ARTERIAL ROADWAY TRAFFIC DATA COLLECTION USING BLUETOOTH TECHNOLOGY

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ARTERIAL ROADWAY TRAFFIC DATA COLLECTION USING BLUETOOTH TECHNOLOGY

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LIST OF ACRONYMS

AFH	Adaptive Frequency Hopping
ATIS	Advanced Traffic Information System
ATMS	Advanced Traffic Management System
CPU	Central Processing Unit
dB	Decibel
dBi	Decibel over Isotropic
dBm	Decibel (referenced to milliwatts)
DIAC	Dedicated Inquiry Access Code
FHS	Frequency Hopping Synchronization
GDOT	Georgia Department of Transportation
GHz	Gigahertz
GIAC	General Inquiry Access Code
GPS	Global Positioning System
GRA	Graduate Research Assistant
HOV	High Occupancy Vehicle
HOT	High Occupancy Toll
IAC	Inquiry Access Code
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific, and Medical
ITS	Intelligent Transportation System
MAC	Media Access Control

Mbps	Megabit per Second
MHz	Megahertz
ms	Millisecond
mW	Milliwatt
RFID	Radio Frequency Identification
OUI	Organizationally Unique Identifier
URA	Undergraduate Research Assistant
USB	Universal Serial Bus

SUMMARY

The use of Bluetooth technology for gathering traffic data is becoming increasingly popular due to the large volume of data that can be gathered at a relatively low cost. The limited number of devices in discoverable mode and potential long discovery time of the Bluetooth devices creates an opportunity for evaluating the sensor array setup that can maximize the sample of devices identified. This thesis investigates several factors that have a significant impact on the quality of the data obtained using Bluetooth, including the number of Bluetooth readers, orientation of the Bluetooth antennas, position of the readers relative to one another, and the location of the Bluetooth stations.

The thesis begins with an overview of Bluetooth technology and literature review on the use of Bluetooth in previous traffic studies. Next, the methodology for the setup of the Bluetooth system and the four tests performed to evaluate the factors affecting the quality of the data are described. Through the results of these tests, it was observed that a “flat” antenna orientation allows for the greatest detection range and that the walls of buildings can prevent detection of Bluetooth devices inside the buildings. In addition, using multiple Bluetooth readers per sensor array resulted in statistically significant increases in number of detections of single reader sensors, and horizontally separated sensor arrays were observed to be more effective than vertically separated sensor arrays. Finally, the thesis concludes with a summary of findings and a discussion of further research needs.

CHAPTER 1: INTRODUCTION

When monitoring the performance of freeways, strategically located built-in loop detectors coupled with a limited number of entry and exit points have enabled traffic engineers to accurately gather real-time data such as volumes and speeds. These data can be used in real time to convey traffic conditions to the public, as well as in planning analysis such as evaluating the before and after effects of roadway improvements, identifying congested areas that need improvements, etc. Gathering traffic data on arterial roadways has proven to be a more challenging task, as the greater number of access points along an arterial corridor requires a larger sample size to gain statistically significant results [1]. Traditional techniques of gathering travel time or origin-destination data, such as floating car or license plate studies, are both time consuming and expensive with each method having its own additional limitations. The proliferation of Bluetooth technology in many standard devices such as cell phones, hands-free headsets, global positioning system (GPS) units, computers, and integrated Bluetooth systems on vehicles has made remote detection of these devices an increasingly popular method of capturing and anonymously identifying a significant portion of the traffic stream at a relatively low cost [2-10]. To calculate travel times from these Bluetooth enabled devices, the same device must be identified at point A then re-identified at point B a certain known distance away. The time difference in the detections of the device at point A and point B can then be used to calculate the travel time between locations. Using these Bluetooth systems requires less post-processing of data, allowing such monitoring systems to be accurately and effectively automated [3, 5, 11].

Previous studies have examined methods to increase sample size through Bluetooth reader placement on medians or on either side of the road [12, 13]. Studies have also been performed to evaluate omni-directional versus directional antennas [12, 14, 15] and the height of the antenna above the road [13]. These studies, however, have not specifically focused on the benefits of using multiple reader arrays. Because the Bluetooth inquiry state can require up to 10.24 seconds before a Bluetooth device is discovered [16, 17], there is a limited probability that an active in-vehicle device will be detected by a reader, as the vehicle may pass through the sensor's detection range before the sensor transmits an inquiry packet on the frequency the in-vehicle device is scanning. Furthermore, when large numbers of Bluetooth devices are present in a traffic stream, one reader may not be capable of reading all of the device Media Access Control (MAC) addresses before they leave the detection range. Thus, using multiple Bluetooth readers in one location has the potential to increase the overall detection rate. If the increase in number of detections is significant, then the benefit of collecting additional data may exceed the additional cost of installing multiple readers.

A Bluetooth travel time test performed in January 2011 established the framework for evaluating multiple sensor array configurations and led to the research discussed in this thesis [18]. The experiment took place on a Friday afternoon and consisted of 3.5 hours of data collection, including both peak and off-peak hours. Bluetooth stations were set up at two sites along Spring Street, a one-way street in Atlanta, GA, with four Bluetooth readers at varying heights configured at each site. Two probe vehicles containing discoverable Bluetooth devices and GPS units continuously drove past the stations throughout the study period. The test is explained in further detail in Section 2.3.

The results of the study showed that gathering travel time data through the use of Bluetooth technology is effective, as the Bluetooth generated travel times matched ground truth travel times determined by the GPS-equipped probe vehicles. At the conclusion of the test, however, there were many questions left unanswered which would require further research to resolve.

1.1 Objectives

The goal of this study is to evaluate the use of Bluetooth technology to efficiently collect the largest possible sample of traffic data on arterial roadways. There are several factors that have a significant impact on the quality of the data obtained using Bluetooth, including the position of the sensor arrays, height of the antennas, number of Bluetooth readers, etc. Because a Bluetooth device needs to be in a discoverable mode to be detected, which is not the default state for most devices, the percentage of devices that can be detected is significantly lower than the number of devices that are both present and powered on. Estimates of the fraction of vehicles with detectable Bluetooth devices usually range from 5% to 10% [1, 4, 8, 13, 19]. It is therefore important to investigate how to maximize detection of these available in-vehicle devices to increase the fidelity and frequency of probe-vehicle-based traffic stream parameters (e.g. travel time) that are obtained, particularly in real-time applications. To maximize these detections, questions generated by the Spring Street test with regard to the range of the Bluetooth readers, interference among Bluetooth readers, and the orientation of the antennas relative to passing vehicles must be addressed. The use of varying numbers of Bluetooth readers per sensor array, located at various heights and positions relative to one another, is explored with the goal of determining the optimal configuration for detecting the largest sample of passing vehicles. The results of these initial tests are used to develop a travel time experiment and further analyze the effects of various Bluetooth reader configurations using a five mile segment of Buford Highway as a case study.

1.2 Overview of Paper

The paper first explains how Bluetooth technology works and provides an overview of the previous work that has been done regarding the use of Bluetooth in traffic engineering applications. The January Spring Street Bluetooth test is also explained in greater detail in Chapter 2. Chapter 3 delves into the design of the multi-reader array experiment, including the technology used for the Bluetooth stations, the methodology for the tests that developed as a result of the Spring Street test, and an overview of the set up for the configuration tests and travel time study on Buford Highway. The results and analysis of these tests are presented in Chapter 4. Finally, the paper concludes with a summary of findings, evaluation of the limitations of Bluetooth technology for traffic applications, and an overview of the need for further research in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of Bluetooth Technology

Bluetooth was developed as a short range communications technology that allows devices to connect to one another without the use of cables [16]. Bluetooth technology uses the industrial, scientific, and medical (ISM) band of 2.4 gigahertz (GHz) to 2.485 GHz to create point-to-multipoint connections that transmit data as quickly as 1 megabit per second (Mbps) [16, 20]. With enhanced data rate capability, Bluetooth devices can process data at faster rates of 2 to 3 Mbps.

The three different classes of Bluetooth devices are based on the range and power of the device's signal. A Class 1 device has the strongest output with a range of at least 100 meters (300 feet) and a maximum power output of 100 milliwatts (mW) or 20 decibels (dBm). Class 2 devices have a minimum range of 10 meters (33 feet) and a maximum power output of 2.5 mW or 4 dBm. Finally, Class 3 Bluetooth devices have a range of at least 1 meter (3 feet) and a maximum power output of 1 mW or 0 dBm. Most commonly owned Bluetooth enabled mobile devices such as cellular phones and global positioning system (GPS) units are designed as Class 2 devices [16].

Bluetooth devices create communication networks known as piconets, which are ad hoc short-range wireless networks, where 'ad hoc' means that they do not require any formal infrastructure to form a connection [16]. Up to eight Bluetooth devices can connect to any one piconet, allowing one device to simultaneously pair with up to seven other Bluetooth devices within that piconet. The Bluetooth device that transmits the initial connection message is called the master device, while the devices that it pairs with are referred to as the slave devices [16, 20]. Each device has its own unique media access control (MAC) address, which is “a 48-bit physical layer address” consisting of 12 hexadecimal characters in six octets [13]. MAC addresses are managed by the Institute of Electrical and Electronics Engineers (IEEE) and consist of two parts. The first part is the organizationally unique identifier (OUI), which is made up of the first three octets (24-bit) and is the equivalent of a unique global company identifier that can be purchased from IEEE [21]. The last six hexadecimals are assigned by the manufacturer of the Bluetooth device [13].

To minimize interference from other wireless and microwave devices, Bluetooth devices transmit messages on a pseudorandom sequence of different frequencies, detecting frequencies that are in use by other devices and avoiding those in future transmissions. This process is called adaptive frequency hopping (AFH) and covers 79 frequencies in the 2.4 GHz ISM band at 1 megahertz (MHz) intervals [20]. Within a piconet, the master and slave devices synchronize the sequence of frequencies through which they alternate so that they can easily maintain communication with one another. This is done through the conveyance of a frequency hopping synchronization (FHS) packet, which allows the slave device to base its hopping sequence off of the master device’s MAC address and clock once a connection is formed [16, 17]. A connection does not have to be made for one device to receive information such as the MAC address and clock time from another Bluetooth device. This information exchange can be done through the inquiry process alone. Section 2.1.1 describes the Bluetooth inquiry and discovery process in greater detail.

2.1.1 Bluetooth Device Discovery Protocol

There are three major Bluetooth states: standby, connection, and park, and seven Bluetooth substates. These substates are page, page scan, inquiry, inquiry scan, master response, slave response, and inquiry response [16]. The page, page scan, master response, and slave response substates are all used to connect to other Bluetooth devices. The inquiry, inquiry scan, and inquiry response substates are part of the discovery process and do not involve an actual connection between devices. To identify the MAC address and clock time of another Bluetooth device, a master device must be in the inquiry substate while the potential slave device must be in the inquiry scan substate. Of the 79 Bluetooth frequencies in the 2.4 GHz band, 32 of them are considered wake-up carriers over which the master device will repeatedly transmit inquiry packets containing the device's inquiry access code (IAC) [16, 17, 22-24]. There are two types of IACs that the master device may transmit. One is a general inquiry access code (GIAC) which looks for any type of Bluetooth device in any class. The other type, a dedicated inquiry access code (DIAC), looks only for one specific type of Bluetooth device. During its inquiry scan, the potential slave device searches for an IAC being emitted from a potential master. According to the Bluetooth specifications, the time between one Bluetooth device's consecutive inquiry scans should be equal to or less than 2.56 seconds [16]. Hence, every 2.56 seconds or less, the slave device will conduct an inquiry scan whereas the master device is operating in constant inquiry mode, unless the master device is processing a connection with a slave device.

Prior to connection in a piconet, the master and potential slave device are not synchronized; therefore, the master device does not know when the slave will be on a wake-up hop frequency or know which frequency it is on. As a result, the discovering device needs to transmit the same inquiry packet over different hop frequencies while listening for a response from the potential slave device. The frequency of the master device in the hopping sequence is determined by the master's clock and changes every 1.28 seconds. The frequency hopping sequence is split into two trains, called A and B, each covering 16 of the 32 wake-up frequencies. One train of frequencies can be covered in 16 slots. One time slot is the equivalent of 1/1600 seconds [23]; therefore, each train can be covered in 10 milliseconds (ms), with a maximum of 3200 hops/second during the inquiry substate. Each train is repeated at least 256 times by the master device during the inquiry substate. In addition, each train goes through two iterations of the 16 slots. This means that an inquiry substate duration of up to 10.24 seconds may pass before a potential slave device receives the master's inquiry packet that allows the devices to discover each other (2 trains × 2 iterations × 256 times × 10 ms = 10.24 seconds) [16, 17].

When the potential slave device receives an inquiry packet from a master device, the slave device will leave the inquiry scan substate and enter the inquiry response substate. The slave device will then enter the standby state "for an integer number of time slots uniformly distributed between 0 and 1,023" [24] before returning a FHS (frequency hopping synchronization) packet to the master. Because each slot is equivalent to 1/1600 seconds, the length of time that the slave device stops scanning after receiving an inquiry packet may range from 0 to 639.375 ms [23, 24]. This pause in the slave device response is built in to the protocol to limit conflicts among multiple scanning devices that may have received the master device's inquiry packet at the same time. Once it returns to the inquiry response substate from the standby substate, the slave returns an FHS packet to the master and will offset the phase of its clock by 1. The master device does not acknowledge receipt of the FHS packet; however, the slave will continue to cycle through the inquiry scan and inquiry response substates as long as it receives inquiry messages from the master device in the inquiry substate [16]. **Figure 1** shows a representation of the Bluetooth discovery process performed by the master and slave devices.

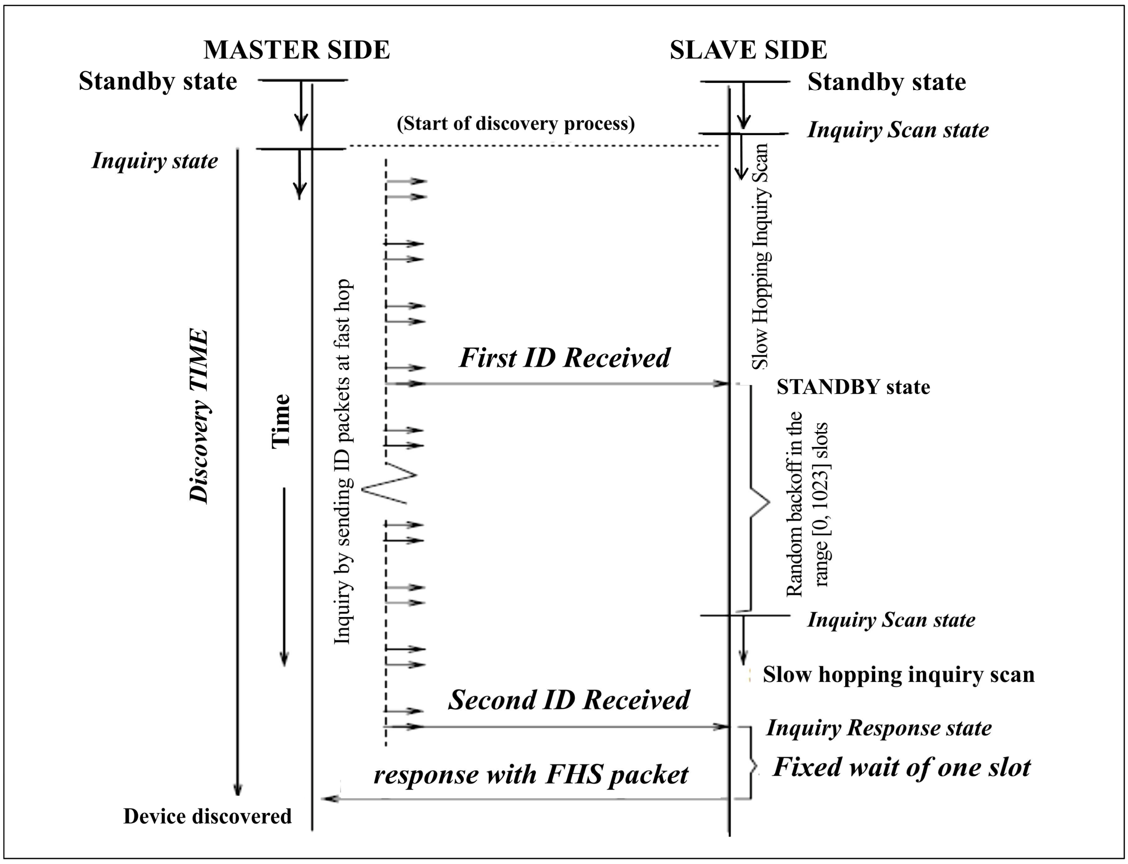


Figure 1: Bluetooth Discovery Process [22]

When the master device is in the inquiry substate, the master device uses a subset of the 79 Bluetooth frequencies; therefore, as Peterson noted, the inquiring device is a source of interference to neighboring piconets [24]. Computer simulation of multiple device inquiries can increase the discovery time of a slave device, especially if the two master devices have similar trains and train change times, as the slave device will go into the standby state after receiving the first inquiry packet, rendering it unable to receive a packet from the next master device whose clock is only slightly behind the first [24]. In addition, as seen in Figure 2, Chakraborty observed that increasing the number of slave devices in the inquiry scan substate that are waiting to be discovered can significantly increase the amount of delay during the inquiry process [23].

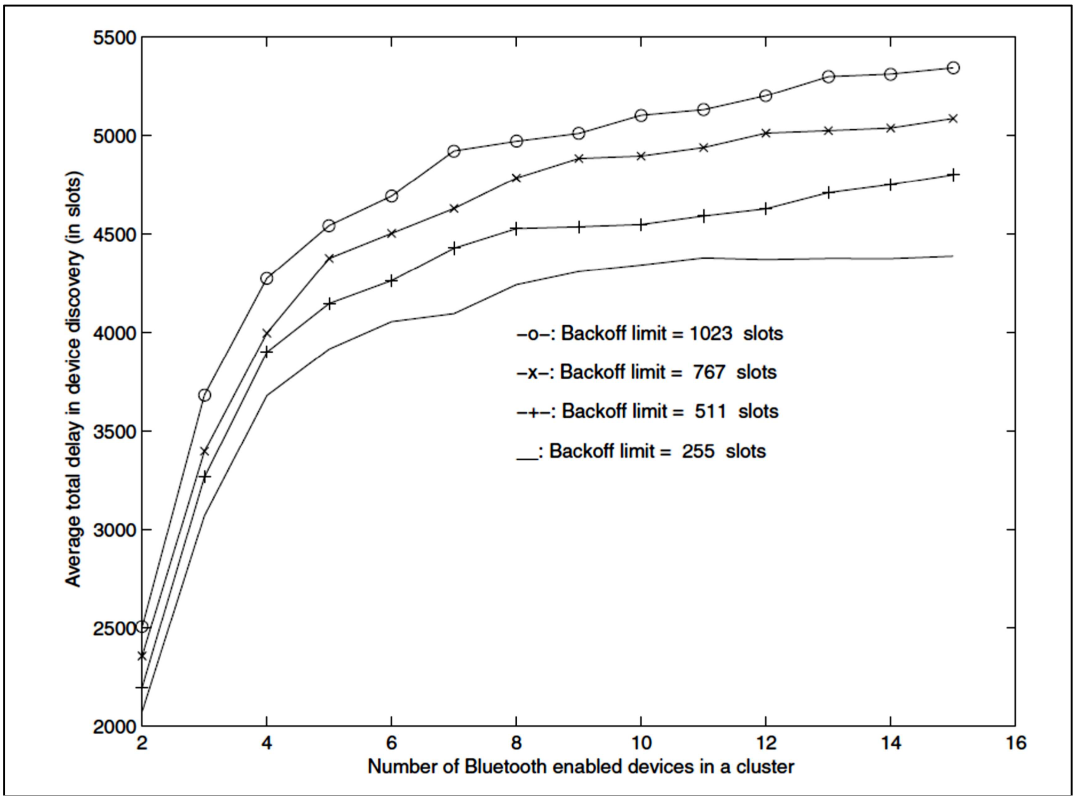


Figure 2: Increase in Discovery Time When More Slave Devices Are Present [23]

Once two devices have discovered one another, they are ready to form a connection to communicate and transfer data from one device to another. To form a connection, the master and slave device will proceed through the paging process, which is similar to the inquiry process [16]. Because the Bluetooth detection systems employed in the field research are only being used to discover a device, no connection between devices is made and the paging process is not discussed further in this paper.

