0.67	Yes	<0.001
12:00-1:00p.m.	112	0.47	0.89	101	0.44	0.92	No	0.647
2:00-3:00p.m.	129	0.41	0.76	106	0.51	0.96	Yes	0.002
4:00-6:00p.m.	270	0.54	0.92	230	0.65	1.12	Yes	<0.001
7:00-9:00p.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

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

	Before			After				
Hour	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**N**	**Standard Deviation**	**Average Travel Time (Minutes)**	**Significant Difference**	**P-Value**
7:00-8:30a.m.	52	0.26	0.58	52	0.21	0.44	Yes	0.005
9:00-11:00a.m.	104	0.20	0.53	113	0.24	0.47	Yes	0.024
12:00-1:00p.m.	99	0.22	0.52	67	0.31	0.44	No	0.057
2:00-3:00p.m.	79	0.34	0.67	71	0.31	0.53	Yes	0.007
4:00-6:00p.m.	161	0.30	0.58	186	0.53	0.73	Yes	0.002
7:00-9:00p.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 CUMMULATIVE GPS-BASED TRAVEL TIME PLOTS

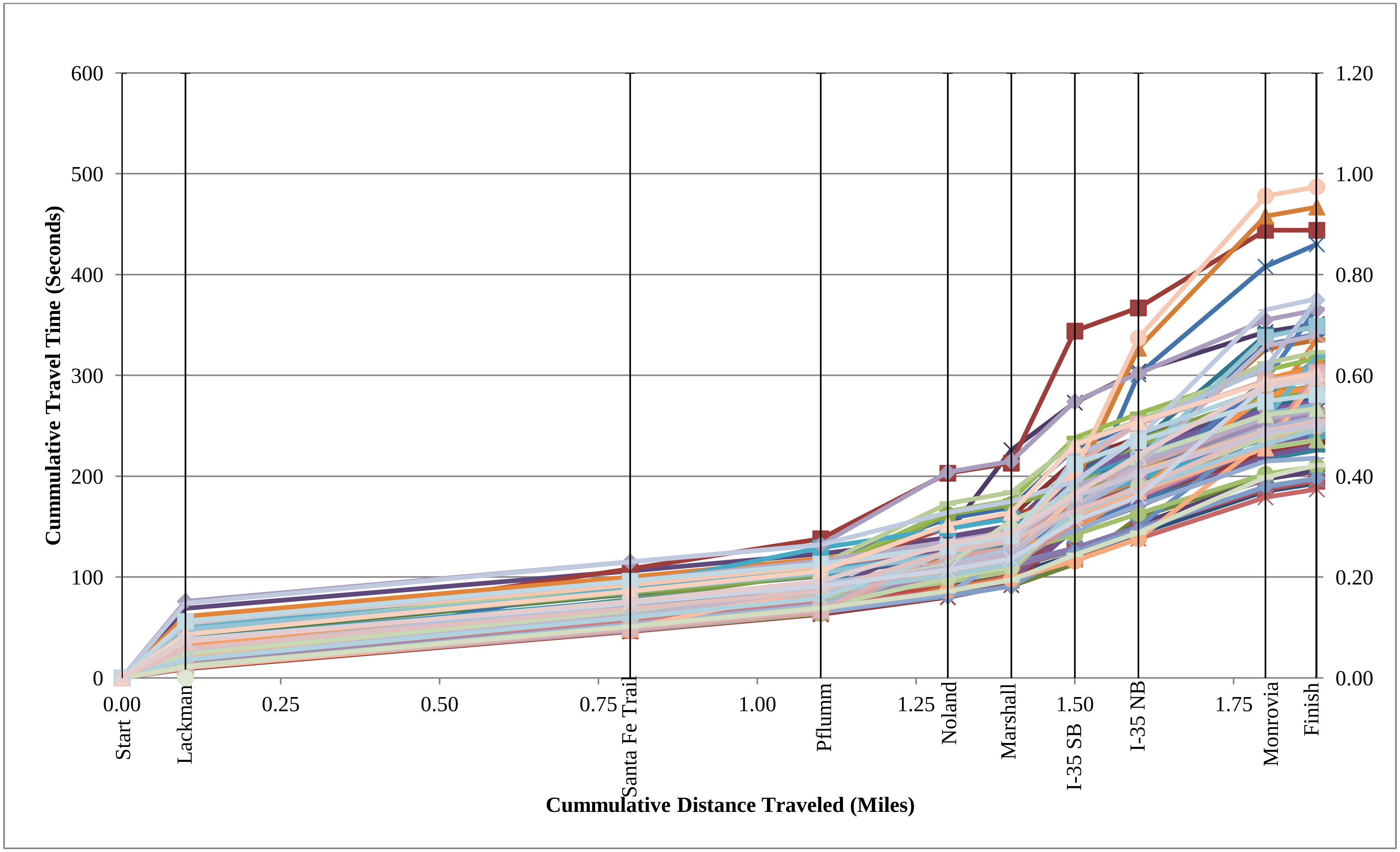

Figure E1 Eastbound 95th Street travel time plot (before)

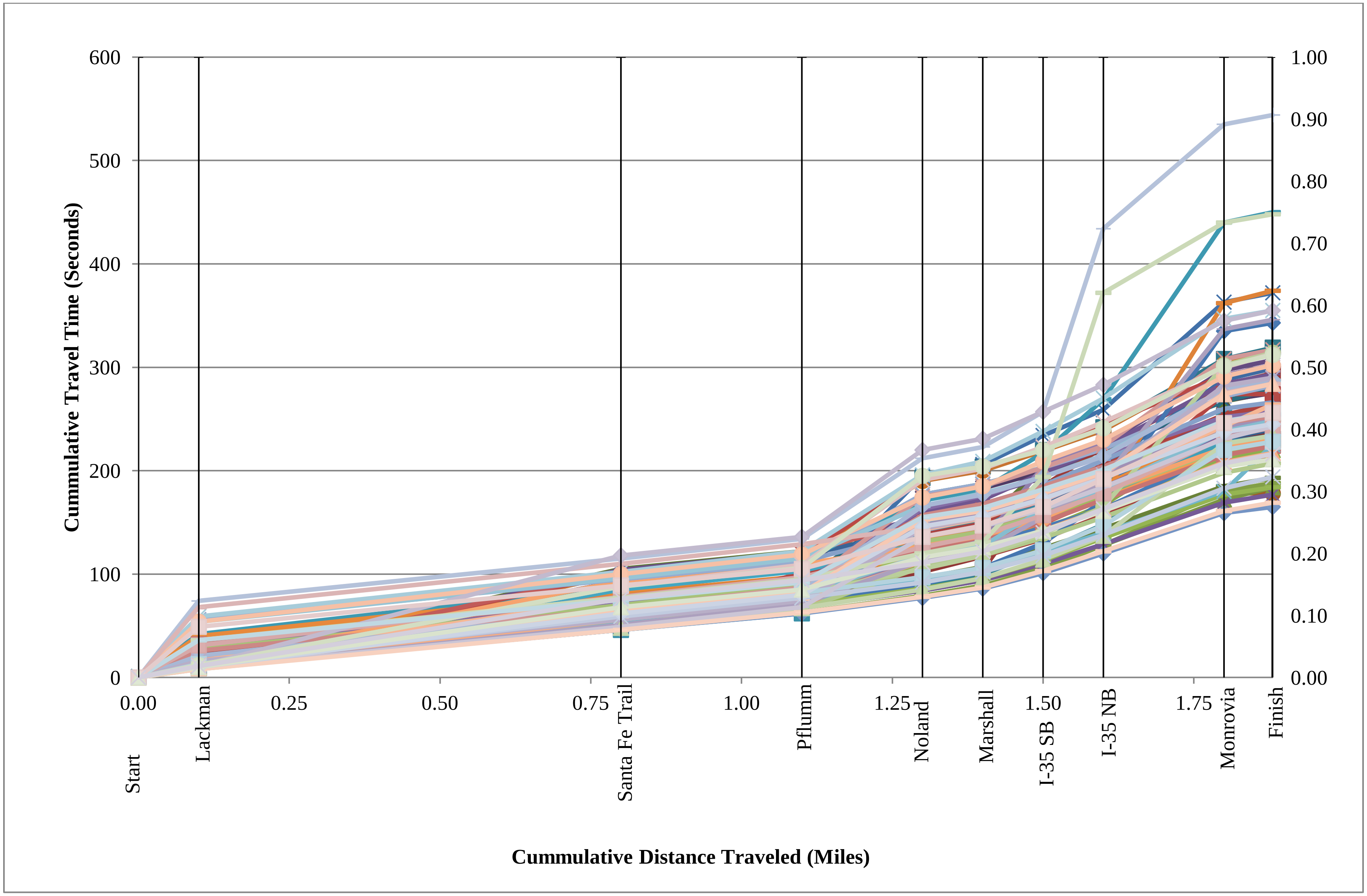

Figure E2 Eastbound 95th Street travel time plot (after)