2.2 Previous Traffic Engineering Applications of Bluetooth Studies

Bluetooth technology has become an increasingly popular method of gathering traffic data for many transportation applications. Most previous studies have focused on using Bluetooth technology to gather data and analyze travel time along freeways [4, 6, 8, 15, 25-27] and arterial roadways [1, 12, 13, 15, 18, 25, 28, 29]. Bluetooth technology has also been suggested as a means of forecasting travel times for use in advanced traffic information systems (ATIS) [30] and advanced traffic management systems (ATMS) [10]. Aside from travel time studies, Bluetooth has also been used to gather traffic data for origin-destination studies [10, 25, 29] including evaluating driver route choice with regard to road closures and official and unofficial detours [19], to compare the results of a signal timing project along a corridor using before and after traffic data [1, 28], and to evaluate the effects of work zones on traffic delays and diversions when drivers were advised or not advised to take an alternate route [27]. In addition, Petty and Kwon explored the use of Bluetooth in combination with intelligent transportation system (ITS) data such as loop detector volumes to measure roadway performance [31].

A few studies have also evaluated various aspects of the Bluetooth station set up with regard to collecting traffic data. Brennan et al. assessed the impact of the height of a Bluetooth reader from the ground as well as the offset of the station from passing vehicles [13]. In two different studies, Malinovskiy et al. looked at placement of readers in the median, or on one or both sides of the road, as well as the effectiveness of different antenna types [12, 14]. The following sections summarize the relevant findings from these previous studies.

2.2.1 Advantages of Bluetooth Technology for Traffic Management Applications

For any purpose, the Bluetooth specifications state that some of the key features of Bluetooth are that it is designed to be robust, cost-effective, and only requires a small amount of power to function [16]. Furthermore, line-of-sight between two Bluetooth devices is not required for them to communicate and transmit data to one another, because the signal can travel through many physical barriers [17].

The primary advantage of using Bluetooth technology to gather traffic data is its low cost [2-10]. A much larger sample of data points can be collected relative to other standard methods of collecting travel time data such as automatic license plate readers, floating car studies, or toll tag readers [2, 3, 7]. These factors result in a significantly lower cost per data point. Young estimated that Bluetooth technology is “500 to 2500 times more economical than drive testing” [4] while Tarnoff estimates that the Bluetooth methodology is 100 times less expensive than floating car studies [9]. Comparing Bluetooth technology to radio frequency identification (RFID) toll tag readers, Puckett and Vickich state that the capital cost for the required Bluetooth equipment is “one to two orders of magnitude less than that for traditional toll tag reader equipment” [5]. In 2010, KMJ Consulting found that the Bluetooth system was one third of the cost of installing an EZPass toll tag reader system with estimates of $9700 to $12,200 per sensor installation for the Bluetooth and $34,000 to $36,000 per reader installation for the RFID [6].

Another advantage of the Bluetooth system is that it is easy to install and maintain [6, 7]. The small Bluetooth adapters are portable and can be used for a variety of studies, whether permanent or temporary installations are necessary on freeways or arterials [2, 3, 7, 9]. Furthermore, with the large range of 100 meters (300 feet) by Class 1 Bluetooth devices, one Bluetooth station can typically detect devices in vehicles traveling in either direction of the roadway [5]. Slone also notes that using Bluetooth technology to gather travel time data is a safer method than using a probe vehicle during a floating car study [3].

2.2.2 Type and Placement of Bluetooth Antennas and Stations

The type of Bluetooth antenna used to detect devices in passing vehicles, as well as the placement of these antennas, can affect the detection rate during data collection. Because of its longer range, a Class 1 Bluetooth antenna with a gain of 1dB is recommended by Puckett and Vickich for traffic applications [5]. Multiple studies have found that using an omni-directional versus a directional antenna, resulted in a greater number of detections [12, 14, 15], because omni-directional antennas have a larger detection zone. Malinovskiy, et al., noted that directional antennas tended to miss more of the faster vehicles, with omni-directional antennas yielding more matched pairs at subsequent sites and more accurate travel time data [14]. Wang found that while omni-directional antennas do detect more devices than directional antennas, having a directional as well as an omni-directional antenna at each of two sites for a travel time test resulted in 3% more matches than only having a single omni-directional antenna at each site. Minimal interference was observed from having two antennas at each site instead of one [15]. Similarly, Malinovskiy, et al., observed that detection rates could be increased and error minimized by placing two omni-directional antennas at each Bluetooth location, one on either side of the road [12]. To minimize bias from detecting more of the vehicles in the lanes closest to the Bluetooth antenna, Brennan et al. suggested a similar placement of placing an antenna either in the median or having one reader on either side of the road [13].

When determining where to locate Bluetooth stations along a roadway, the distance between the stations, height of the readers, and location along the roadway are all factors to consider. For arterials, Day, et al., and Quayle and Koonce suggest installing the Bluetooth readers at midblock locations rather than at intersections [1, 29]. Day, et al., explain that while intersections are better for long-term installation with regard to access to communications and power, a midblock location reduces error that can be induced by stopped traffic at a signal [1]. For travel time studies, increased distance between consecutive sites decreases travel time prediction error [12, 15]. Bluetooth devices have rather large detection zones and given the potential time it takes for the devices to connect, vehicles may be detected anywhere within that detection zone, not at a specific point in space. Schneider suggests that consecutive Bluetooth sampling locations should be separated by a distance of one to two miles [2].

One final study assessed the impacts of variable height of Bluetooth antenna placement above the road. Brennan et al. found that sensor height had an effect on the detection rate of passing Bluetooth devices in vehicles and recommend a "mounting height of at least 8 feet above the pavement grade" [13]. This height was determined by testing five sensors at heights of 0 feet, 2.5 feet, 5 feet, 7.5 feet, and 10 feet. It was found that the 7.5 foot and 10 foot antennas identified more than twice the number (2600/day) of devices than the zero-foot sensor (1135/day) [13].

2.2.3 Detection Rates

The vehicle detection rate is one of the primary means of evaluating the effectiveness of Bluetooth technology with regard to collecting traffic data. For the purposes of this study, vehicle detection rate is defined as the total number of different MAC addresses detected by the reader divided by the total volume of vehicles passing by the site. This definition assumes that each MAC address corresponds to a Bluetooth device in a separate vehicle and that no other Bluetooth devices, such as those carried by pedestrians, are detected and that no vehicle is carrying more than one discoverable Bluetooth device. Given the rapid proliferation of Bluetooth devices, future studies are needed to assess the reasonableness of these assumptions. Nevertheless, the presence of multiple Bluetooth devices in some of the vehicles detected in this study will not significantly impact the findings of this study.

Previous studies have consistently found vehicle detection rates for Bluetooth devices ranging from around 5% to 10% regardless of the location of the study or type of roadway observed. Day et al. presented the full range of 5-10% based on their study along an arterial roadway in Indiana [1], as did Brennan et al. in their twenty-four hour evaluation of an Indianapolis freeway [13]. In other Indiana studies, Hainen et al. found a 7-10% detection rate along arterials while Martchouk noted a 10% detection rate on the interstates. On I-95 between Washington D.C. and Baltimore, Maryland, Young noted that discoverable Bluetooth devices were observed with a detection rate of 5%, while Tarnoff et al. published percentages between 5-7%, also for data along I-95 [9]. The only outlier in the percentage of discoverable Bluetooth devices identified as part of this research effort is a paper by Asudegi which reported that approximately 3-5% of the total traffic volume contained discoverable Bluetooth devices, also for the I-95 Maryland corridor [32]. Wang et al. found a detection rate between 5-10% for all of their tests on both freeways and arterials in Seattle, Washington [15].

One study of Bluetooth saturation with pedestrians took place in England in 2006. Through the study, O'Neill found that 7% of pedestrians carried discoverable Bluetooth devices [33].

2.2.4 Data Filtering

For travel time applications of Bluetooth technology, outliers in the data must be identified and removed. Outliers can result from a variety of factors: drifting clocks in the Bluetooth readers, identification of the same MAC address multiple times at the same station, reader malfunction, vehicles leaving the roadway for some purpose and later re-entering the roadway, or detection of Bluetooth devices belonging to bicyclists and pedestrians rather than drivers [2, 11]. Multiple methodologies have been developed to identify potential outliers.

With respect to multiple-read situations, one common method of minimizing travel time errors is to use either only the first read of a MAC address at each site (first-to-first analysis) or only the last read at each site (last-to-last analysis). Malinovskiy et al. explains that this is necessary due to the detection area of passing vehicles being a zone instead of a single point, which can lead to spatial errors [12]. Slone's filter uses the last-to-last method to generate travel time data. Any other previously identified reads of the same MAC address at one site are deleted. A time filter is also employed [3].

Puckett and Vickich filter their travel time data using an average of the travel times along the roadway. A percentage difference (for example, 25%) is selected and any values that differ by more than this are considered outliers and discarded. It was found that this method was successful for freeways; however, the innate variability in travel times along arterials led to many valid points falsely being discarded by the filter demonstrating the need for a more sensitive and dynamic filtering method to give reliable real-time traffic data [5].

Schneider et al. manually excluded outliers based on the previous and following travel times in a data set. This method worked to exclude unusually slow times which may have been the result of a vehicle leaving then re-entering the roadway prior to passing the second site. In addition, the second data point of any two different MAC addresses detected at the exact same time at one site was considered a second device in the same vehicle and was removed from the data set [2]. With respect to these studies being conducted in Atlanta, caution would need to be exercised in applying such a filtering method. The large detection zone and long inquiry time of 10.24 seconds could result in devices in different vehicles being identified at the same time by one reader or different devices in the same vehicle being detected by the same reader at different times.

Van Boxel et. al developed a statistical methodology to eliminate outliers from Bluetooth travel time data sets. The methodology uses a Greenshield traffic flow model and incorporates a “least quantile of squares” estimator. The filter also uses upper and lower thresholds for the standardized residuals. This method allows for outlying data points to be removed in real-time, allowing the potential for real-time conveyance of traffic data [11]. Roth also employs a statistical algorithm for identifying and removing outliers based on a time series approach. Grubbs' Test, Chauvenet's Criterion, and the Modified Z-Test were all evaluated, with the Modified Z-Test proving the most effective in filtering outliers from the data set [34].

2.3 Bluetooth Travel Time Case Study on Spring Street

The January 2011 case study of Bluetooth travel time [18] was the initial research experiment performed by our research group leading up to the tests covered in this thesis. The study involved two sites approximately 0.9 miles apart, with one Bluetooth sensor array at each location. Each sensor array consisted of four Bluetooth adapters, one at a height of 7 feet, two at 10 feet, and one at 14.5 feet. Data were collected from 3:00PM to 6:30PM on Spring Street, a four-lane, one-way street in Atlanta, GA, displayed in Figure 3. Two probe vehicles equipped with GPS devices and discoverable Class 1 and Class 2 Bluetooth devices circulated the sites throughout the study period. One traveled in the lane closest to the Bluetooth readers while the other traveled in the lane farthest from the stations. Video cameras were used to capture the volume of passing vehicles at each site.

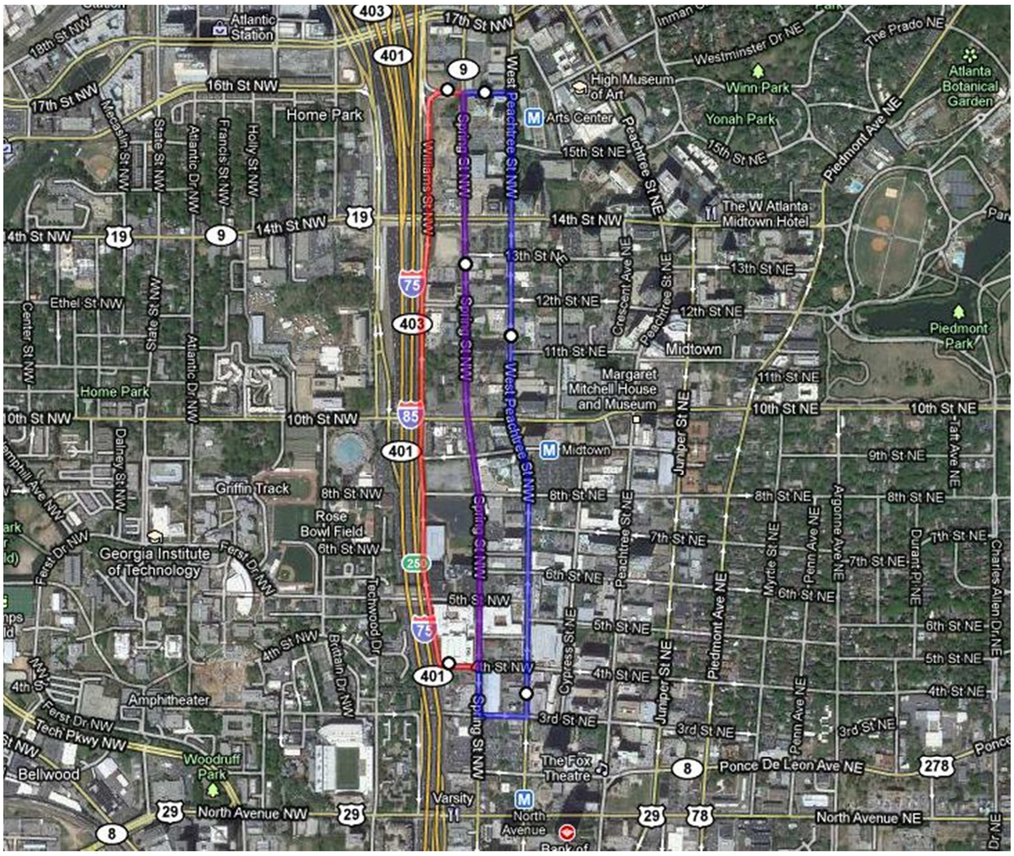


Figure 3: Site Layout for the January 2011 Test [18]

At Site 1, a total of 261 different MAC addresses were detected over a volume of 5,876 vehicles during the 2.5 hours, a detection rate of 4.44%, slightly lower than that commonly found in the literature. Site 2 had a higher detection rate of 8.27%, with 328 different MAC addresses over 3,964 vehicles. This was attributed to congestion near Site 2 that resulted in a longer dwell time for passing vehicles and could have increased the likelihood that a discoverable device was detected. The two readers placed together at 10 feet were seen to behave as a single reader at both sites, as the total number of detections by the pairs was comparable to the number of detections by the single readers at 7 feet and 14.5 feet. At Site 1 and Site 2, respectively, only 15% and 27% of the MAC addresses detected by at least one of the 10 feet readers at that site were detected by both of the 10 feet readers. At the time, the research team hypothesized that this behavior was a result of interference in the adaptive frequency hopping of the two non-separated readers.

Probe vehicle data from the Bluetooth readers and the GPS loggers were also analyzed. The probe devices in the vehicle traveling in the lane closest to the Bluetooth sensor were detected more often than those in the vehicle in the lane farthest lane. As expected, the Class 1 probe devices were detected more often than the Class 2 devices. The travel times determined by the Bluetooth readers were based on the first detection of a MAC address at each site. Excluding the runs that occurred during congestion, these Bluetooth travel times were comparable to the travel times calculated from the probe vehicle GPS data. During congestion, the Bluetooth times were shorter than the GPS travel times, which indicates that while the first-to-first read analysis is a feasible method of collecting travel times during free-flow conditions, it performs poorly during periods of high congestion.

Full details of the Spring Street Bluetooth experiment can be found in Vo’s *An Investigation of Bluetooth Technology for Measuring Travel Times on Arterial Roadways: A Case Study on Spring Street* [18].

CHAPTER 3: DESIGN OF EXPERIMENT

Given the positive results of the initial travel time test on Spring Street, the research group was motivated to further explore Bluetooth technology performance and undertake another travel time experiment. Throughout this thesis, the experiment will be referred to as the Buford Highway Travel Time Test. Before the Buford Highway test could be undertaken, however, there were many questions that needed to be answered regarding the design of the experiment. Many of these questions were generated by the results of the Spring Street case study.

First, the actual range of the Bluetooth readers needed to be evaluated. The higher number of detections at the 771 Spring St. location led to the question of whether discoverable devices in the surrounding buildings could have affected the results. It was determined that further tests were required to assess the effects of devices in the area surrounding the 771 Spring St. site. Next, it was desired to know how the orientation of the Bluetooth reader relative to passing vehicles affects its ability to detect MAC addresses. Finally, questions were raised concerning the configuration of the Bluetooth readers on the sensor arrays. Did having two readers at ten feet with no separation cause interference that resulted in a reduced number of reads from both adapters? Also, does using multiple readers on one sensor array increase the detection rate, and therefore the sample size, of passing vehicles?

Given the need for additional lab and field testing prior to performing another travel time Bluetooth experiment, three additional tests were developed: a Bluetooth detection zone observation test, a Bluetooth antenna orientation test, and a Bluetooth configuration test. All three of these tests and the Buford Highway travel time test used a similar Bluetooth equipment design.

3.1 Equipment

3.1.1 Design of Bluetooth Reader

The basic sensor array setup for this study is identical to the setup used during the Spring Street travel time study. Each sensor array consists of a minimum of one Bluetooth reader, defined as a Class 1 IOGEAR Bluetooth adapter with enhanced data rate, attached to a netbook using a universal serial bus (USB) extension cable. The netbook's internal Bluetooth is disabled, allowing the IOGEAR adapter to serve as the only means of detecting discoverable Bluetooth devices. The netbook operates on an Ubuntu Linux operating system to take advantage of the flexibility of the Bluez Bluetooth protocol stack available on Linux. Two PERL scripts are run on the netbook. The first script triggers a continuous series of scans from the attached adapter for Bluetooth devices within range of the adapter. The second script monitors the scan logs and records the date and time (0.1 second resolution) that the device was detected and the device's MAC address. This information is saved to a .log file, which is later transferred to a central database for analysis. Each Bluetooth adapter is attached to a heavy-duty tripod at a specified height. The corresponding netbook is stored at the base of the tripod. The legs of each tripod are weighted using sandbags to ensure stability. Finally, high visibility cones are placed near the base of the tripod to alert pedestrians to the presence of the equipment. Examples of the full setup are shown in **Figure** 4.

All of the Bluetooth readers in this study used the same basic setup, with only a few modifications for certain tests. The PERL scripts in the first two tests, the detection zone and antenna orientation tests, were run in Ubuntu running as a virtual machine over a Windows 7 operating system. For the configuration tests and the Buford Highway travel time tests, Ubuntu was installed as the base operating system on the netbooks allowing for better utilization of the hardware resources of the netbook. The second PERL script was also updated for the last two experiments to change the scanning frequency to once every tenth of a second rather than scanning continuously which could have an impact on the scanning efficiency as the same CPU is used by both the scaning log the Bluetooth data. This was done to reduce the load on the central processing unit (CPU), as one CPU is used to both scan for Bluetooth devices and log the Bluetooth data.

The third experiment varied the orientation of the Bluetooth antenna relative to the ground. The way in which the antenna was attached to the tripod was not standardized during the detection zone test but was the variable studied during the orientation test, as this test was investigating the impact of antenna orientation. The results of the orientation test influenced the positioning of the adapter during the following configuration experiments. Based on the results of all of the previous tests, one consistent antenna orientation was used for the travel time tests. All other aspects of the Bluetooth reader equipment were consistent throughout the study.

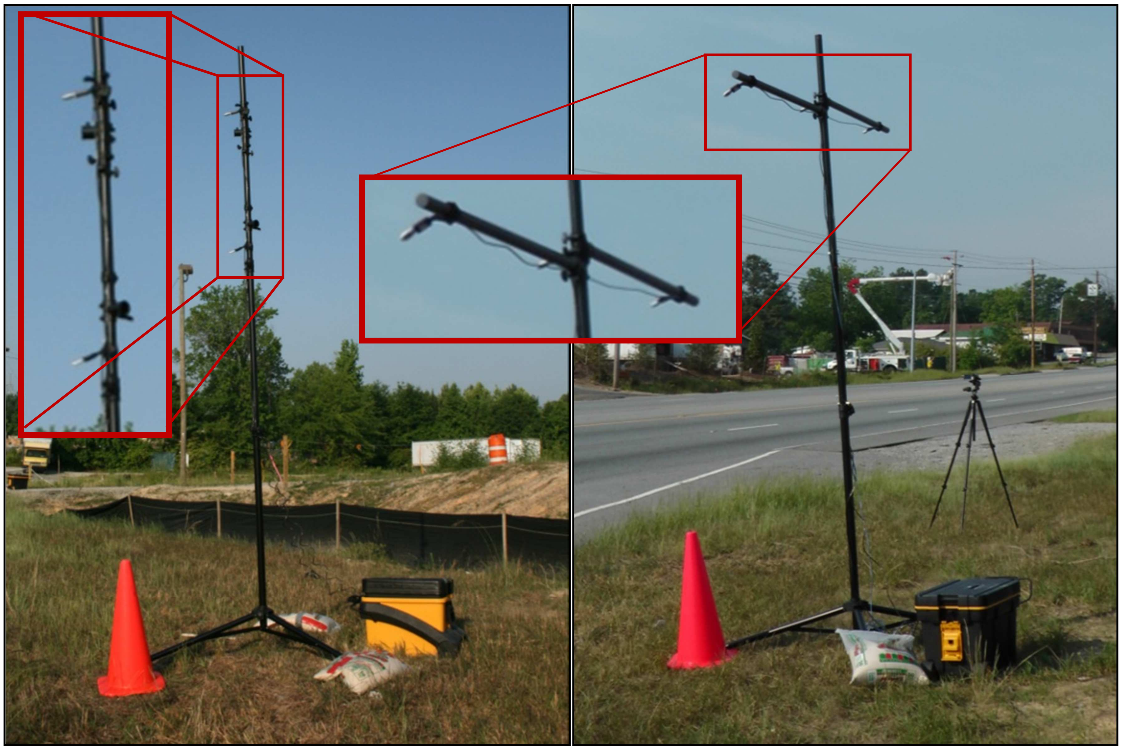


Figure 4: Typical Bluetooth Reader Setup for Vertical (Left) and Horizontal (Right) Sensor Arrays

3.1.2 Probe Vehicles and Global Positioning System

Probe vehicles serve two purposes in these studies: 1) the probe vehicles carry known Bluetooth-enabled devices and 2) the probe vehicle travel times between the Bluetooth reader sites serve as a ground truth. Multiple discoverable Bluetooth devices were placed at various locations within the probe vehicle. The MAC address and location of each discoverable device was recorded prior to the test. Probe devices were placed on the dash, front passenger seat, and on the floor in front of the passenger seat to simulate Bluetooth enabled GPS units or cell phones that may be placed in these same locations. A Class 2 Bluetooth enabled GlobalSat BT-335 GPS device was positioned on the dash of each probe vehicle to both track the vehicle and serve as another discoverable device. Details of what Bluetooth enabled devices were placed in the vehicles and in which locations for each specific test are included in Section 3.4.4 and Section 3.5.4, which also explain the probe vehicle setup for the Bluetooth configuration tests and the Buford Highway travel time tests, respectively.

3.1.3 Cameras

Cameras were used during the study to collect both license plate data and volume counts. All video recording was done using high definition Panasonic HDC-TM700 video cameras mounted on tripods. For license plate data, the cameras were zoomed in to the full extent and the 1080/60p setting was used. At most two lanes of license plate data could be collected by one camera. For volume counts, a wide angle view of the road proved advantageous.

3.2 Bluetooth Detection Zone Observations

The larger number of Bluetooth detections but lower traffic volume at Site 2 during the Bluetooth travel time case study on Spring Street (refer to [18] for further details) highlighted the uncertainty on the part of the researchers regarding the Bluetooth reader's range and whether discoverable devices inside nearby buildings could be detected. While Bluetooth specifications state that Class 1 adapters have a range of 100 meters (300 feet) [16], this is only a minimum required value. Manufacturers can build the devices to have a larger range [18]. In addition, line-of-sight is not necessary for Bluetooth pairing to occur [17]. While some of the increase in detection rates at Site 2 can be attributed to the slower vehicle speeds during congestion, the higher density of the surrounding buildings relative to Site 1 and the proximity of a busy crosswalk approximately 500 feet north of the site led to the hypothesis that devices inside adjacent buildings or pedestrians in the crosswalk could be a source of the increased number of detections at Site 2.

To test this notion, a detection zone experiment was performed in front of the Crum and Forster building at 771 Spring Street, the same location as Site 2 of the previous Spring Street Bluetooth test in Atlanta, GA. One researcher (Researcher 1) monitored the scan log of a Bluetooth reader set up at a height of ten feet. The other researcher (Researcher 2) carried the discoverable Bluetooth devices shown in Table 1. The iPhone, NB8 internal adapter, BT-335 GPS, and Qstarz BT-Q1000 GPS are all Class 2 Bluetooth devices. Class 2 Bluetooth has a minimum range of 10 meters (33 feet) [16]. The Sabrent adapter is a Class 1 Bluetooth device with a minimum range of 100 meters (300 feet). The two researchers communicated via cell phone as Researcher 2 walked to various locations around the site such as the parking deck across from the site, inside the adjacent bookstore, and to the crosswalk 500 feet north of the reader. The locations are represented in Figure 5.

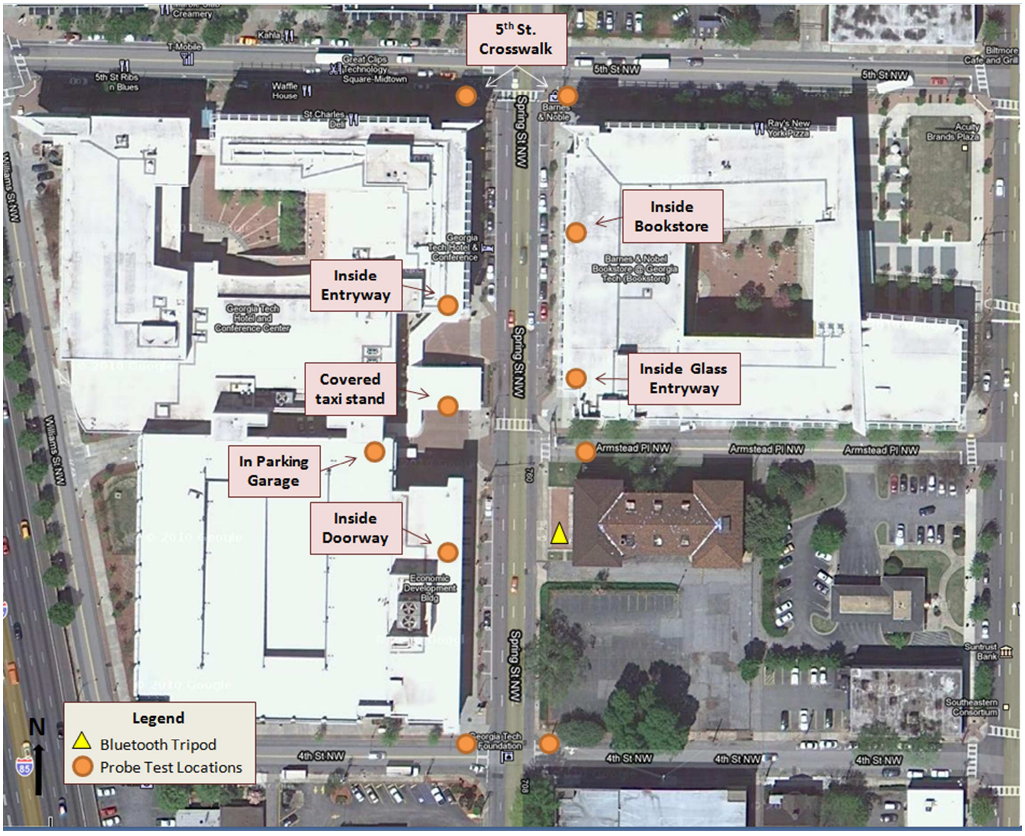


Figure 5: Probe Locations (Researcher 1 Destinations) for the Detection Range Tests

At each specified location Researcher 2 would stop for at least twenty seconds while Researcher 1 would communicate which devices, if any, were detected by the reader. The location of Researcher 2, the direction he was facing, and which devices were detected at that location were recorded to create a map of the Bluetooth reader's range both inside and outside the surrounding buildings. This map is shown in Section 4.1. Researcher 2 also walked as far from the reader as possible while remaining in the detection zone, pausing every few steps to check the status of the Bluetooth devices with Researcher 1. The farthest detectable location was also recorded on the map. The full deployment plan for the detection zone test can be found in Appendix A, and the results of this test are discussed in Section 4.1.

Table 1: Discoverable Bluetooth Device Locations

Bluetooth Device	Device Name	MAC Address	Location on Researcher
iPhone	Trunger's iPhone	00:26:4A:C7:2C:02	Front left pocket
NB8 internal adapter	HOV2HOT-NB8	74:F0:6D:A1:9C:17	In backpack furthest from body
BT-335 GPS	BT-GPS-38BA15	00:0D:B5:38:BA:15	Front right pocket
QT-BT1000 GPS	Qstarz 1000XT	00:1C:88:13:05:8B	Back right pocket
NB9 with Sabrent adapter 1	HOV2HOT-NB0	00:30:91:40:08:1D	In backpack closest to body

3.3 Determination of Optimal Bluetooth Antenna Orientation

Discussions regarding the range of the Bluetooth readers generated from the detection zone test led to questions concerning whether the orientation of the Bluetooth antenna relative to the passing vehicles, and therefore their discoverable devices, influenced the range of the readers and their ability to detect passing Bluetooth devices. The orientation of the readers during the January Spring Street test was not recorded; however, after the test the hypothesis was suggested that the direction of the antennas could have influenced the number of MAC addresses detected by the various readers.

To test the influence of antenna orientation on a Bluetooth reader's detection range, an experiment was designed to measure the distance from which a device could be detected by a stationary reader at various orientations. The test was performed on a large, flat field to minimize interference and to facilitate keeping the reader and discoverable device at the same elevation. A Class 2 Bluetooth Q-Starz BT-Q1000 GPS unit was used as the discoverable device in this experiment. Initially, a Class 1 IOGEAR adapter connected to a netbook was attempted for use as the probe device; however, the device was detected at over 600 feet and there was insufficient space to continue the experiment. The Class 2 Bluetooth reader was set up as described in Section 3.1.1, using a camera tripod instead of a heavy-duty tripod. The reader was initially attached to the tripod in a "flat" orientation, where the long, flat part of the adapter is parallel to the ground (see Figure 6 for an example) and leveled using the built-in tripod level. Researcher 1 monitored the PERL script as Researcher 2 walked away from the reader with the GPS unit along a straight line at an angle of zero degrees from the adapter. Zero degrees is defined as having the long straight part of the adapter parallel to the line along which Researcher 2 walked, with the antenna facing the researcher. The farthest distance away that the Bluetooth device could reliably be detected was recorded. To be considered reliably detectable, the device had to be identified a minimum of three times in one minute, with no more than 30 seconds in between each read.

Once a reliably detectable distance was recorded, the camera tripod was rotated 15 degrees in the clockwise direction and the test was repeated, with Researcher 2 walking along the same line as during the previous test. Once again, the maximum reliably detectable distance was recorded, and the orientation of the Bluetooth reader on the camera tripod was again changed. This process was repeated in 15 degree intervals up to a rotation of 180 degrees. It was assumed that the results for 180 degrees to 360 degrees would mirror the results between zero and 180 degrees. Once the flat orientation of the Bluetooth adapter had been tested at all angles, the orientation of the adapter on the camera tripod was changed and the experiment repeated, beginning at zero degrees. The other orientations that were tested were "on edge" where the narrow long part of the adapter was parallel to the ground (see Figure 7) and "vertical" (Figure 8), where the long, flat part of the adapter is perpendicular to the ground. In this situation, zero degrees is defined as having the flat side of the adapter with the IOGEAR symbol on it facing the Bluetooth emitting device. The same Bluetooth adapter was used for all tests. The results of the orientation test are discussed in Section 4.2.

Figure 6: Top and Side Views of a Flat Orientation from 90 Degrees

Figure 7: Top and Side Views of an On Edge Orientation from 90 and 270 Degrees

Figure 8: Side Views of a Vertical Orientation from 0 and 270 Degrees

3.4 Bluetooth Reader Configuration Tests

The results of the earlier Spring Street Bluetooth test suggested that using multiple Bluetooth readers at one site may increase the number of overall detections as well as the detection rate of passing vehicles. Conversations concerning interference between readers based on the reduced number of detections from the two readers at ten feet during the Spring Street tests also generated the question of whether the orientation of the devices relative to one another could affect the amount that one adapter interferes with an adjacent adapter. The researchers needed to assess whether having two readers at ten feet with no separation caused interference that would result in a reduced number of detections from both adapters. To evaluate the impact of reader-to-reader interference and examine whether configurations with multiple adapters are beneficial, a set of experiments was designed to analyze how several sensor arrays with different reader configurations would compare with regard to detection rate and number of unique devices detected.

The design of the experiment involved setting up three or four sensor arrays in one location where the same vehicles would pass by each of them but still have the sensor arrays far enough apart to be considered independent. Initially, four days of configurations were planned from Tuesday May 10th to Friday May 13th. To obtain a larger sample of vehicles, the tests were scheduled for a two-hour period between the commute hours of 7:00AM and 10:00AM. Based on the results of these experiments, two additional mornings with supplementary configurations were included in the study on Friday June 3rd and Monday June 6th, also between 7:00AM and 10:00AM. The variables for the reader configurations included number of readers, orientation of the readers, separation distance between adjacent readers, and position of the readers relative to one another (whether they were separated vertically or horizontally). Complete descriptions of the different configurations that were tested each day are described in Section 3.4.2.

3.4.1 Study Location

A 0.5 mile segment of Buford Highway between Pittman Circle and Smith Ridge Trace in Norcross, GA was identified as an ideal location for the study as it experiences high traffic volumes of around 24,220 AADT [35] with no cross-streets or high-volume driveways. As the study was to be conducted during the morning commute hours, a site with sufficient space for four sensor arrays to be spaced at least 50 feet apart was identified. The west side of the road was chosen because Buford Highway has a strong directional traffic flow into Atlanta in the morning and northbound out of Atlanta during the evening. While it was expected that vehicles traveling in both directions would be detected, previous studies [13, 18] have shown that the likelihood of detecting a Bluetooth device decreases as the distance from the reader is increased. The final study site was located in front of Atlas Furniture Wholesalers at 5015 Buford Highway. The sensor arrays were set up with an 85 foot separation from each other with a 25 foot setback from the edge of the nearest travel lane (see Figure 9). On the day that employed only three-sensor-array configurations, the locations in Figure 9 labeled “Sensor Array 1”, “Sensor Array 2”, and “Sensor Array 3” were used. All four sensor arrays were used for the other five test days.

Figure 9: Location of Configuration Test Sensor Arrays *(Background image from [36])*

3.4.2 Sensor Array Configurations

The configurations for each of the sensor arrays differed during each day of the study. For the first five days of testing, a single reader at a height of 10 feet served as the control tripod for a base comparison, as previous studies generally involved only one reader per sensor array. The configuration of the other sensor arrays varied depending on the variable that was being tested. When using multiple readers per sensor array, each reader was separated by three feet from its adjacent adapter unless the design setup called for no separation between readers. A distance of three feet was selected, as this length was determined to be sufficient to consider the antenna in the far field of its neighboring antenna based on the Bluetooth frequency of 2.4 GHz and wavelength of approximately 12.5 cm. The far field is defined as the distance away from an antenna where the antenna pattern no longer changes with distance (Fraunhofer region). For a theoretical dipole (half wave antenna), the Rayleigh Distance (F) (i.e. beginning of the Fraunhofer zone) is given by:

$$F = 2r^2/\lambda \qquad \text{Eq. 1}$$

Where λ is the wavelength and “r” is the maximum dimension of the antenna (i.e. $\lambda/2$ for the dipole case). For this case, the Fraunhofer radius is approximately 6.25 cm. To obtain 30 dB isolation (typical specification for consumer grade receivers) receivers will need to be separated by approximately 15*F assuming ideal inverse square behavior consistent with the 90 cm (3 foot) separation used in the study.

3.4.2.1 Day 1: Tuesday May 10th, 2011

The first day of the study involved testing the effectiveness of horizontally-separated versus vertically-separated readers. For a permanent installation, a vertical configuration would be much simpler and therefore more cost effective to install, as all readers could be mounted on one pole without the need for crossbars; however, if the horizontal configuration showed a greater number of detections, then the relative cost of lost data and a smaller sample size would also have to be considered. The following are the reader configurations for Tuesday’s tests. A description of a “flat” reader orientation can be found in Section 3.3.

- Sensor Array 1: one reader at 10’ with antenna placed “flat”
- Sensor Array 2: two readers at 8.5’ and 11.5’ with antenna placed “flat”
- Sensor Array 3: two readers at 10’ separated by 3’ with antennas placed “flat”

3.4.2.2 Day 2: Wednesday May 11th, 2011

Based on the results of the first day's tests, questions arose regarding whether the orientation of the antennas as flat caused more interference between vertically separated readers than between horizontally separated readers. To test this hypothesis, the configurations on Sensor Arrays 1 through 3 on the second day of tests were similar to the first, except with the readers oriented on edge instead of flat. In addition, a fourth sensor array was used to test whether two readers at a height of 10 feet with no separation, as in the Spring Street case study, would result in a decreased number of reads relative to the other configurations. The sensor array reader configurations are listed below. Examples of an "on edge" antenna orientation can be found in Section 3.3.

- Sensor Array 1: one reader at 10 feet with antenna placed "on edge"
- Sensor Array 2: two readers at 8.5' and 11.5' with antennas placed "on edge"
- Sensor Array 3: two readers at 10' separated by 3' with antennas placed "on edge"
- Sensor Array 4: two readers at 10' with no separation between antennas and with antennas placed "flat"

3.4.2.3 Day 3: Thursday May 12th, 2011

For the third day of the study, sensor arrays with one, three, and five readers were tested to assess the effects of increasing the number of readers per sensor array. The readers were all oriented flat and separated horizontally based upon the results of the previous two days of testing. In addition, the sensor array configuration with three readers was duplicated to study the innate variability in Bluetooth detections. With identical configurations, it was expected that the two three-reader sensor arrays would show very similar results, as any interference from having three readers in one location, a flat orientation, or horizontal displacement from each other would be consistent across both sensor arrays. The configurations for Day 3 are listed below.

- Sensor Array 1: three readers all at 10’ separated by 3’ with antennas placed “flat”
- Sensor Array 2: three readers all at 10’ separated by 3’ with antennas placed “flat”
- Sensor Array 3: five readers all at 10’ separated by 3’ with antennas placed “flat”
- Sensor Array 4: one reader at 10’ with antennas placed “flat”

3.4.2.4 Day 4: Friday May 13th, 2011

On Day 4, a test similar to the one performed the previous day was undertaken. Again, the goal was to evaluate the effects of using multiple readers as one detection unit at a site. The number of Bluetooth readers ranged from one to four and all were placed at a height of 10 feet. The orientation of all antennas was also flat. The specific configuration for each sensor array is shown below.

- Sensor Array 1: two readers all at 10’ separated by 3’ with antennas placed “flat”
- Sensor Array 2: four readers all at 10’ separated by 3’ with antennas placed “flat”
- Sensor Array 3: one reader at 10’ with antennas placed “flat”
- Sensor Array 4: three readers all at 10’ separated by 3’ with antennas placed “flat”

3.4.2.5 Day 5: Friday, June 3rd, 2011

A fifth day of testing was added to further investigate the vertical configuration performance. The results of the first four tests (presented in Section 4.3) showed a large amount of variability in the number of Bluetooth devices detected by any one reader, even for a single configuration. With this in mind, the Day 4 tests were repeated using vertical separation between readers instead of horizontal. The distance between adjacent readers remained three feet and once again all antennas were oriented flat. The configurations for each sensor array are listed below.

- Sensor Array 1: one reader at 10’ with antennas placed “flat”
- Sensor Array 2: two readers at 8.5’ and 11.5’ with antennas placed “flat”
- Sensor Array 3: four readers at 5.5’, 8.5’, 11.5’, and 14.5’ with antennas placed “flat”
- Sensor Array 4: three readers at 7’, 10’, and 13’ with antennas placed “flat”

3.4.2.6 Day 6: Monday, June 6th, 2011

On the final day of testing, the goal was to directly compare the performance of two vertical and two horizontal configurations. No control sensor array was configured, as there were insufficient tripods to deploy five configurations. This experiment placed two of each type of configuration at the site. All sensor arrays held three readers, each separated from its neighbor by three feet. The horizontally separated readers were all placed at a height of 10 feet, while the vertically separated readers were at heights of 7 feet, 10 feet, and 13 feet. The specific configuration for each sensor array is listed below.

- Sensor Array 1: three readers at 7’, 10’, and 13’ with antennas placed “flat”

- Sensor Array 2: three readers all at 10’ separated by 3’ with antennas placed “flat”
- Sensor Array 3: three readers at 7’, 10’, and 13’ with antennas placed “flat”
- Sensor Array 4: three readers all at 10’ separated by 3’ with antennas placed “flat”

3.4.2.7 Summary

A summary of the configurations for all six days of the configuration tests is displayed in Table 2.