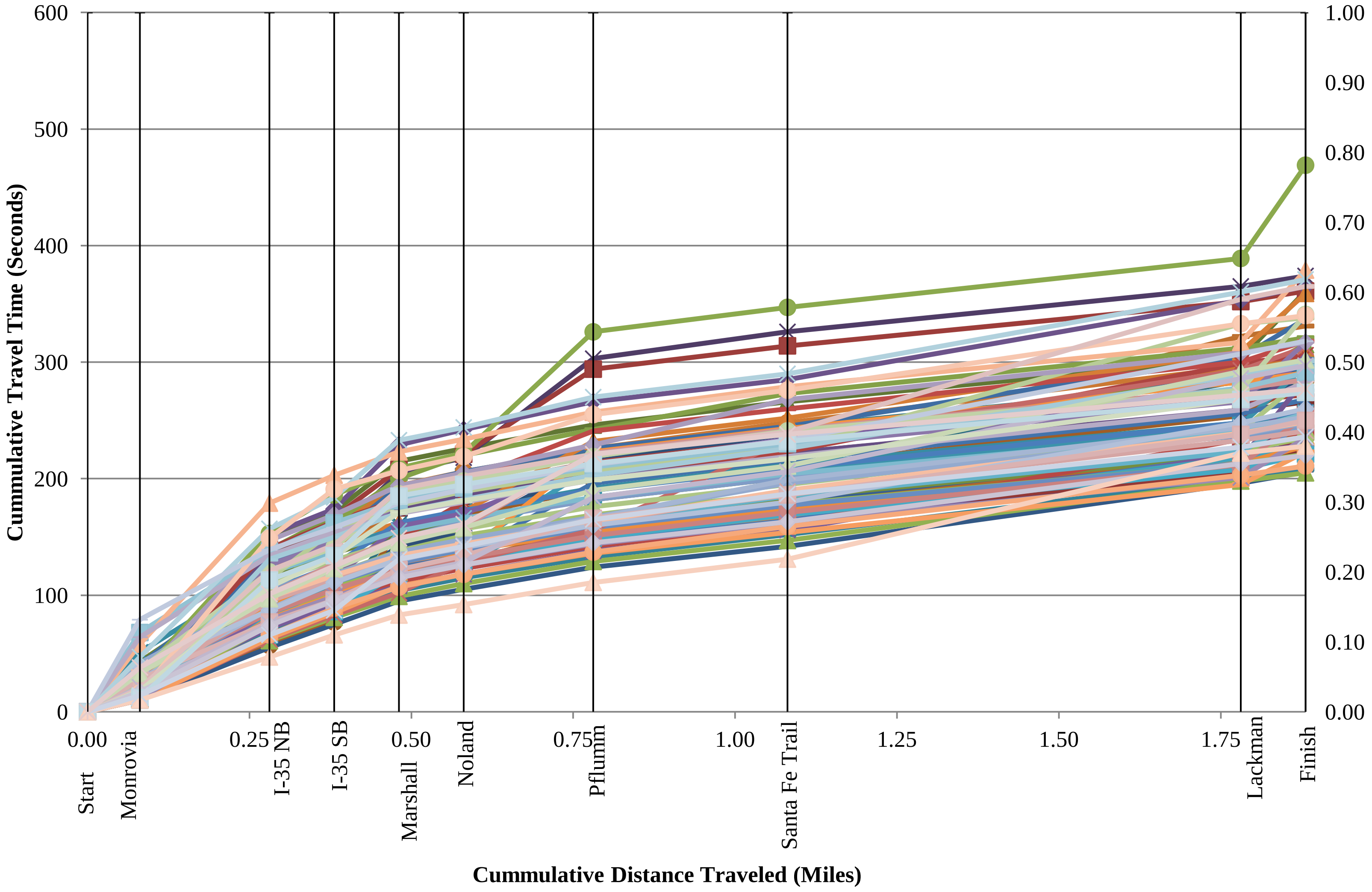

Figure E3 Eastbound 95th Street travel time plot (before

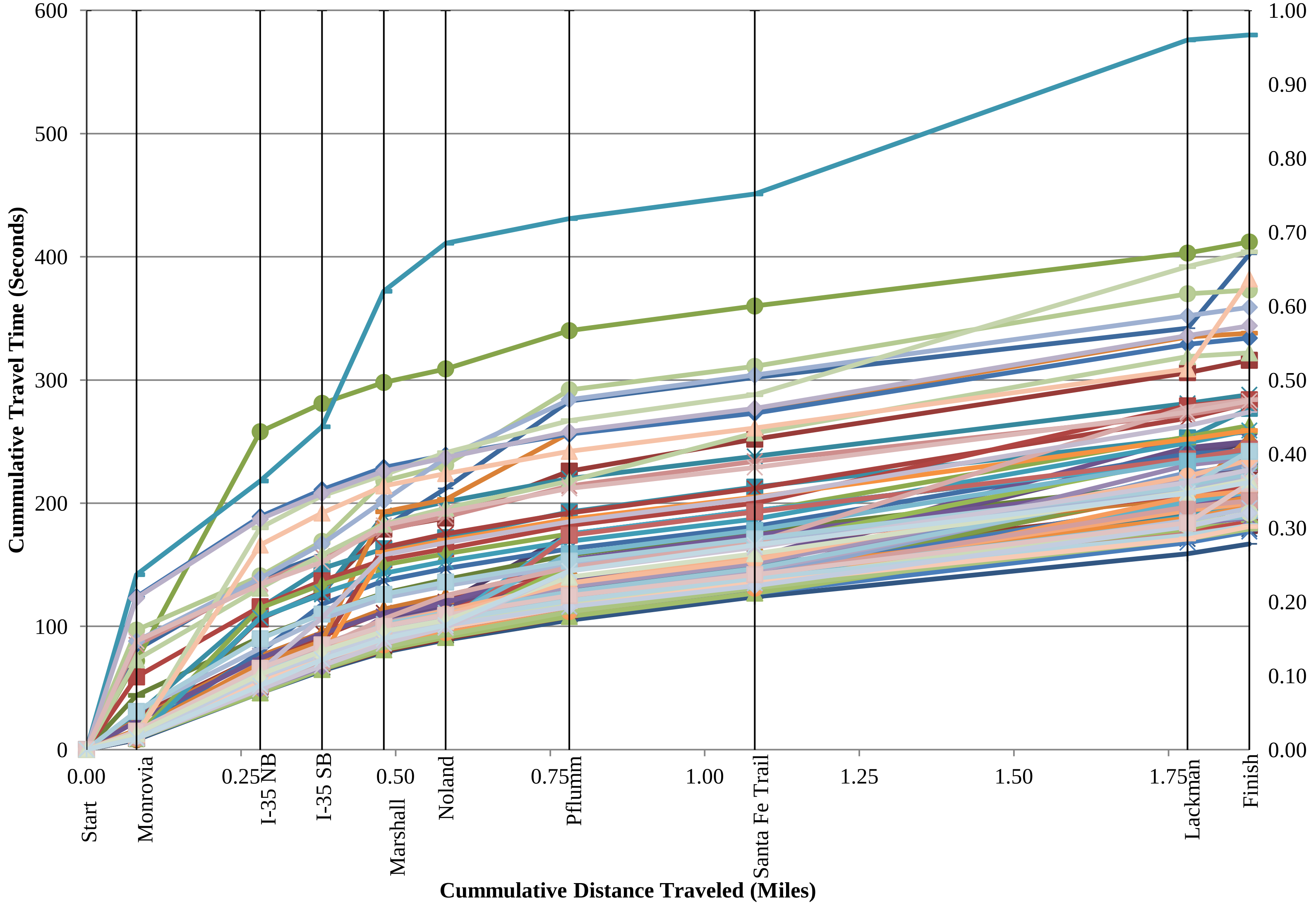