Table 2: Summary of Configuration Test Configurations

Day #	Date	Array 1	Array 2	Array 3	Array 4
1	Tuesday May 10, 2011	Control (10’) Flat	2 Vertical (8.5', 11.5') Flat	2 Horizontal (10', 10') [1] Flat	N/A
2	Wednesday May 11, 2011	Control (10’) On Edge	2 Vertical (8.5', 11.5') On Edge	2 Horizontal (10', 10') [1] On Edge	2 Horizontal (10', 10')[2] Flat
3	Thursday May 12, 2011	3 Horizontal (10', 10', 10')[1] Flat	3 Horizontal (10', 10', 10') [1] Flat	5 Horizontal (all at 10') [1] Flat	Control (10’) Flat
4	Friday May 13, 2011	2 Horizontal (10', 10') [1] Flat	4 Horizontal (all at 10') [1] Flat	Control (10’) Flat	3 Horizontal (10', 10', 10') [1] Flat
5	Friday June 3, 2011	Control (10’) Flat	2 Vertical (8.5’, 11.5’) Flat	4 Vertical (5.5’, 8.5’, 11.5’, 14.5’), Flat	3 Vertical (7’, 10’, 13’) Flat
6	Monday June 6, 2011	3 Vertical (7’, 10’, 13’) Flat	3 Horizontal (10’, 10’, 10’)[1] Flat	3 Vertical (7’, 10’, 13’) Flat	3 Horizontal (10’, 10’, 10’)[1] Flat

[1] Three foot separation between readers

[2] No separation between readers

3.4.3 Video Data

During the study, video from two cameras was collected. One camera filmed a wide angle view of the road to obtain volume counts in both directions of Buford Highway. The other was focused in the southbound direction to obtain license plate data of passing vehicles, as it was expected that the majority of traffic would be traveling in this direction. The wide angle video data was analyzed by counting the number of vehicles traveling in the southbound and northbound directions in five minute intervals during the two-hour study period for each day of data collection.

3.4.4 Probe Vehicles

Two probe vehicles drove a designated route past the study site throughout the two-hour study period of each experiment. The first probe vehicle drove in the right lane heading northeast through the study segment. The second probe vehicle traveled in the left lane heading southwest through the study segment. Each vehicle was equipped with a Bluetooth enabled BT-335 GPS data logger and three IOGEAR class 1 Bluetooth adapters attached to netbooks. The GPS data logger was attached to the center of the dashboard, and the three Bluetooth adapters were attached to the right side of dashboard, to the front passenger seat, and to the floor in front of the front passenger seat in each vehicle. All of the devices were in discovery mode and were able to be detected by the Bluetooth readers. The location and MAC address of each device was recorded. Details regarding the probe vehicle routes are included in Appendix BB, and the results of the study are discussed in Section 4.3.

3.5 Buford Highway Travel Time Tests

The Buford Highway travel time study was performed after the previous reader configuration studies were completed. The Buford Highway Travel Time Tests consisted of five days of data collection during the morning and evening commute hours from Monday June 13th to Friday June 17th. The morning study period was generally from 7:00AM to 9:00AM and the evening study period from 4:30PM to 6:30PM. Various factors led to late starts for a few of the tests, but weather permitting, a total of two hours of Bluetooth and license plate data was collected during each session. One probe vehicle with discoverable Bluetooth devices and a GPS unit installed in it was driven continuously throughout the eight two-hour travel time test periods.

3.5.1 Locations

As part of the high occupancy vehicle (HOV) to high occupancy toll (HOT) lane conversion on I-85 [37], it was desired to monitor the performance of the parallel arterial, SR-13, also known as US-23 or Buford Highway. As a result, the portion of Buford Highway between Chamblee Tucker Road and Old Peachtree Road was initially selected as the study segment for the Bluetooth travel time tests. This 13-mile segment of Buford Highway is a four to six lane urban principal arterial [38] that runs from the City of Chamblee in DeKalb County to the City of Duluth in Gwinnett County, GA. There is a strong directional traffic flow on Buford Highway with the majority of vehicles traveling southbound (into Atlanta) in the mornings and northbound in the evenings. Identifying regular commuters along this corridor was another goal of the data collection effort; therefore, four segments were identified between the two end streets, using three major intersections that provide access to I-85 as the dividing lines to capture any new commuters who may have entered the study corridor at one of these high-volume intersections. The roads that begin and end each segment are, from south to north, Chamblee Tucker Road, I-285, Jimmy Carter Boulevard, Beaver Ruin Road, and Old Peachtree Road. These major intersections are shown in Figure 10.

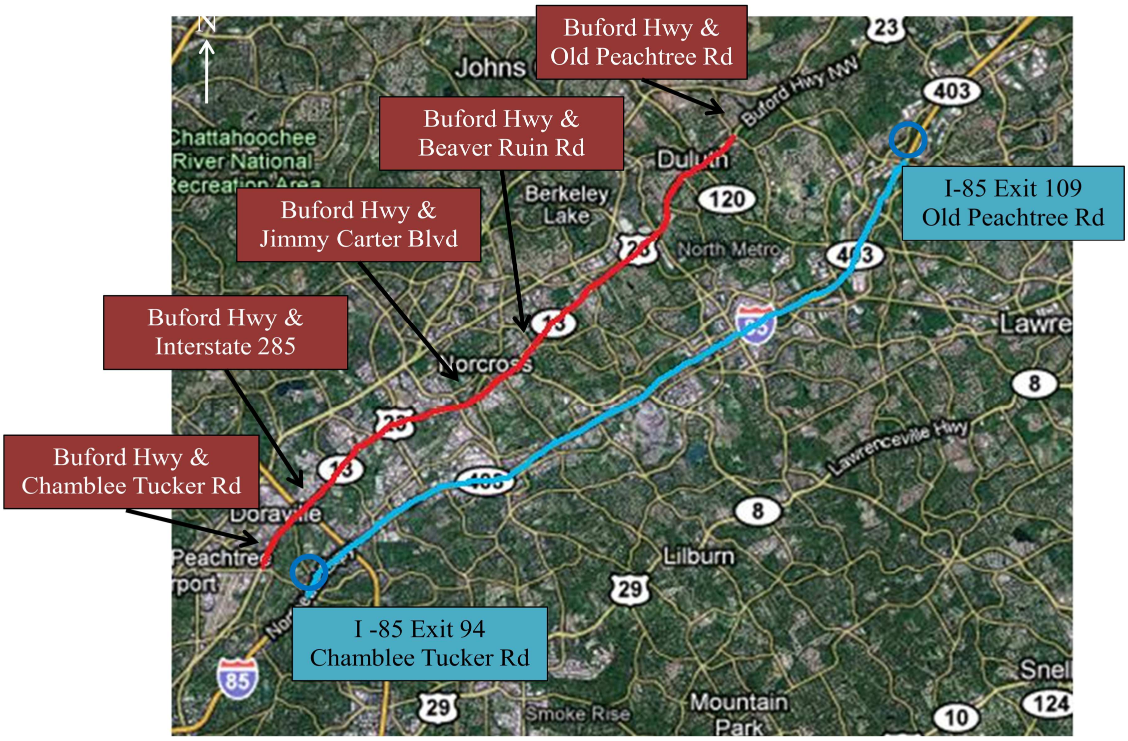


Figure 10: Major Intersections Dividing the Buford Hwy Test Segments

Specific sites within each segment were selected as data collection sites based on their suitability for setting up video cameras for license plate data. Midblock locations were preferred to avoid a stopped or closely-following vehicle from blocking the license plate of the vehicle in front of it. The midblock locations are also ideal for Bluetooth stations for a number of reasons. At an intersection, the Bluetooth readers can detect vehicles traveling on the cross-street. This will increase the detection rates of vehicles that are not traveling through the corridor and are irrelevant to the travel time study (the percent of the total volume passing the site that is detected). Also, the extended amount of time that a vehicle may be within range of the Bluetooth reader at an intersection introduces error in the calculated travel time. Data collection at intersections can create a large disparity between first-to-first and last-to-last travel times. For example, assume Vehicle 1 is initially detected as the red phase begins and Vehicle 2 is initially detected as the red phase is ending. If they both pass the second site at the same time, their first-to-first travel times would differ by the length of the red phase, as it took Vehicle 1 that much longer to reach the second site. Based on last-to-last detection travel times, however, Vehicle 1 and Vehicle 2 would have similar travel times. Had the reader been farther upstream of the signal, the last-to-last travel times would also differ by the length of the red phase.

A total of eight locations were chosen as potential data collection sites: four on the west side of the roadway and four on the east side of the roadway to accommodate morning and evening directional traffic volumes, respectively. Due to limited resources, two of the original four segments of Buford Highway were chosen for the study, resulting in four total sites, two in the peak AM direction and two in the peak PM direction. The two segments were from Chamblee Tucker Road to I-285 and from Jimmy Carter Boulevard to Beaver Ruin Road. The sites are numbered using the original eight-site naming convention, increasing in the direction of peak travel. The first letter indicates whether it is an AM or PM site. Figure 11 shows an overview of the location of the four selected sites for this study. Detailed maps of each site are included in Appendix C.

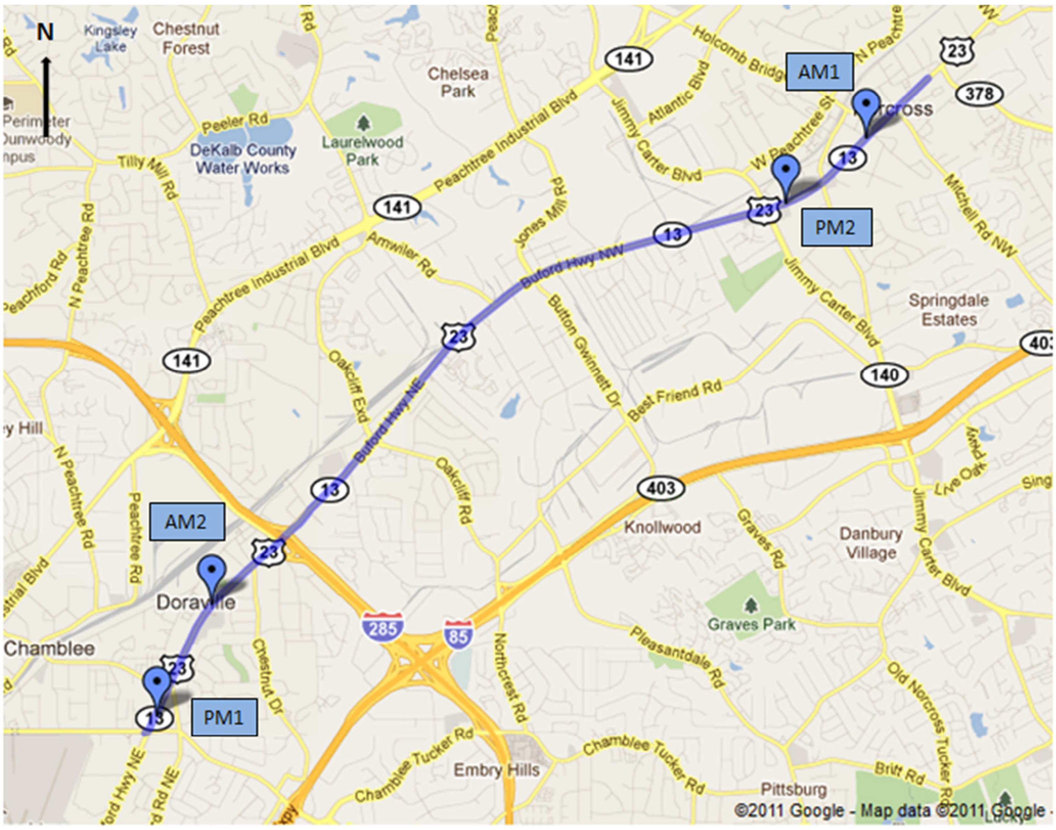


Figure 11: Location Map of Sites for the June 2011 Tests

3.5.1.1 AM Data Collection Sites

The morning data collection locations consist of Sites A2 and A4, described below. The two sites are on the west side of the road, allowing for a camera to be positioned to capture the license plates of southbound vehicles traveling into Atlanta during the morning commute. The distance between the two sites is 5.1 miles along Buford Highway.

Site A2: 5825 Buford Highway

Site A2 is located on the segment of Buford Highway between Jimmy Carter Boulevard and Beaver Ruin Road. The location is immediately south of Carlyle Street, outside of the offices at 5825 Buford Highway. Buford Highway has two lanes in each direction and a two-way left turn lane at this location.

Site A4: 5302 Buford Highway

Site A4 is along the segment of Buford Highway between Chamblee Tucker Road and I-285, south of Park Avenue. The site is in the parking lot of the Korean Town plaza at 5302 Buford Highway. The roadway has three lanes in each direction and a two-way left turn lane at this location.

3.5.1.2 PM Data Collection Sites

The evening data collection locations consist of sites P1 and P3, described in detail below. The two sites are on the east side of the roadway, enabling a video camera to be set up to collect the license plates of northbound traveling vehicles during the evening commute period. The two sites are 5.4 miles apart.

Site P1: 4949 Buford Highway

Site P1 is along the segment of Buford Highway between Chamblee Tucker Road and I-285. This location is just north of Chamblee Tucker Road in the parking lot at 4949 Buford Highway. Buford Highway has three lanes in each direction and a two-way left turn lane at this location.

Site P3: 6355 Buford Highway

Site P3 is located on the segment of Buford Highway between Jimmy Carter Boulevard and Beaver Ruin Road. The site is in front of the Carter Crossing shopping center. The location is just north of Jimmy Carter Boulevard at 6355 Buford Highway. The roadway has two lanes in each direction and a two-way left turn lane by this site.

3.5.2 License Plate Capture

Finding locations suitable for collecting video license plate data along an arterial is challenging. For the best view, the camera needs to be positioned above the roadway with a straight-on view of the plates. The height minimizes blockage of license plates due to large trucks and buses or vehicles following too closely. Also, large angles between the camera view and the direction of travel of the vehicles decreases plate clarity. Ideally, the best location is a camera set up on an overpass directly between the two lanes being recorded.

The challenge of locating sites on Buford Highway was the lack of an overpass, as the only bridge throughout the study segment is the I-285 overpass. Instead, sites were initially sought that had flat, elevated ground within a small setback of the road. These sites were difficult to find, although the video quality from these types of locations was good. Initial field assessments indicated that better video could be obtained by focusing the camera on a curve in the road. The best video was obtained where there was both a curve in the road and an increase in elevation as the vehicles traveled away from the camera, as this reduced the amount of blockage by other vehicles and allowed for a straight-on view of the plates. Figure 12 shows an example of this ideal view.

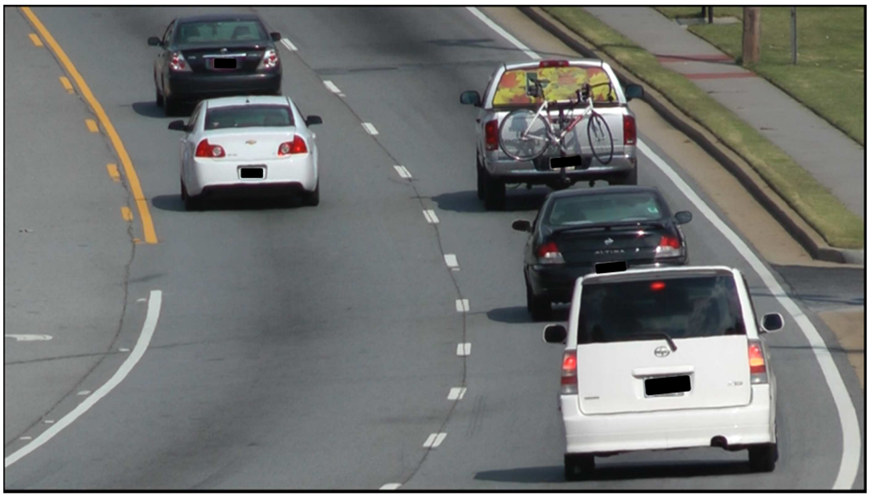


Figure 12: Ideal Camera View for Arterial Roadway License Plate Captures

This ideal view was obtained by mounting the high resolution video camera on a tripod with the tripod legs extended to the fullest extent. The camera is then zoomed in as far as possible and focused as shown in Appendix C. License plate data of vehicles traveling in the commute direction is recorded for the duration of each two-hour study period. One camera is used at Site A2 and Site P3 where only two lanes of vehicle license plates are needed. At Site A4 and Site P1, three lanes of traffic are present in each direction, requiring two cameras per site. These cameras were configured to capture two lanes each, with the middle lane captured twice for redundancy and cross-checking purposes. The videos were later manually processed using video software that allows the data entry processor to maneuver back and forth between video frames, select the best view, and enter the vehicle classification, state, and license plate information. The software then records the time stamp of that frame along with the inputted information and transfers it to a database.

3.5.3 Bluetooth Sensor Configurations

Two Bluetooth sensor arrays were configured at each of the two sites during the morning and evening study periods. One sensor array at each site was always the control station, with one Bluetooth reader set up at a height of 10 feet. The other sensor array's configuration varied and was tested once during the morning and once during the evening study period. The variables for the second sensor array included the number of Bluetooth readers and the direction of the Bluetooth readers relative to one another (in a line horizontally or vertically). All readers were oriented flat relative to the ground throughout the travel time study (see Section 3.3).

Sections 3.5.3.1 through 3.5.3.5 describe the configurations for each day of travel time tests. Four different configurations were planned for the second sensor array. These configurations were originally planned to be tested in four days, with the same configuration during the AM and PM commute period of each day; however, inclement weather caused the four configurations to be conducted over the course of five days instead. The configurations were based on the results of the previous configuration study described in Section 3.4 as well as the results of the antenna orientation test detailed in Section 3.3. This new deployment provided the opportunity to further test the performance of multiple readers in vertical versus horizontal arrangements, as well as further experiment with multiple numbers of readers per sensor array to assess the cumulative benefit of adding one more reader to a sensor array. For this deployment, the total number of Bluetooth readers on the second sensor array ranged from three to five.

3.5.3.1 Day 1: Monday June 13, 2011

On the first day of the travel time study, Monday June 13, 2011, the same configuration was tested during the morning and evening commute hours. Three readers were attached to the second sensor array, all at a height of 10 feet. The readers were separated from each other horizontally by three feet as demonstrated in Figure 13.

Figure 13: Monday Configuration with Three Horizontally Separated Readers

3.5.3.2 Day 2: Tuesday June 14, 2011

The second day of travel time tests also consisted of matching configuration during the morning and evening periods. Three readers were attached to the second sensor array at each site and the adapters were placed three feet apart; however, this time the adapters were separated vertically with one at 7 feet, one at 10 feet, and one at 13 feet. Figure 14 shows an example of this configuration.

Figure 14: Tuesday Configuration with Three Readers Separated Vertically

3.5.3.3 Day 3: Wednesday June 15, 2011

The third day of travel time tests involved a sensor array of five readers at each site during both the morning and evening study periods. The readers were placed at a height of ten feet and separated horizontally with three feet in between each adapter. Two large tripod bases connected by a horizontal crossbar were required for this configuration, as shown in Figure 15.

Figure 15: Wednesday Configuration with Five Readers Separated Horizontally

3.5.3.4 Day 4: Thursday June 16, 2011

On the fourth day of the study, data were only collected during the afternoon commute, as rain necessitated the cancelation of Thursday morning's test. The configuration for the day consisted of four readers separated vertically by three feet at heights of 5.5 feet, 8.5 feet, 11.5 feet, and 14.5 feet, as seen in Figure 16.

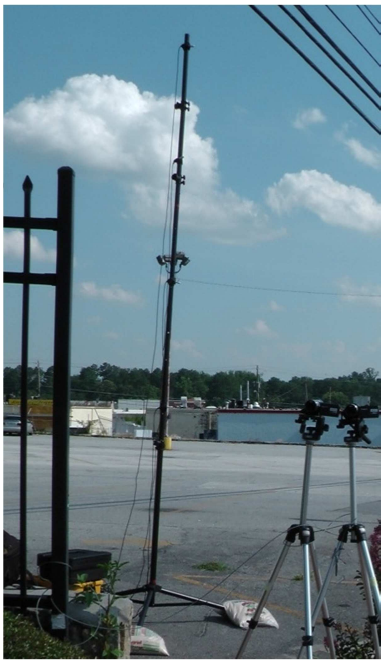


Figure 16: Thursday and Friday Configuration with Four Readers Separated Vertically

3.5.3.5 Day 5: Friday June 17, 2011

On Friday June 17th, the cancelled experiment from Thursday morning was performed during the AM commute hours. The configuration for the second sensor array at each site was identical to the Day 4 afternoon configuration detailed in Section 3.5.3.4.

3.5.3.6 Summary

Table 3 shows a summary of the configurations for all eight study periods during the Buford Highway Travel Time Test.

Table 3: Summary of Buford Highway Travel Time Test Configurations

Date	Site AM1/PM1 Array 1	Site AM1/PM1 Array 2	Site AM2/PM2 Array 1	Site AM2/PM2 Array 2
Monday June 13, 2011 AM	3 Horizontal (10', 10', 10')	Control (10’)	Control (10’)	3 Horizontal (10', 10', 10')
Monday June 13, 2011 PM	Control (10’)	3 Horizontal (10', 10', 10')	Control (10’)	3 Horizontal (10', 10', 10')
Tuesday June 14, 2011 AM	3 Vertical (7', 10', 13')	Control (10’)	Control (10’)	3 Vertical (7', 10', 13')
Tuesday June 14, 2011 PM	Control (10’)	3 Vertical (7', 10', 13')	Control (10’)	3 Vertical (7', 10', 13')
Wednesday June 15, 2011 AM	Control	5 Horizontal (all at 10')	Control (10’)	5 Horizontal (all at 10')
Wednesday June 15, 2011 PM	5 Horizontal (all at 10’)	Control (10’)	Control (10’)	5 Horizontal (all at 10’)
Thursday June 16, 2011 PM	Control (10’)	4 Vertical (5.5', 8.5', 11.5', 14.5')	Control (10’)	4 Vertical (5.5', 8.5', 11.5', 14.5')
Friday June 17, 2011 AM	Control (10’)	4 Vertical (5.5', 8.5', 11.5', 14.5')	Control (10’)	4 Vertical (5.5', 8.5', 11.5', 14.5')

Three foot separation between all horizontal readers. All readers placed flat.

3.5.4 Probe Vehicle

Throughout the two-hour study period of each of the five days of travel time tests, a probe vehicle circulated Buford Highway equipped with a Bluetooth enabled BT-335 GPS device and three discoverable Class 1 IOGEAR Bluetooth adapters connected to netbooks. The devices were attached to the vehicle in the locations specified in Table 4. The internal Bluetooth adapter in Netbook 8 was also detectable during most of the tests. During the Monday evening test, Netbook 10 was used as a replacement netbook for a Bluetooth reader, resulting in only three discoverable devices in the probe vehicle.

Table 4: Locations of Probe Vehicle Devices

Device Type	MAC Address	Name	Location
Netbook 8 with IOGEAR adapter	00:02:**:**:**:F7	IOGear 8	Front Passenger Floor
Netbook 9 with IOGEAR adapter	00:02:**:**:**:68	IOGear 9	Front Passenger Seat
Netbook 10 with IOGEAR adapter	00:02:**:**:**:64	IOGear 10	Dash on Passenger Side
GPS Data Logger	00:0D:**: **:**:22	GPS BT-335	Center of Dash (AM)
GPS Data Logger	00:0D:**: **:**:15	GPS BT-335	Center of Dash (PM)

The probe vehicle route differed slightly during the morning and evening sessions; however, both routes led the vehicle to drive directly past each site in the northbound and southbound direction. Detailed route descriptions and maps are included in Appendix C.

CHAPTER 4: RESULTS

4.1 Bluetooth Detection Range Observations

The Bluetooth detection range observations provided insight on the results from the Spring Street test and on the performance of the IOGEAR Class 1 Bluetooth adapters used in this study. The test showed that while literature states that Bluetooth does not require line-of-sight and that the signal can go through most physical barriers [17], line-of-sight does affect the ability of a Bluetooth device to be detected. Figure 17 shows the locations where at least one probe device was detected and the locations where no Bluetooth devices were able to be detected. As seen in the map, line-of-sight had a considerable effect on the detection zone, as none of the probe devices were identifiable inside any building, even behind only one glass door approximately 100 feet away from the Bluetooth reader in the Georgia Tech Economic Development Building doorway. In addition, outdoor locations that were not within sight of the reader, such as on Armstead Place and at the northeast corner of Spring Street and 4th Street, were also out of the detection range. None of the probe devices could be identified near these locations until the researcher carrying them walked into the line-of-sight of the reader.

As the devices were all in either a pocket or a backpack, direct line-of-sight is not required; however, the density of the obstruction seemed to influence the probability of detection. The direction the researcher was facing changed which probe devices were detectable. For example, if the researcher was facing the Bluetooth reader, then the iPhone and the BT-335 GPS unit, located in the researcher’s front left and front right pockets, respectively, were detected; however, the QT-BT1000 GPS unit and the netbooks which were located in the researcher's back right pocket and backpack, respectively, were not detected. The opposite occurred when the researcher was facing away from the Bluetooth reader, leading to the conclusion that the probe devices' Bluetooth radio waves could not pass through the researcher's body, although they could pass through the fabric of a pair of jeans or a backpack. Building walls and glass doors also appeared to be obstructions that the Bluetooth signal could not pass through.

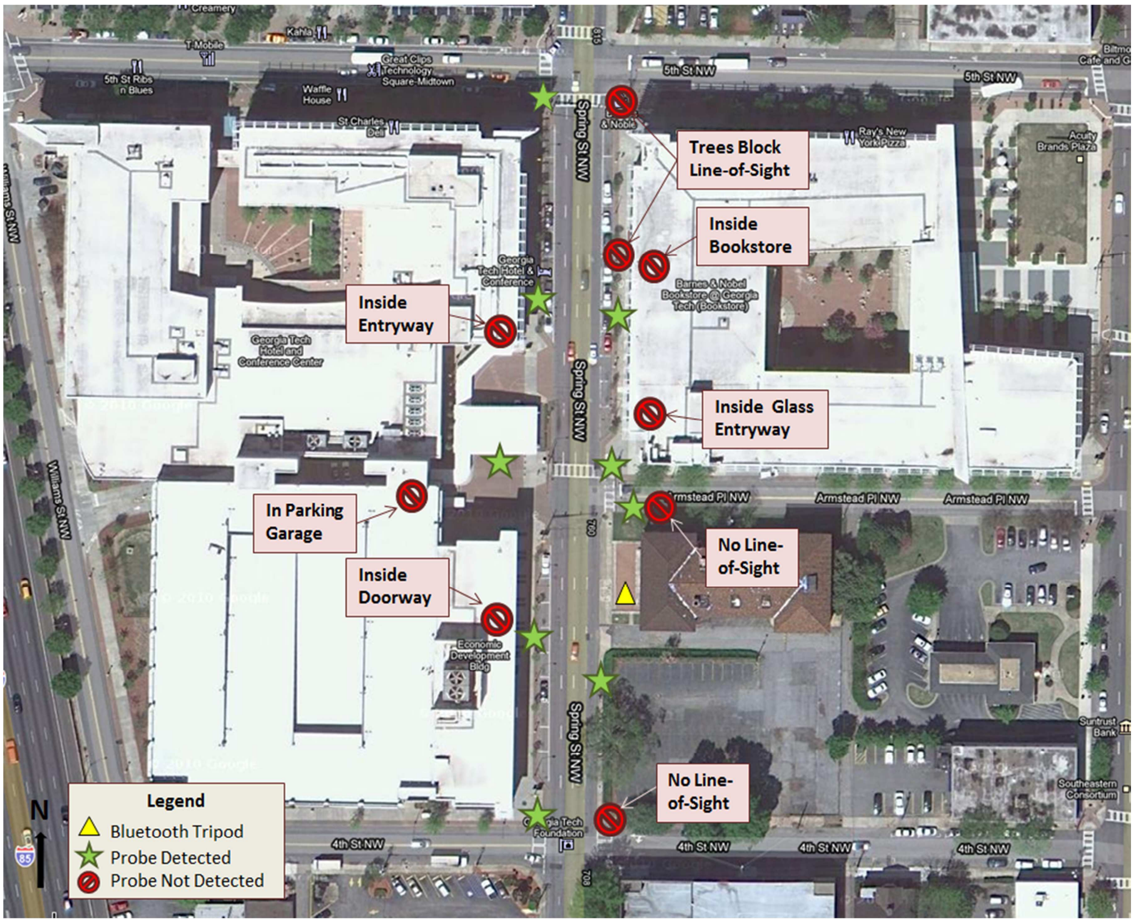


Figure 17: Map of Spring Street Detection Zone Results ***(Background image from [36])***

While these results show that discoverable devices located in the surrounding buildings on Spring Street would not have affected the results of the January Spring Street travel time case study, pedestrians near the intersection of Spring Street and 5th Street may have had an influence on the detection rate. The probe devices were detected at the southwest corner of the intersection, where a large volume of pedestrians wait to cross the street. The devices were not detected on the southeast corner, likely due to a lack of a direct line-of-sight to the reader because of the trees along Spring Street. The probe devices were detected at all other outdoor locations between 5th Street and 4th Street that had a direct line-of-sight to the Bluetooth reader, including under the awning of the Georgia Tech Hotel and Conference Center taxi stand.

4.2 Determination of Optimal Bluetooth Reader Orientation

The Bluetooth reader orientation tests showed that antenna orientation does change the maximum distance at which a Bluetooth device can be detected. There was a strong indication that the flat reader orientation allows for the greatest detection range. As shown in Table 5, at an angle between zero and 75 degrees a consistent detection distance of 360 feet was found. At an angle above 75 degrees the reader was more inconsistent with detection distances between 355 feet and 370 feet. At 180 degrees, where the Bluetooth antenna is facing the exact opposite direction of the discoverable device, no consistent detection distance was found. The probe device was detected at least once in the same 355 feet to 370 feet range, but never three times in one minute.

Table 5: Maximum Detection Distance Based on Reader Orientation

Orientation		Maximum Detection Distance (ft) Flat	On Edge	Vertical
Angle (degrees)	0	360	325	325
	15	360	315	-
	30	360	-	-
	45	360	-	-
	60	360	-	-
	75	360	-	-
	90	355	-	330
	105	360	-	-
	120	355	-	-
	135	360	-	-
	150	370	-	-
	165	365	-	-
	180	Inconsistent	-	-

When the adapter was positioned on edge, the maximum detection distance decreased significantly. At an angle of zero degrees and 15 degrees, the range was only 325 feet and 315 feet, respectively. At an angle of 30 degrees, the reader was also showing a much shorter detection range. The exact distance of a reliable range for the other angles was not measured, as the flat orientation was shown to have a greater maximum detection distance. Similarly, the initial results of the vertical orientation test did not show a need to test all thirteen angles. At zero degrees, the vertical orientation had a detection range of 325 feet. An angle of 90 degrees was tested to evaluate whether there would be a major difference in range at that angle. The result showed a detection distance of only 330 feet, which indicated that testing the other vertical orientation angles was unnecessary as the flat orientation showed a greater maximum detection range.

The varying detection distances for a flat reader at an angle of 90 to 180 degrees suggest that the best reader orientation for placement along a roadway is with the adapter placed flat and at zero degrees (with the long part of the adapter perpendicular to the direction of the roadway). This allows for a detection angle of between zero and 90 degrees as vehicles approach, pass, and leave the site, resulting in a maximum detection range equivalent to 360 feet for Class 2 devices for most of the portion of the detection zone covering the roadway. A visual representation of this detection zone is shown in Figure 18. The detection range for detecting Class 1 devices is expected to be greater as their specification requires a range of at least 100 meters (300 feet) versus the 10 meter (30 feet) minimum range requirement of the Class 2 device [16] used for this test.

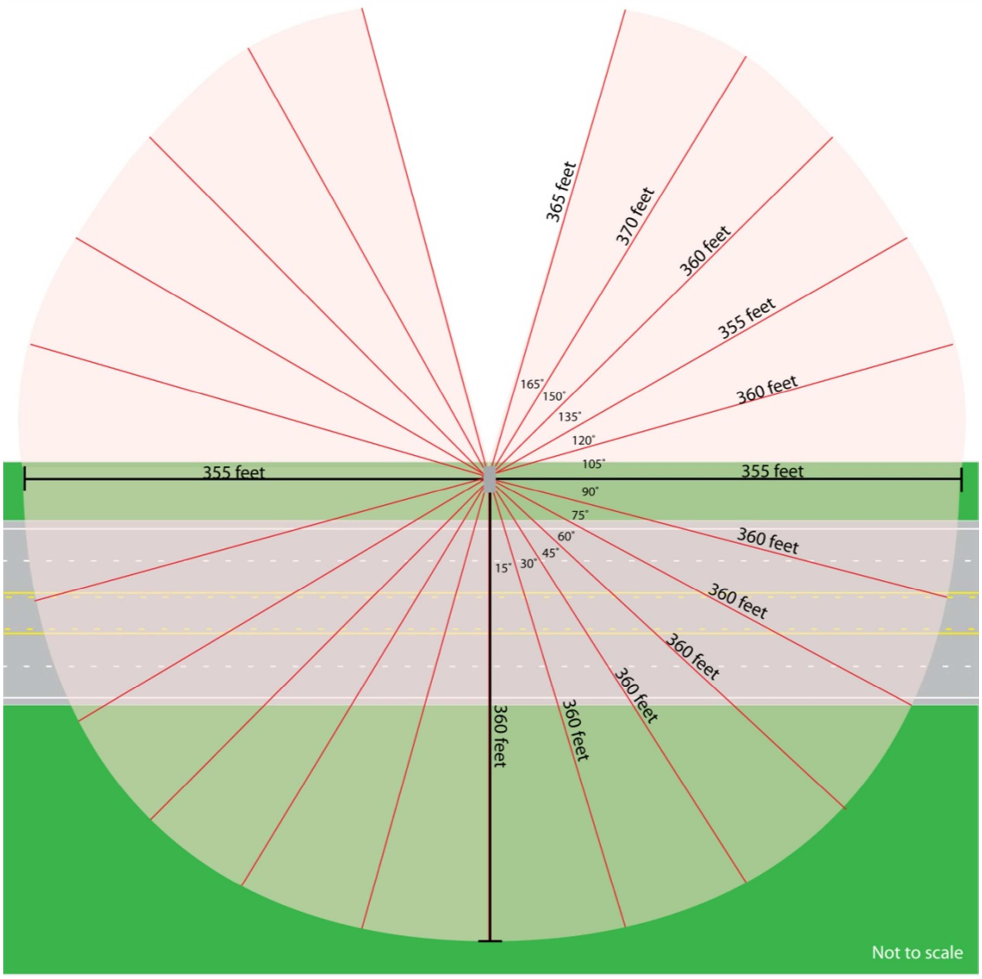


Figure 18: Visual Representation of a Flat Reader Orientation Detection Zone

4.3 Comparison of Bluetooth Reader Configurations

The Bluetooth reader configuration tests were analyzed based on an assortment of variables with the goal of evaluating the factors that have the most influence on the number of vehicles detected during the study period. The main performance metric used to evaluate the effectiveness of the various configurations was vehicle detection rate, defined as the number of different MAC addresses detected divided by the volume of passing vehicles. Each device's MAC address may be detected multiple times by individual or multiple readers during the study period; therefore, the number of *different*

MAC addresses is used in analyzing the results to ensure that each device is only counted once per reader. For sensor array total detections, devices detected by multiple readers are also only counted once. Unless specifically stated, the MAC addresses of the probe devices were excluded from all results, including volume data.

4.3.1 Day 1 Results

The first day of the configuration tests involved comparing two readers separated by three feet horizontally and two readers separated by three feet vertically to a single reader sensor array, the control. The two hour study period for Tuesday's test was from 8:00AM to 10:00AM. The volume data showed that the majority of vehicles travel in the southbound direction during the morning commute hours, as shown in Figure 19. The total volume in both directions over the two hours was 3,334 vehicles, with 2,270 of those vehicles traveling in the southbound direction.

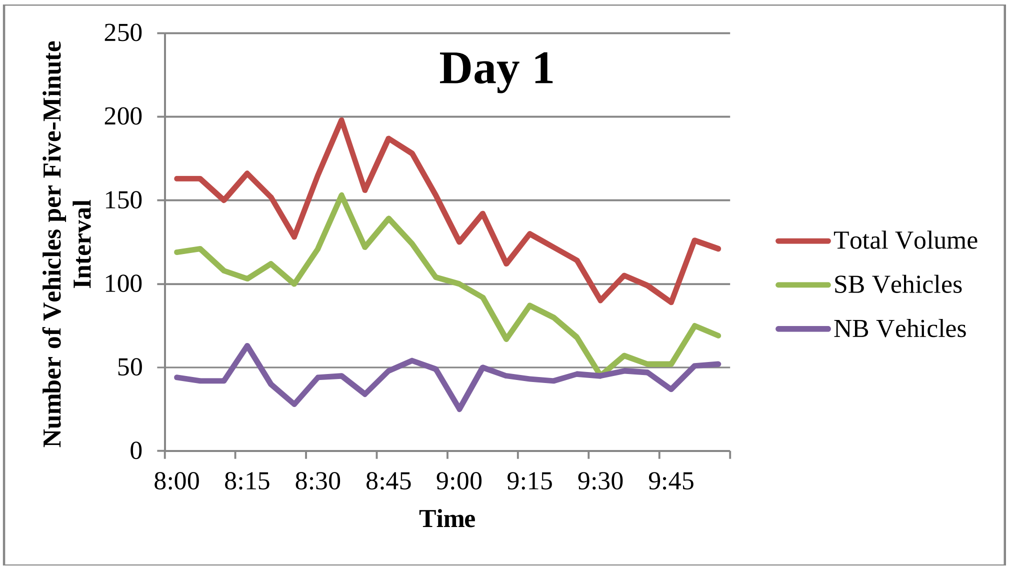


Figure 19: Day 1 Configuration Test Volumes

A summary of the number of different MAC addresses detected by each reader is shown is Table 6. The last column indicates the number of different MAC addresses that were detected by each sensor array. The number is not the sum of the detections per reader, as one device may have been detected by multiple readers on the same array. A total of 241 different MAC addresses were detected during the two-hour data collection period on Day 1, which results in an overall vehicle detection rate of 7.23%.

Table 6: Summary of Day 1 Readers and Number of MACs Detected

Variable	Sensor Array	Reader #	Height (feet)	Antenna Orientation	# of Different MACs Detected	Total Different MACs per Sensor Array
Control	1	15	10	Flat	113	113
Vertical	2	16	8.5	Flat	106	146
	2	17	11.5	Flat	78	
Horizontal	3	18	10	Flat	117	175
	3	19	10	Flat	127	

Figure 20 shows the detection rate of the three-sensor arrays over each five-minute period of the test. As seen in the figure and in Table 7, the maximum detection rate of 10.1% of the horizontal sensor array configuration was higher than that of either the vertical or control sensor arrays at 9.6% and 7.0%, respectively. The same trend was seen for the overall detection rates of each sensor array during the full two-hour period. A summary of these detection rates is shown in Table 7. It is noted that the overall control detection rate was 3.4%, which is lower than the 5% to 10% commonly reported in the literature.

Table 7: Summary of Day 1 Detection Rates

Configuration	Maximum Detection Rate	Overall Detection Rate
Control	7.0%	3.4%
Vertical	9.6%	4.4%
Horizontal	10.1%	5.3%

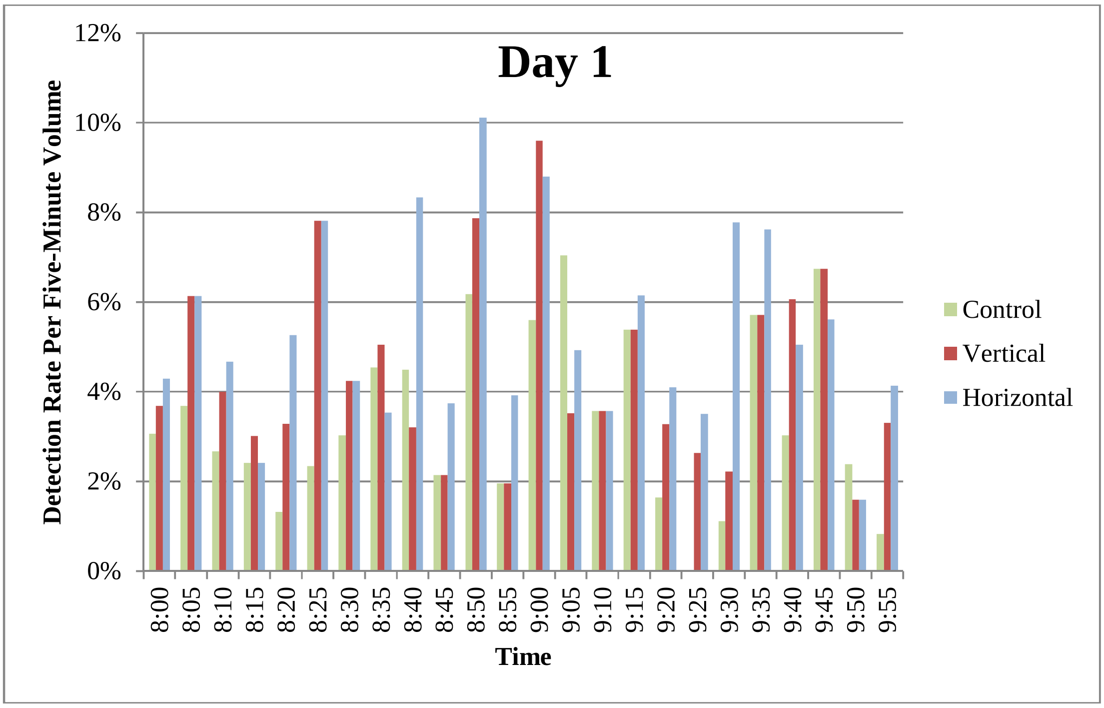


Figure 20: Day 1 Detection Rates by Sensor Array

Figure 21 shows the increase in the number of different MAC addresses detected by the horizontal and vertical sensor arrays, each with two readers, relative to the single control reader. The results indicate that having multiple readers per sensor array increases the number of devices that are detected at that location, as both multi-reader arrays detected more devices than the control during almost all of the five-minute time periods. In total, the vertical and horizontal sensor arrays detected 33 (29%) and 62 (55%) more devices, respectively, than the control array.