Figure E4 Westbound 95th Street travel time plot (after

APPENDIX F: 95th STREET BLUETOOTH SPEED DISTRIBUTIONS

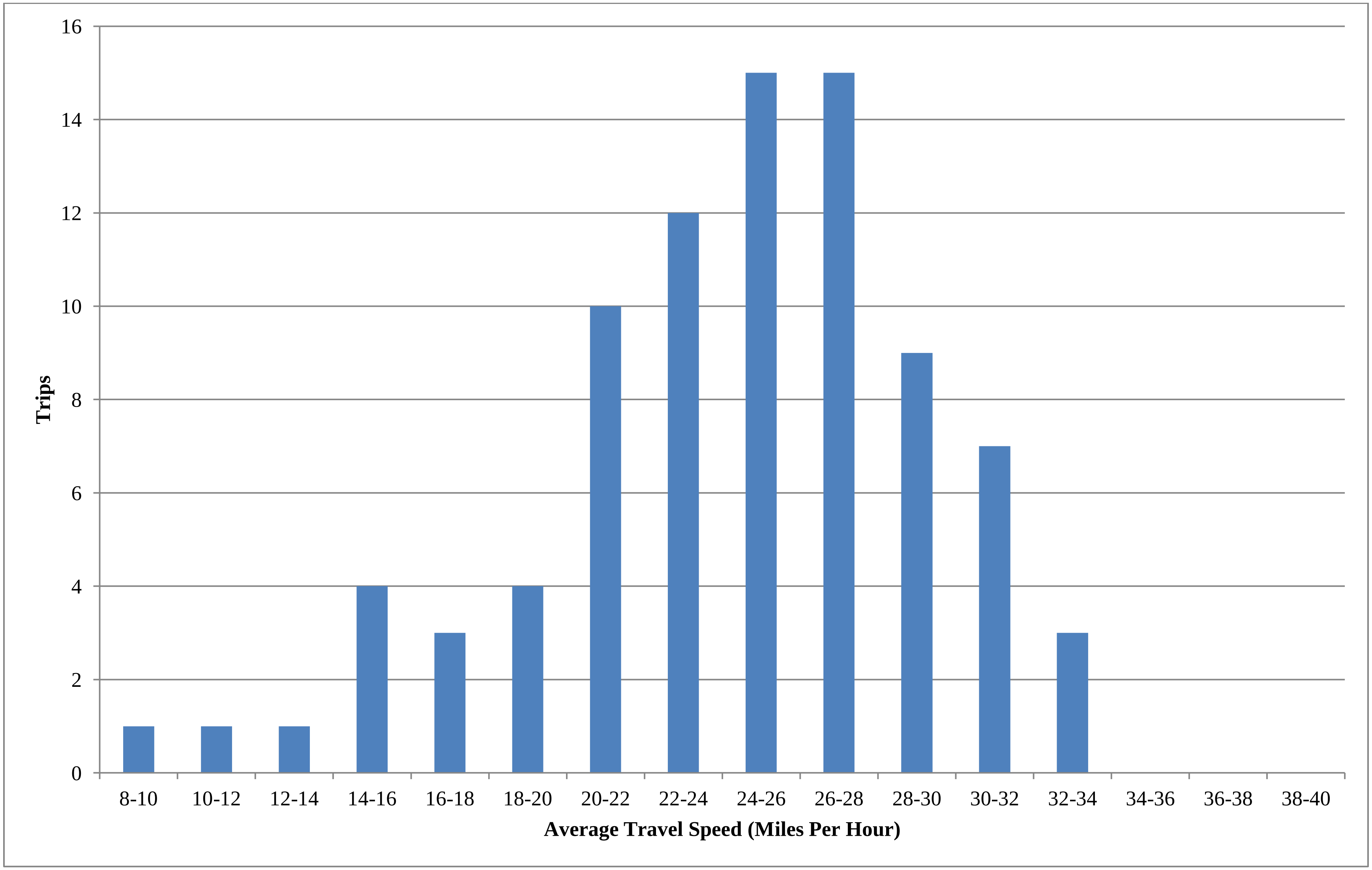

Figure F1 Eastbound 95th Street speed distribution for all time periods (before). n=86