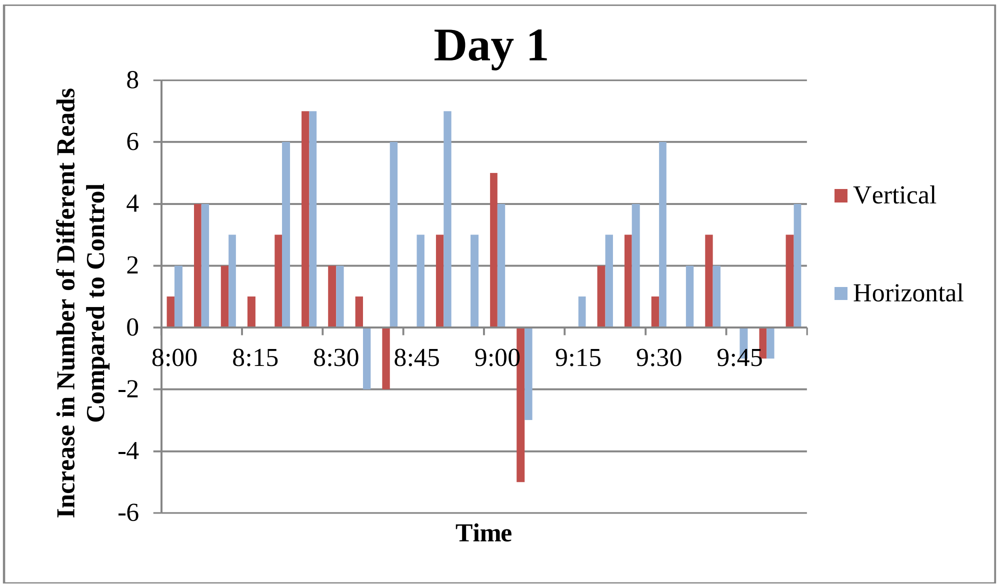


Figure 21: Comparison of Day 1 Sensor Array Configurations by Increase in Different Detections

Although the total number of detections per sensor array increased, there was a decrease in the number of different MAC addresses detected by the individual readers on the vertical sensor array. As displayed in Table 6, a total of 113 different MAC addresses were detected by the control sensor array while the two readers on the vertical sensor array detected only 106 and 78 MACs, respectively. This could be due to interference from having two readers only three feet apart; however, the two readers on the horizontal sensor array each detected more MAC addresses than the control reader, with 117 and 127 detections, respectively, leaving the reason for the variation in number of detections inconclusive. Regardless, the higher number of different MAC addresses in the combined sensor array data indicates that any decrease in one reader's detections due to potential interference was negated by the larger number of different reads that were detected by the other reader on the array.

4.3.2 Day 2 Results

Data were collected from 7:45AM to 9:45AM on Wednesday May 11th, 2011. The volumes on Buford Highway during the study period were similar to those measured the previous day and again showed strong southbound directional traffic. Figure 22 provides a visual representation of the volume trend over the two hours, grouped by five minute bin. The total volume was 3,581 vehicles, with 2,451 traveling in the southbound direction. The results of Day 2's configuration tests were analyzed to further compare horizontal and vertical separation of readers, as well as to assess the effect of having no separation between two readers. Day 2 data were compared to Day 1 data; however, there were too many variables that changed between the two days to directly study the effect of the "flat" versus the "on edge" orientation of the readers.

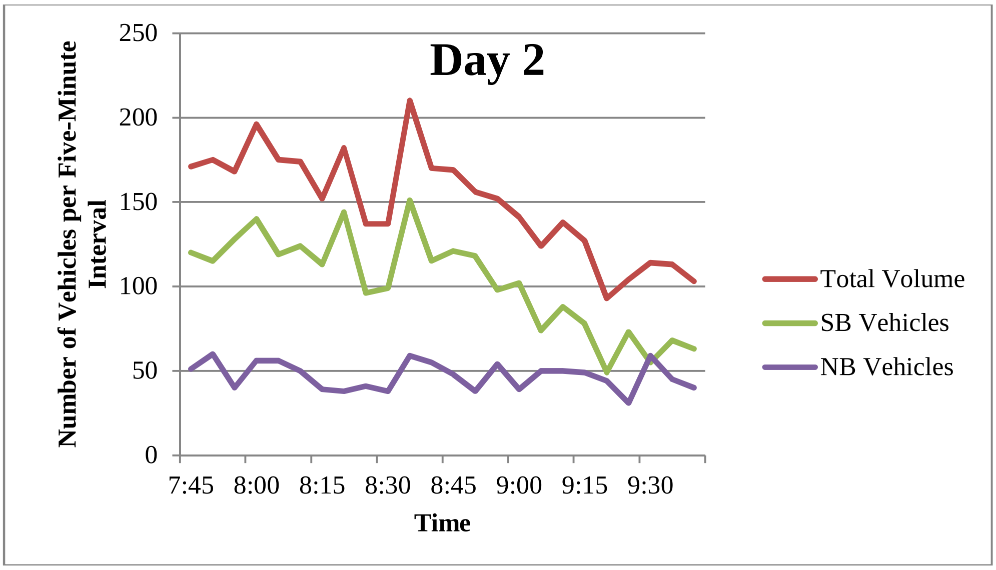


Figure 22: Day 2 Configuration Test Volumes

Table 8 summarizes the various configurations for the Day 2 tests as well as the number of different detections by each reader and the cumulative number of different detections by each sensor array. Similar to the previous day's results, the horizontal array showed the largest number of different MAC addresses with 171 detections, followed by the vertical array with 144 detections. The sensor array consisting of two readers with no separation showed a large decrease in the number of MAC addresses detected by each individual reader, although the total of 89 is similar to the 93 total detections found by the control sensor array. This indicates that combining the detections of the two non-separated readers during analysis of the Spring Street test results [18] likely gave an accurate measure of how one single reader at ten feet would have performed.

Table 8: Summary of Day 2 Readers and Number of MACs Detected

Variable	Sensor Array	Reader #	Height (feet)	Orientation	# of Different MACs Detected	Total Different MACs per Sensor Array
Control	1	15	10	On Edge	93	93
Vertical	2	16	8.5	On Edge	87	144
	2	17	11.5	On Edge	103	
Horizontal	3	18	10	On Edge	114	171
	3	19	10	On Edge	116	
No Separation	4	20	10	Flat	53	89
	4	21	10	Flat	49	

Table 9 and Figure 23 display the detection rates for the Day 2 sensor array configurations. Although the increasing trend in the detection rates of the control, vertical, and horizontal configurations is the same as the previous day's test results, both the maximum and overall detections rates are lower for all three configurations relative to the previous day's comparable arrays. The overall detection rate for all sensor arrays combined at the site for Day 2 was lower than the previous day at 6.42% with a total of 230 different MAC addresses detected. The decrease could be due to a variety of factors: a change in the orientation of the readers, an increase in the total number of readers at the site, or a decrease in the percent of the traffic stream that had discoverable Bluetooth devices.

Table 9: Summary of Day 2 Detection Rates

Configuration	Maximum Detection Rate	Overall Detection Rate
Control	5.11%	2.82%
Vertical	7.06%	4.24%
Horizontal	8.00%	5.00%
No Separation	5.26%	2.71%

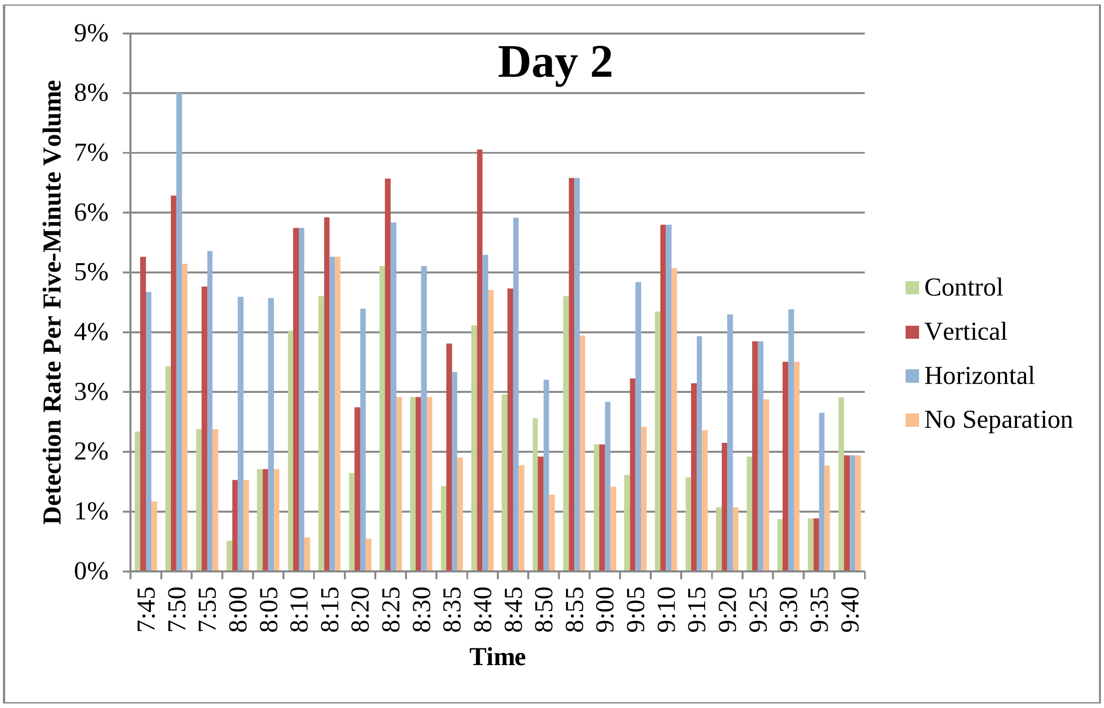


Figure 23: Day 2 Detection Rates by Sensor Array

The increase in the number of detections by each multi-reader array over the single reader array is shown in Figure 24. The vertical and horizontal arrays consistently showed positive increases in detection rates during each five-minute period, with the control reader only detecting more different devices than either the vertical or horizontal array twice during the two-hours of data collection. This finding complements Day 1 results that having multiple readers separated by three feet on one sensor array allows for a larger sample size to be collected.

By contrast, the sensor array comprising of two readers with no separation had multiple periods with a decrease in the number of detections relative to the single reader array. At most, Sensor Array 4 had three more detections than the control during any one five-minute time period. Overall, the detector array with no separation between detectors exhibited a detection rate that was 0.1% lower than the control array. This indicates that there is no benefit to placing multiple readers on a sensor array without a separation between them.

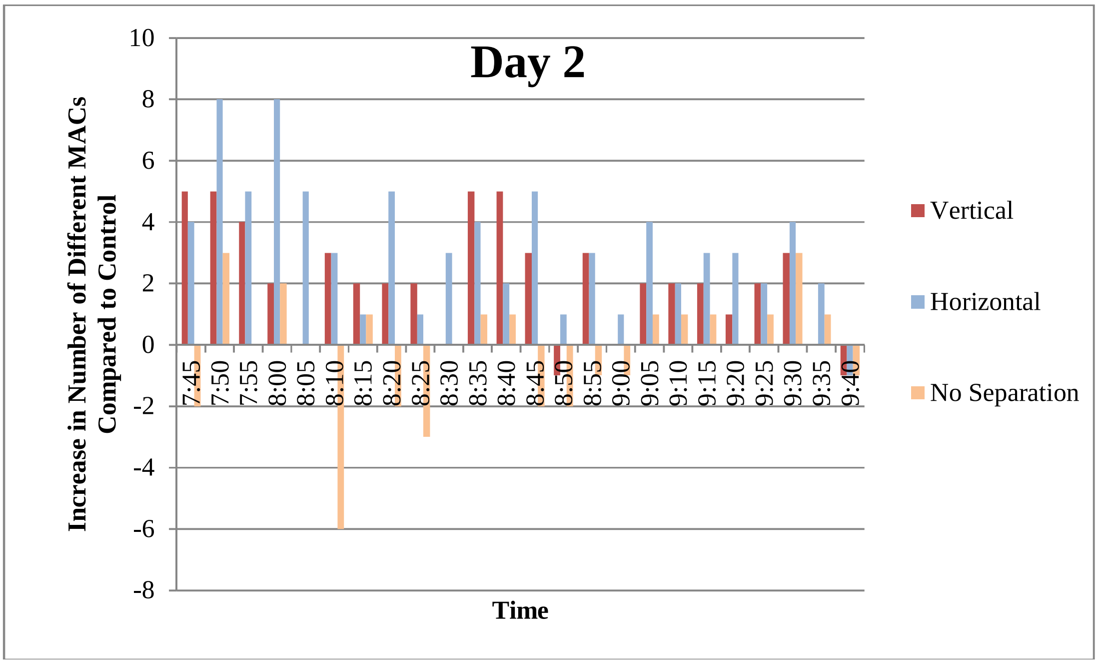


Figure 24: Comparison of Day 2 Sensor Array Configurations by Increase in Different Detections

4.3.3 Day 3 Results

On Thursday May 12th, 2011, configuration test data were collected between 7:45AM and 9:45AM. Four sensor arrays were again compared at the site: a control, two three-reader arrays (Sensor Array 1 and Sensor Array 2), and a five-reader array. The results were analyzed to evaluate whether increasing the number of readers per sensor array would affect the performance of the array. As Sensor Array 1 and Sensor Array 2 had identical configurations, variability within the same type of configuration was also assessed. Day 3 volume data binned in five-minute intervals are displayed in Figure 25. The total volume during the two-hour study period was 3,425 vehicles, with 2,379 vehicles traveling in the southbound direction.

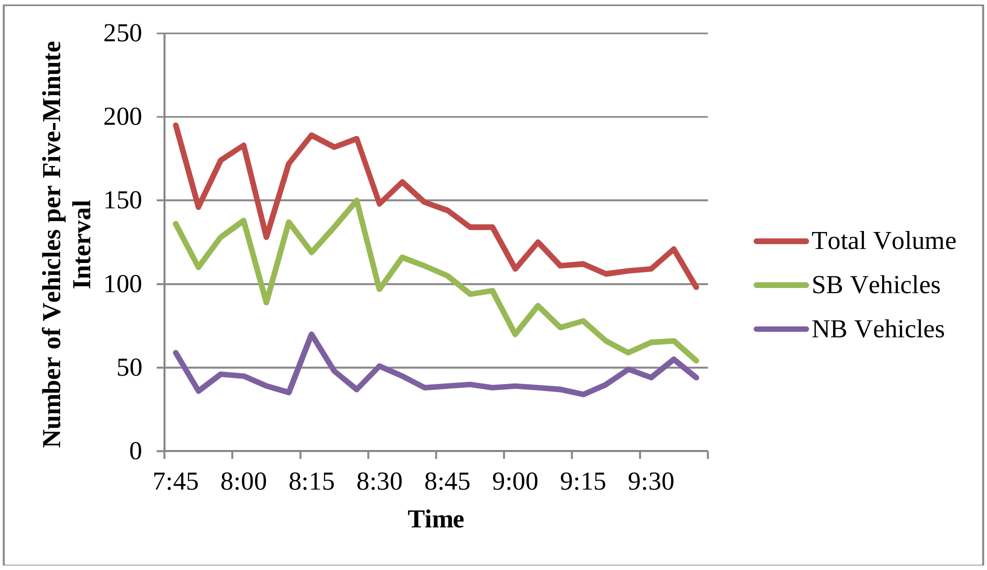


Figure 25: Day 3 Configuration Test Volumes

A summary of the Day 3 sensor array configurations and the number of different MAC addresses detected is in Table 10. The two three-reader arrays detected a comparable number of total MAC addresses detections; however, the individual reader detections varied immensely, from 18 to 103 detections. This indicates that the adjacent adapters may interfere with one another, with a higher detecting adapter limiting the number of MAC addresses that its neighboring reader can detect. When the different detections per sensor array are summed, the numbers appear to even out. For example, on Sensor Array 2, the higher number of detections from Reader 14 appears to have compensated for the extremely low number of reads from Reader 16, resulting in 134 total detections, which is comparable to the 127 detections gathered from the more evenly-distributed readers on Sensor Array 1. As shown in Figure 26, the number of detections by each sensor array during each five-minute period of the study varied. At times, Sensor Array 1 detected more devices and at times Sensor Array 2 detected more devices. On average though, the total number of MAC addresses for any five-minute period only differed by 0.29 detections. The two three-reader arrays had a total difference of 7 detections overall.

Table 10: Summary of Day 3 Sensor Arrays and Number of MACs Detected

Variable	Sensor Array	Reader #	Height (feet)	Orientation	# of Different MACs Detected	Total Different MACs per Sensor Array
Control	4	22	10	Flat	97	97
3 Readers (Array 1)	1	11	10	Flat	50	127
	1	12	10	Flat	68	
	1	13	10	Flat	72	
3 Readers (Array 2)	2	14	10	Flat	103	134
	2	15	10	Flat	49	
	2	16	10	Flat	18	
5 Readers	3	17	10	Flat	65	164
	3	18	10	Flat	55	
	3	19	10	Flat	72	
	3	20	10	Flat	63	
	3	21	10	Flat	45	

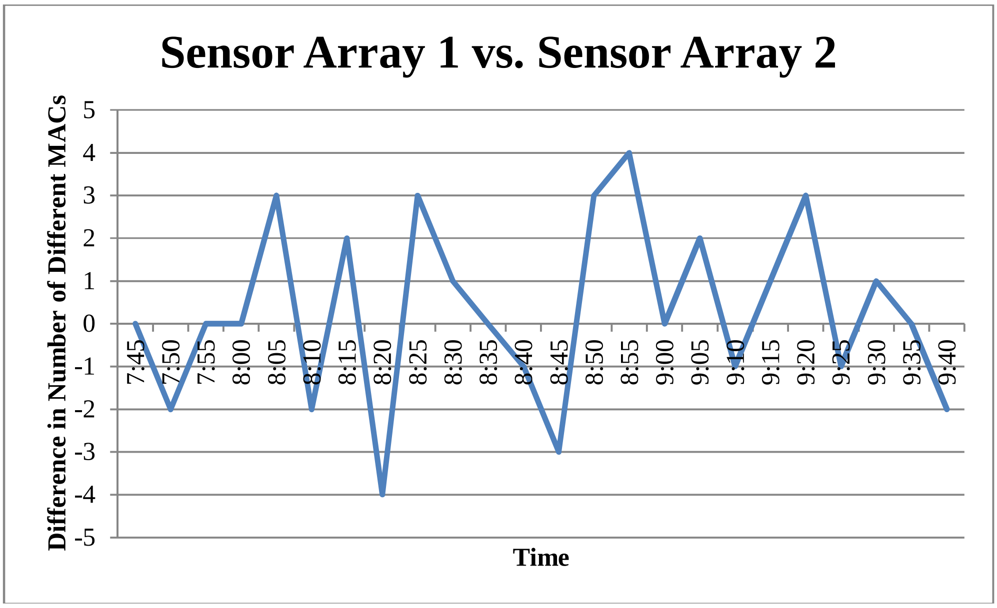


Figure 26: Comparison of Detections by the Three-Reader Sensor Arrays

Of the four different sensor arrays, the one with five readers had the largest overall detection rate at 4.79% of all vehicles. The maximum detection rate of the five-reader array for any five-minute period was 9.03%, also the highest of the four sensor arrays. The two three-reader arrays showed similar detection rates of 3.71% and 3.91%, while the single-reader control array was the lowest at 2.83%. These results are summarized in Table 11 and Figure 27. The overall detection rate for the control sensor array was comparable to the Day 2 control detection rate of 2.82%. Combining the data from all of the sensor arrays for the day's experiment, a total of 220 different devices were detected, resulting in an overall detection rate of 6.42%.