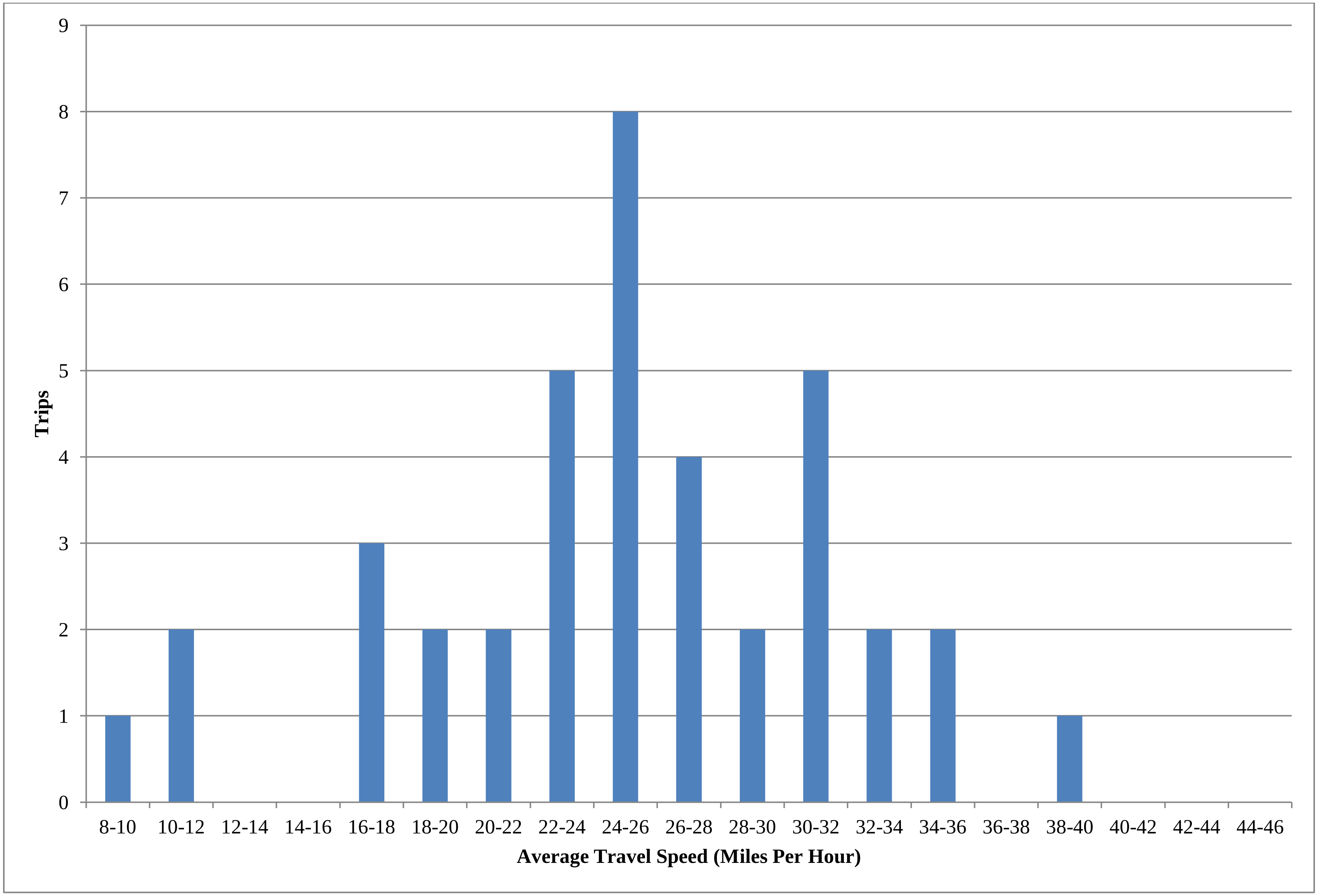

Figure F2 Eastbound 95th Street speed distribution for all time periods (after). n=41