Table 11: Summary of Day 3 Detection Rates

Configuration	Maximum Detection Rate	Overall Detection Rate
Control	6.31%	2.83%
3 Readers (Array 1)	7.14%	3.71%
3 Readers (Array 2)	8.49%	3.91%
5 Readers	9.03%	4.79%

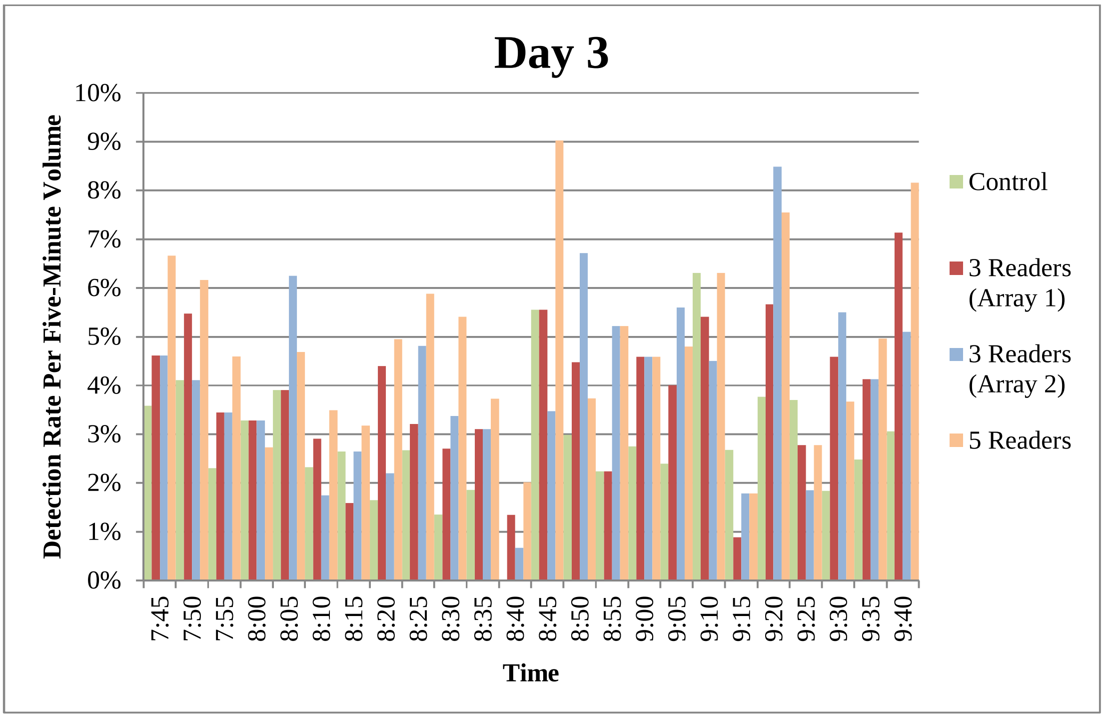


Figure 27: Day 3 Detection Rates by Sensor Array

As previously discussed and indicated in Figure 28, the three-sensor arrays with multiple readers at ten feet all showed consistently higher detections than the single control reader. There were a few five-minute periods where there was a decrease in the number of different MAC addresses detected, but overall the values are mostly positive. The five-reader sensor array showed the highest increases in number of different devices detected. This indicates that a greater number of readers per sensor array will allow for the detection of a larger sample size of passing vehicles.

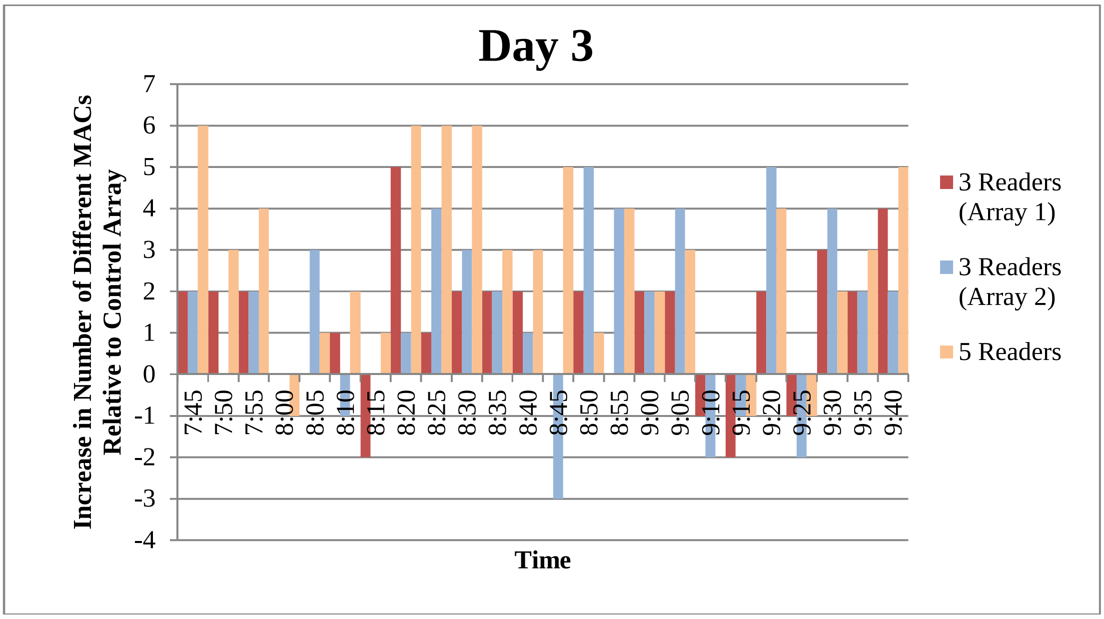


Figure 28: Comparison of Day 3 Sensor Array Configurations by Increase in Different Detections

4.3.4 Day 4 Results

Data for the fourth day of the study were collected between 7:50AM and 9:50AM on Friday May 13th, 2011. The four configurations consisted of all readers placed flat at a height of ten feet, each separated by three feet horizontally. The variable was the number of readers per sensor array, which ranged from one to four. The results were assessed to further evaluate the effect of increasing the number of readers per sensor array. The camera stopped before the full two hours of volume data were recorded; therefore, data involving volumes (including detection rates) are only calculated from 7:50AM to 9:45AM. Once again, a strong directional traffic flow occurred, with 2,325 vehicles of a total 3,430 vehicles traveling in the southbound direction. The volume counts by five-minute period are displayed in Figure 29.

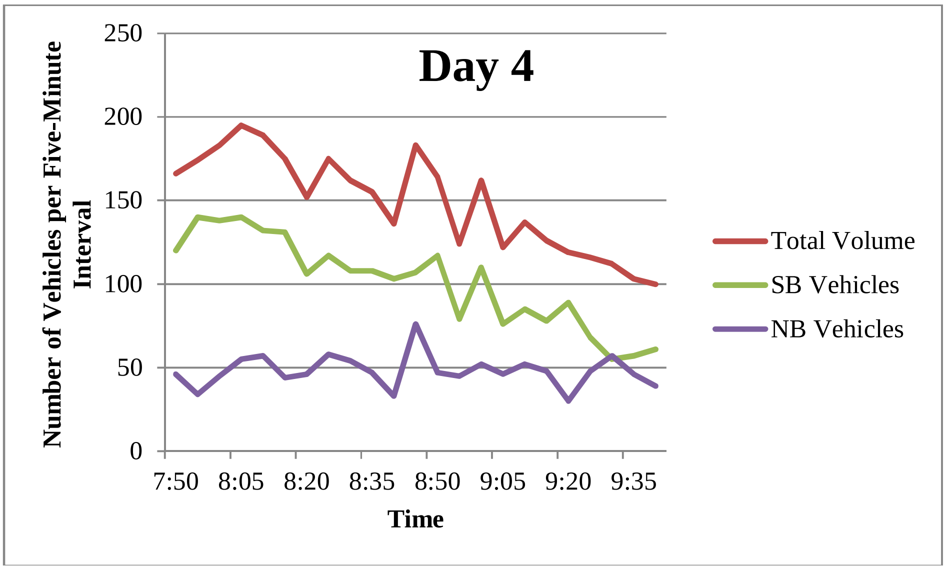


Figure 29: Day 4 Configuration Test Volumes

Table 12 summarizes the Day 4 sensor array configurations and the number of different MAC addresses detected per reader and per sensor array. The data complement the previous day's results, indicating that installing multiple readers per sensor array results in a larger number of detected MAC addresses. Interestingly, however, the two-reader sensor array detected a total of 164 devices, while the three-reader array only detected a total of 149 different MACs. This suggests that while the number of detections increases with the use of multiple readers, it may not increase sequentially with each additional reader.

Table 12: Summary of Day 4 Sensor Arrays and Number of MACs Detected

Variable	Sensor Array	Reader #	Height (feet)	Orientation	# of Different MACs Detected	Total Different MACs per Sensor Array
Control	3	18	10	Flat	88	88
2 Readers	1	12	10	Flat	104	164
	1	13	10	Flat	124	
3 Readers	4	19	10	Flat	84	149
	4	20	10	Flat	73	
	4	21	10	Flat	74	
4 Readers	2	14	10	Flat	102	196
	2	15	10	Flat	124	
	2	16	10	Flat	71	
	2	17	10	Flat	83	

The maximum detection rate per five-minute period and the overall detection rate of each sensor array configuration are listed in Table 13. Figure 30 shows the distribution of different MAC addresses detected for each five minutes of the study period. The four reader sensor array consistently had the highest or one of the highest detection rates throughout the experiment. Combining the detections of the four sensor arrays, a total of 253 different MAC addresses were detected, resulting in a total detection rate of 7.38% for the two-hour study period.

Table 13: Summary of Day 4 Detection Rates

Configuration	Maximum Detection Rate	Overall Detection Rate
Control	4.60%	2.47%
2 Readers	7.94%	4.48%
3 Readers	8.04%	4.11%
4 Readers	8.73%	5.43%

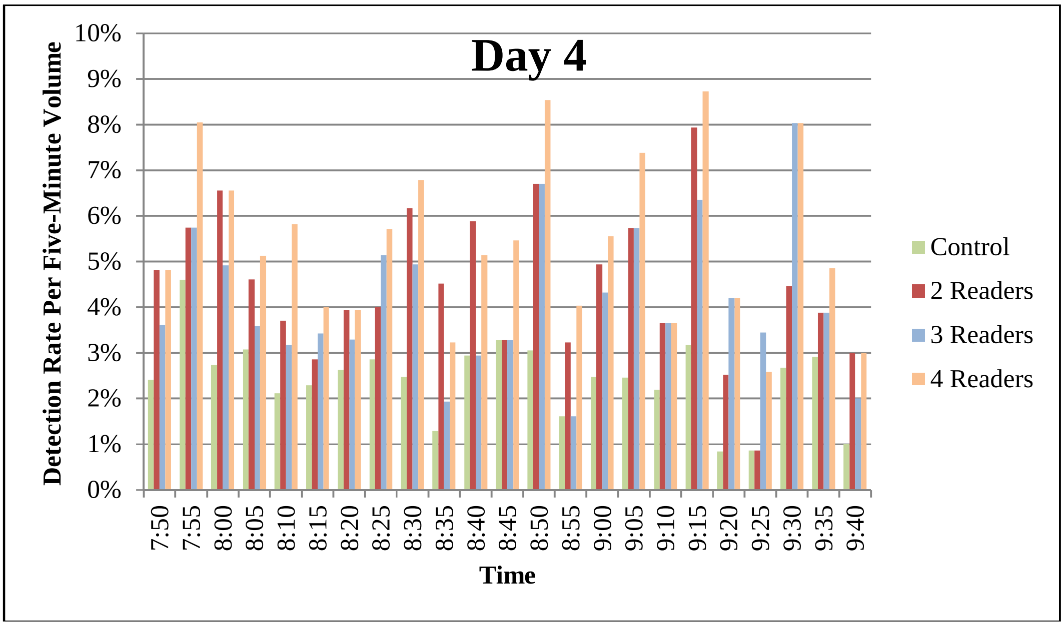


Figure 30: Day 4 Detection Rates by Sensor Array

Figure 31 shows the increase in number of detections for the two-, three-, and four-reader arrays over the single-reader array during each five-minute data collection period. Unlike the previous days' results, the multi-reader sensor arrays had an equivalent or greater number of detections relative to the control array during all of the five-minute periods of the study.

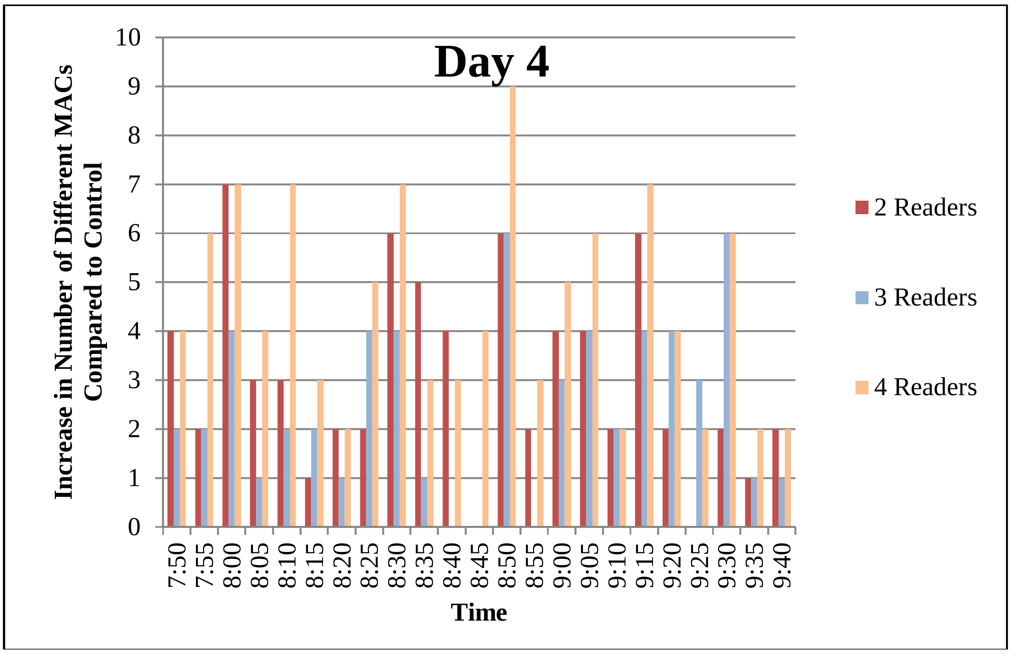


Figure 31: Comparison of Day 4 Sensor Array Configurations by Increase in Different Detections

4.3.5 Day 5 Results

On the fifth day of the configuration tests, Friday June 3rd, data were collected between 7:15AM and 9:15AM. The test configurations were two, three, and four readers per sensor array, each separated vertically from the adjacent reader by three feet with the readers centered at a height of ten feet. The similar reader configurations to the previous day's test allows for further evaluation of the effects of increasing the number of readers per array with the added variable of vertical instead of horizontal separation. The single control sensor array malfunctioned during the test; therefore, no comparison with the control array after 9:00AM is possible for these data and no analysis of the control can be done for the full two hours of data collection. Volume data for Day 5 are displayed in Figure 32. Once again, the majority of vehicles (2185) were traveling in the southbound morning commute direction. In total there was a volume of 3169 in both directions during the two-hour study period.

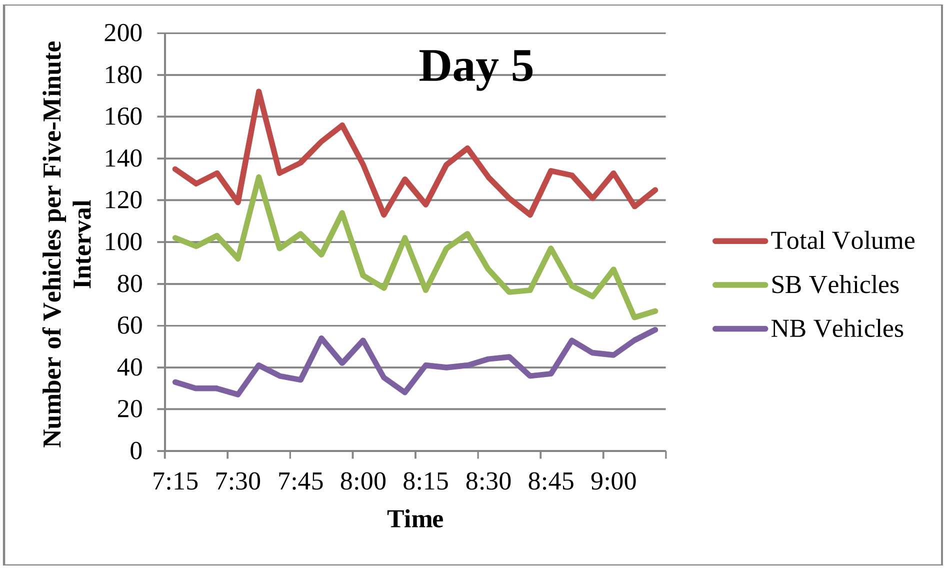


Figure 32: Day 5 Configuration Test Volumes

Table 14 shows a summary of the configurations for the Day 5 tests, as well as the number of devices detected by each reader and by sensor array. Once again, the two-reader sensor array performed better than the three-reader sensor array, with 16 more detections. Day 4 results showed an increase of 15 detections on the two-reader sensor compared to the three-reader array. This indicates that regardless of whether the readers are separated horizontally or vertically, assuming one MAC address corresponds to one vehicle, having two readers per sensor array produces a larger sample size of passing vehicles than having three readers per sensor array.

Table 14: Summary of Day 5 Sensor Arrays and Number of MACs Detected

Variable	Sensor Array	Reader #	Height (feet)	Orientation	# of Different MACs Detected during 2 hrs	Total Different MACs per Sensor Array during 2 hrs (1 hr 45 mins)
Control	1	13	10	Flat	N/A	N/A (77)
2 Readers	2	14	8.5	Flat	60	97 (91)
	2	15	11.5	Flat	62	
3 Readers	3	20	7	Flat	38	81 (71)
	3	21	10	Flat	36	
	3	22	13	Flat	38	
4 Readers	4	16	5.5	Flat	55	128 (117)
	4	17	8.5	Flat	58	
	4	18	11.5	Flat	60	
	4	19	14.5	Flat	47	

Similar to the Day 4 results, the four-reader sensor array again had the highest maximum and overall detection rates, as seen in Table 15. Overall, the detection rate for each vertically separated multi-reader array is more than 1% lower than the detection rate for the comparable horizontally separated multi-reader array. For the 1 hour 45 minutes that the control reader collected data, the overall detection rate was 2.76%, slightly higher than the previous day's 2.47%. This suggests that there was at least a comparable percent of discoverable devices in the traffic stream on Day 5 and supports Day 1 and Day 2 data that the vertically separated sensor arrays are less effective than horizontally separated sensor arrays. A visual representation of the detection rates for each sensor array by five-minute period of the experiment is displayed in Figure 33. Not including the MAC addresses only detected by Reader 13, which malfunctioned after approximately 1 hour and 45 minutes, there was an overall detection rate of 5.30% for the day. Including the devices only detected by the control sensor array during the time that it was functioning, the overall detection rate for the two-hour period is increased to 5.65%.