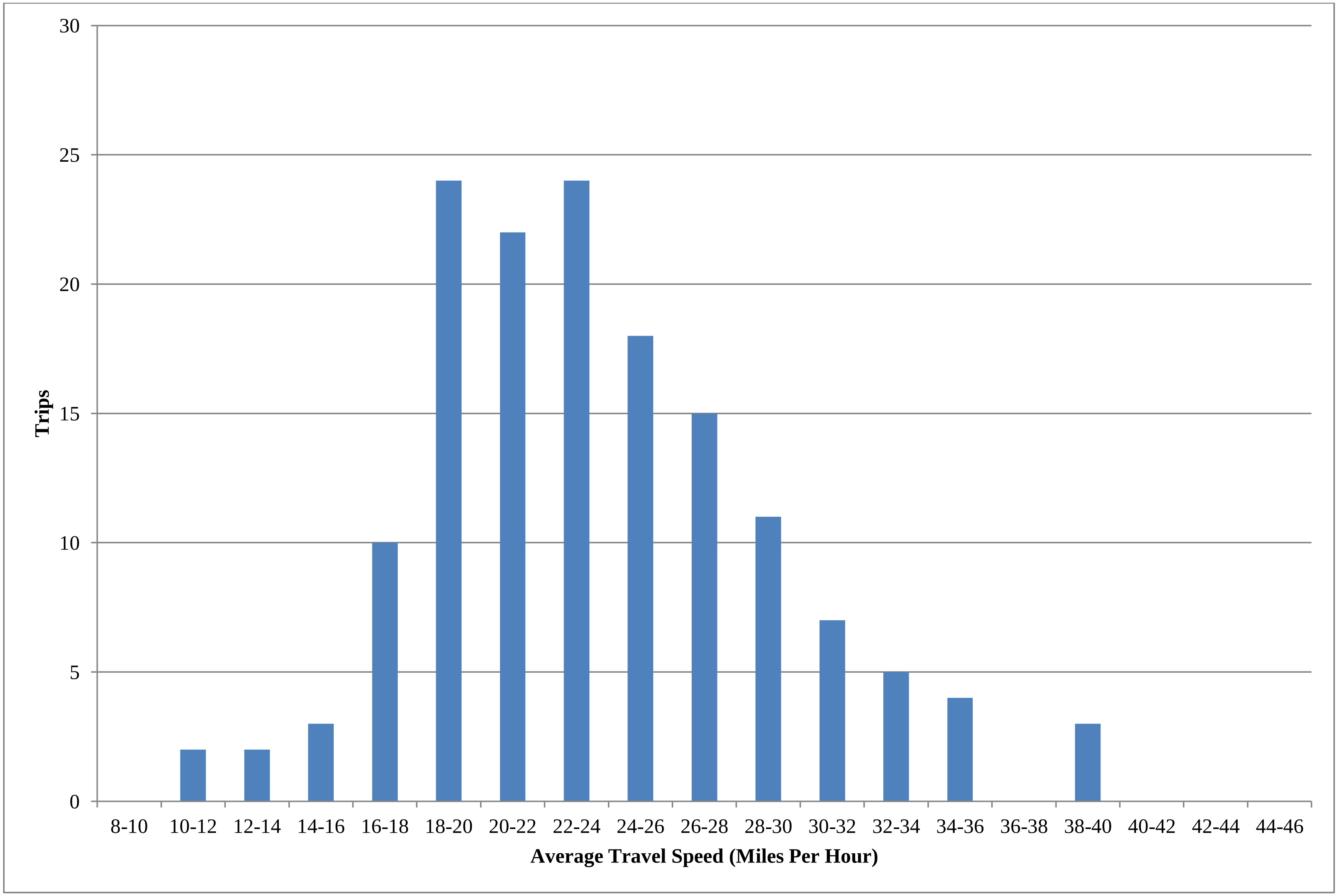

Figure F3 Westbound 95th Street speed distribution for all time periods (before). n=151

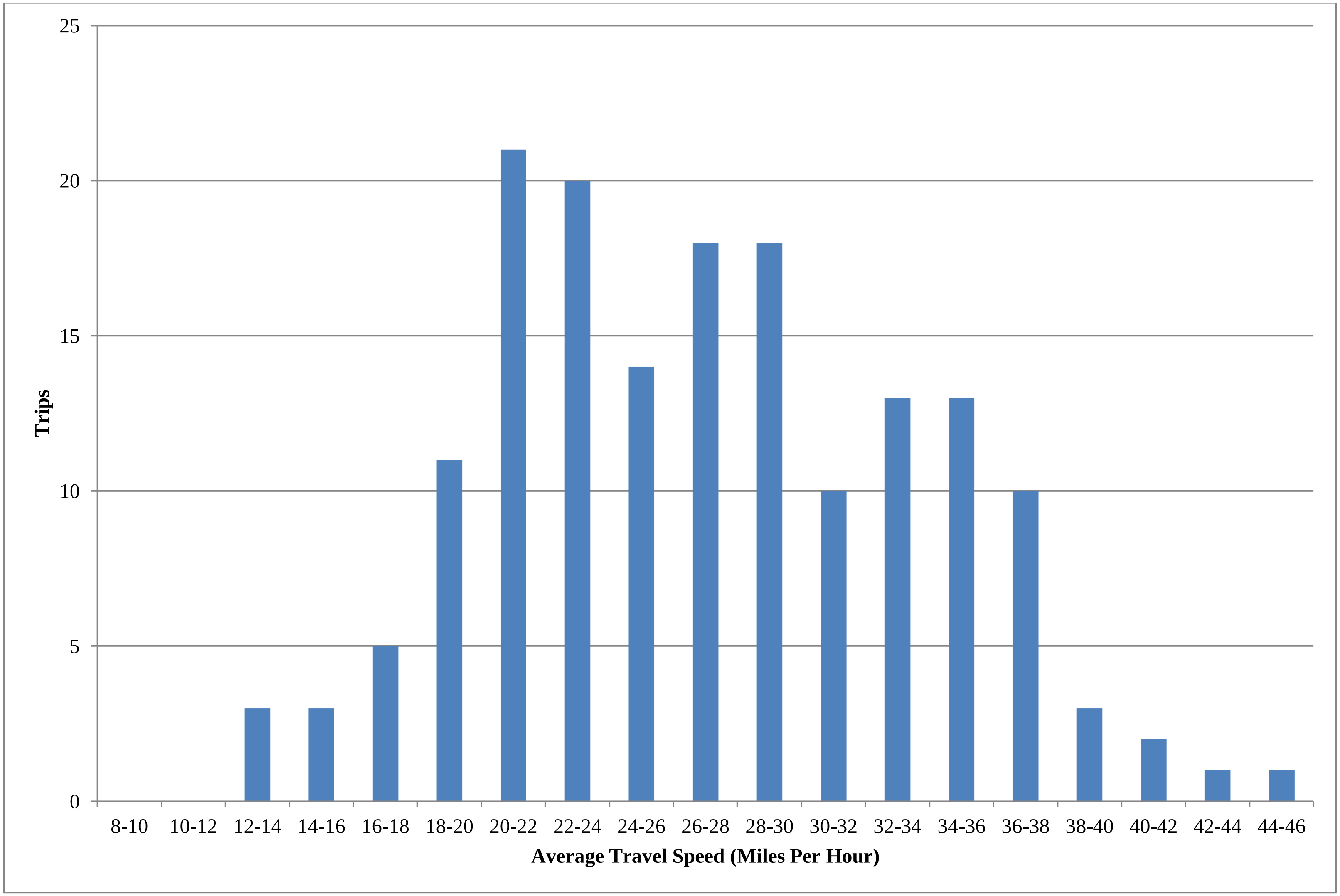

Figure F4 Westbound 95th Street speed distribution for all time periods (after). n=167

APPENDIX G: COMPARISON 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**
7:00-8:30AM	4	0.35	4.42	13	0.74	4.43	No	0.970
9:00-11:00AM	7	0.63	4.15	20	0.65	4.84	Yes	0.021
12:00-1:00PM	10	2.06	6.07	7	1.53	6.41	No	0.703
2:00-3:00PM	7	0.37	4.52	9	0.34	5.00	Yes	0.018
4:00-6:00PM	18	1.50	5.57	16	1.24	5.76	No	0.699
7:00-9:00PM	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**
7:00-8:30AM	5	0.52	3.83	18	0.51	3.95	No	0.642
9:00-11:00AM	8	0.72	4.76	21	0.47	4.25	No	0.076
12:00-1:00PM	0	-	-	8	0.80	4.97	-	-
2:00-3:00PM	0	-	-	9	0.54	4.17	-	-
4:00-6:00PM	11	3.57	7.57	14	1.47	5.84	No	0.145
7:00-9:00PM	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**
7:00-8:30AM	4	0.57	4.12	13	0.90	5.11	Yes	0.019
9:00-11:00AM	10	1.37	4.68	20	0.50	4.55	No	0.787
12:00-1:00PM	16	1.23	4.86	8	0.71	6.14	Yes	0.004
2:00-3:00PM	11	0.75	4.82	9	0.53	5.35	No	0.083
4:00-6:00PM	42	1.09	5.51	15	1.13	5.84	No	0.330
7:00-9:00PM	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**
7:00-8:30AM	6	0.76	3.81	15	0.49	3.65	No	0.639
9:00-11:00AM	10	0.79	4.22	21	0.38	3.53	Yes	0.014
12:00-1:00PM	9	1.07	4.77	8	0.98	4.24	No	0.300
2:00-3:00PM	16	1.65	4.55	10	0.84	4.30	No	0.611
4:00-6:00PM	40	1.28	5.31	16	1.58	5.30	No	0.980
7:00-9:00PM	21	0.46	3.45	21	0.48	3.70	No	0.090
Total	**102**	-	-	**91**	-	-	-	-
Unique	**93**	-	-	-	-	-	-	-

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