Table 15: Summary of Day 5 Detection Rates

Configuration	Maximum Detection Rate	Overall Detection Rate
Control	5.41%*	2.76%*
2 Readers	8.26%	3.06%
3 Readers	5.79%	2.56%
4 Readers	9.09%	4.04%

** Control rates are only for 7:15AM-9:00AM*

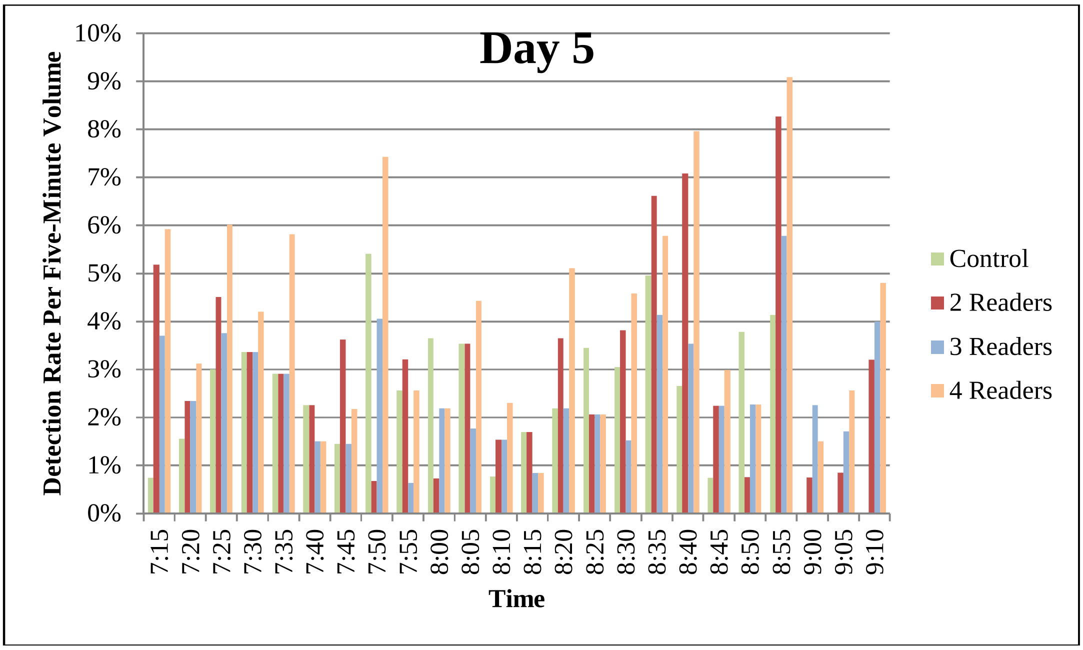


Figure 33: Day 5 Detection Rates by Sensor Array

Figure 34 shows the increase in number of devices detected for each multi-reader sensor array when compared to the single-reader array. Results are only shown from 7:15AM to 9:00AM to exclude the 15 minutes when the control array was not collecting data. The four-reader array detected more MAC addresses fairly consistently throughout the study period, as did the two-reader array. There were a few periods, however, when the control detected 4 or more MAC addresses than the two-reader sensor array. The only other day of the configuration tests that this large of a difference was seen from separated multi-reader arrays was on Day 1, again with two vertically separated readers. Furthermore, for the time period where all four sensor arrays were working, the three-reader array detected only 71 MAC addresses, six fewer than the control array. These results support previous observations that vertically separated readers are not the ideal sensor array configuration.

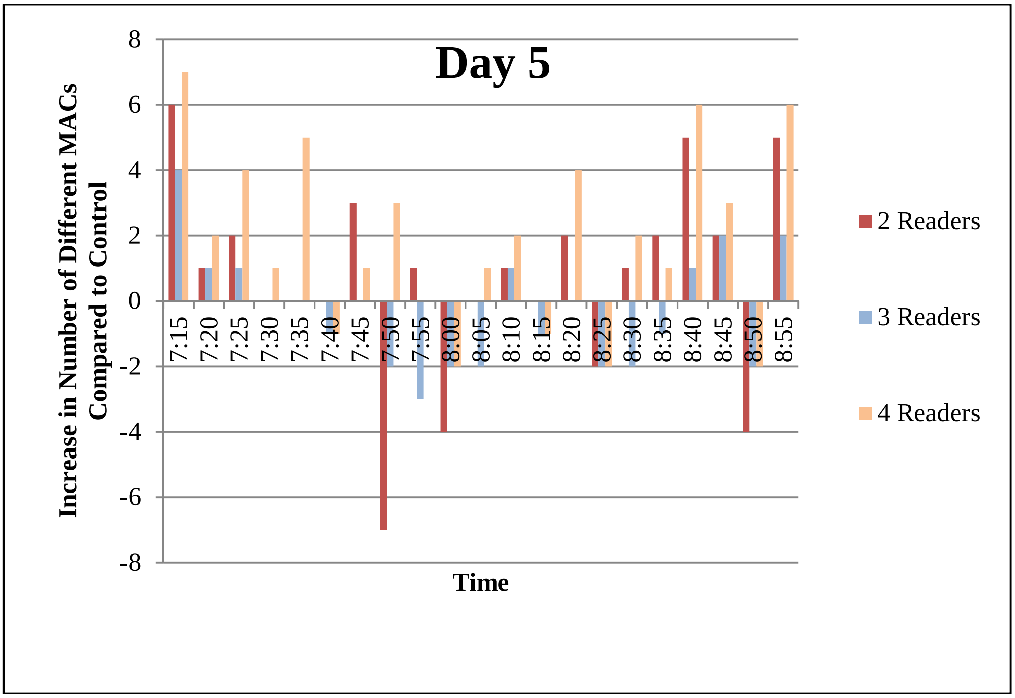


Figure 34: Comparison of Day 5 Sensor Array Configurations by Increase in Different Detections

4.3.6 Day 6 Results

Data were collected on Day 6, Monday, June 6th, 2011 from 7:15AM-9:15AM. The day six configurations consisted of four sensor arrays, two with three readers separated vertically at 7 feet, 10 feet, and 13 feet, and two with three readers separated horizontally, all at a height of 10 feet. The day's data were analyzed to further compare the performance of vertical and horizontal sensor arrays, as well as evaluate the variability between identical types of sensor arrays. The volume data for the two-hour data collection period is shown in Figure 35, binned in five-minute intervals. There was a total volume of 3,455 vehicles over the two hours, with 2,482 vehicles traveling in the southbound direction.

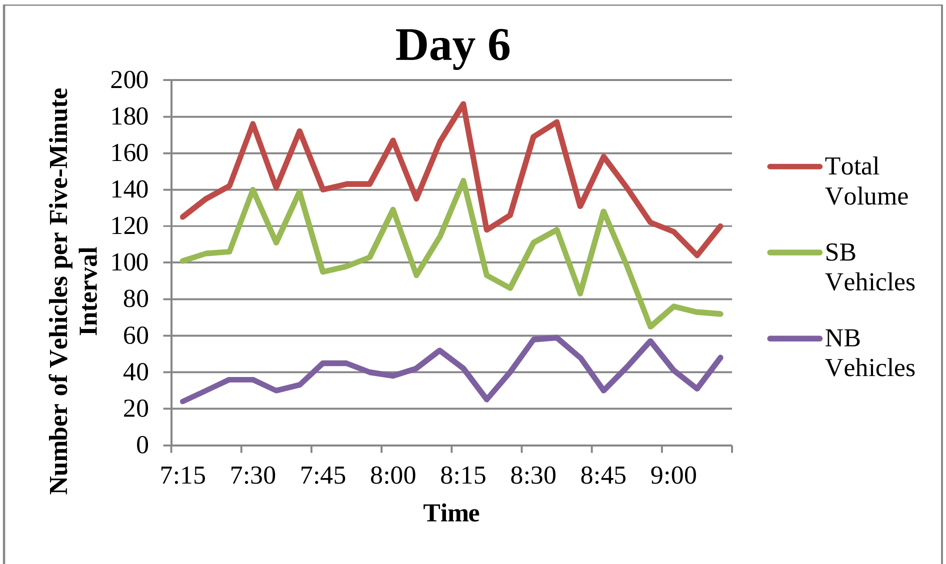


Figure 35: Day 6 Configuration Test Volumes

Table 16 gives a summary of the sensor array configurations for Day 6, including the number of different devices detected by each reader on the array. The detections across all readers ranged from 40 to 69 different MAC addresses, except for Reader 14 and Reader 22, which identified 93 and 81 devices, respectively. These readers were both on separate horizontally configured sensor arrays and contributed to the larger number of detections by the horizontal arrays than the vertical arrays. No trend is evident in the number of detections based on the height of the readers on the vertically separated arrays.

Table 16: Summary of Day 6 Sensor Arrays and Number of MACs Detected

Variable	Sensor Array	Reader #	Height (feet)	Orientation	# of Different MACs Detected	Total Different MACs per Sensor Array
Vertical (Array 1)	1	11	7	Flat	59	110
	1	12	10	Flat	40	
	1	13	13	Flat	67	
Horizontal (Array 2)	2	14	10	Flat	93	141
	2	15	10	Flat	69	
	2	16	10	Flat	61	
Vertical (Array 3)	3	17	7	Flat	59	106
	3	18	10	Flat	53	
	3	19	13	Flat	43	
Horizontal (Array 4)	4	20	10	Flat	59	123
	4	21	10	Flat	46	
	4	22	10	Flat	81	

As indicated in Table 17 and Figure 36, Sensor Array 2 and Sensor Array 4, both with horizontal reader configurations, showed the highest detections rates of the four sensor arrays with overall detection rates of 4.08% and 3.56%, respectively. The vertical sensor arrays had detection rates of 3.18% and 3.07%. The maximum detection rates for any five-minute period were highest for the horizontal configurations as well. This observation continues the trend seen in previous days' data in that horizontally separated arrays appear to be more effective than vertically separated sensor arrays. Overall, a total of 198 different devices were detected by any reader or sensor array at the site on Day 6.

Using the assumption of one device per vehicle and the counted volume of 3,455 vehicles, this indicates that combining the detections from all the arrays, there was a total vehicle detection rate of 5.73% for the study period.

Table 17: Summary of Day 6 Detection Rates

Configuration	Maximum Detection Rate	Overall Detection Rate
Vertical (Array 1)	6.78%	3.18%
Horizontal (Array 2)	8.40%	4.08%
Vertical (Array 3)	5.42%	3.07%
Horizontal (Array 4)	7.63%	3.56%

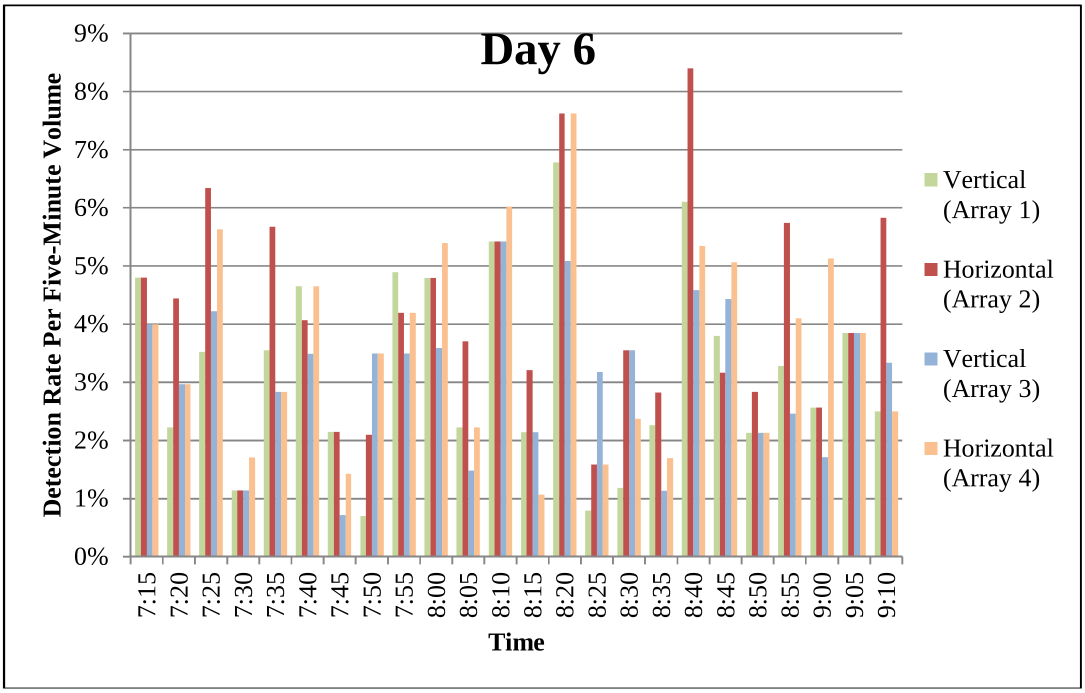


Figure 36: Day 6 Detection Rates by Sensor Array

Figure 37 and Figure 38 show the variability in detections across sensor arrays of the same configuration. During each five-minute period, both the vertical and horizontal arrays varied by at most 4 detections. In total there was only a 4 MAC address difference in the vertical sensor arrays and an 18 MAC address difference in the horizontal sensor arrays, which correspond to percent differences of only 0.93% and 3.41%, respectively. This suggests that while there is some variability in the MAC addresses detected by a sensor array, identical sensor arrays gather comparable numbers of detections. These results coincide with the Day 3 results which also showed little variability in the two identical sensor array configurations.

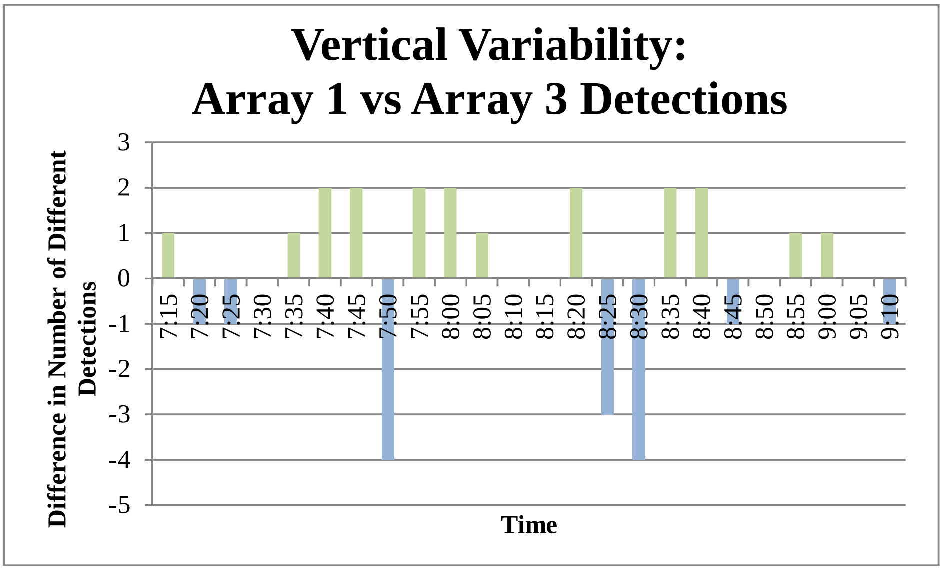


Figure 37: Difference in Detections by Five-Minute Periods for the Vertical Sensor Arrays

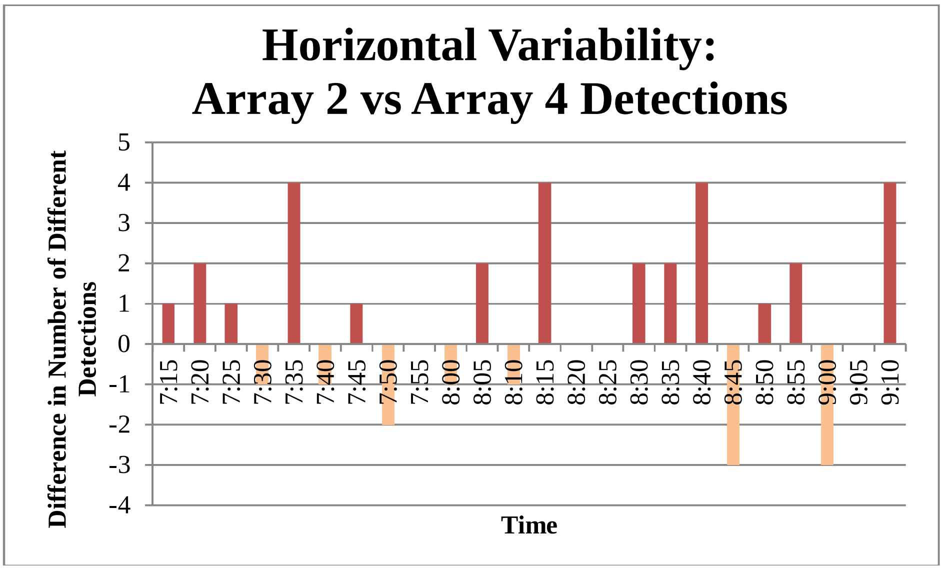


Figure 38: Difference in Detections by Five-Minute Periods for the Horizontal Sensor Arrays

4.4 Travel Time Tests

The data from the week of June 13th, 2011 were collected to evaluate the viability of collecting travel time data using Bluetooth technology on Buford Highway, as well as to further assess the various sensor array configurations explored during the previous configuration tests. Due to the location of the two sites, there were a limited number of vehicles that traveled through the entire five-mile corridor. The presence of I-285 and Jimmy Carter Boulevard in between the sites resulted in few vehicles traveling past both sites. In this analysis, a matched pair is defined as a MAC address that was detected by at least one Bluetooth reader at each site. The number of matched pairs from each data collection period with a full set of results at each site is shown in Table 18. When a device was observed multiple times at the same site, only the first detection is included. As seen in the table, there were insufficient matched pairs to allow for conclusions to be drawn about the travel times along the corridor. As with the previous tests, unless specifically stated, all probe vehicle data has been removed from the results. While statistically reliable travel times cannot be measured using the data from this study, the effectiveness of each different sensor array configuration can still be evaluated based on the results of the tests.

Table 18: Number of Matched Pairs for Each Study Period

Study Period	Number of Matches
Monday AM	26
Tuesday AM	14
Thursday PM	12
Friday AM	13

4.4.1 Monday AM Results

Data were collected on the morning of Monday June 13th, 2011 from 7:00AM to 9:00AM. The variable sensor array configuration was three readers at 10 feet, each separated by three feet horizontally.

4.4.1.1 Travel Time Results

The Monday morning travel time matches are displayed in Figure 39. The small number of data points is not sufficient to draw any statistically significant conclusions or identify any trends in the traffic flow during the two hours, but the test did demonstrate that travel times can be gathered through the use of Bluetooth technology. Furthermore, the three outliers, one in the southbound direction and two in the northbound direction, are easily recognized, as they had travel times above 35 minutes. This indicates that some form of data filtering would be necessary to identify outlying data points; however, there were insufficient travel time pairs to analyze outliers during this study, with a total of 388 MAC addresses detected at either of the two sites and 26 matched pairs for the Monday morning study. It is important to note that this is a relatively small sample of the entire traffic stream. Much larger samples will be necessary to verify matched pair data and to assess the confidence bounds around the net detection rate.

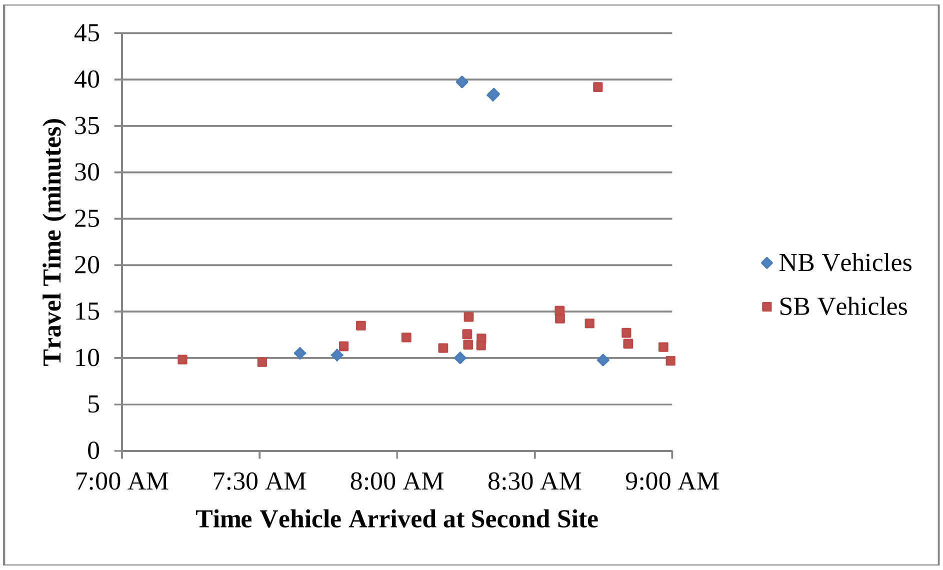


Figure 39: Monday AM Travel Times

4.4.1.2 Site A2 Results

At the northbound site, Site A2, 155 different MAC addresses were detected by Sensor Array 1, the control, while 275 different MAC addresses were detected by Sensor Array 2, a 77% increase over the single reader sensor array. Combining both sensor arrays, a total of 293 different devices were identified at Site A2. The added benefit of having multiple readers per sensor array can be seen in Figure 40. The three-reader array identified an additional 138 MAC addresses over those detected by the single-reader array. In addition, each individual reader on the three-reader array detected at least 20 MAC addresses that were not detected by any other reader on either array.

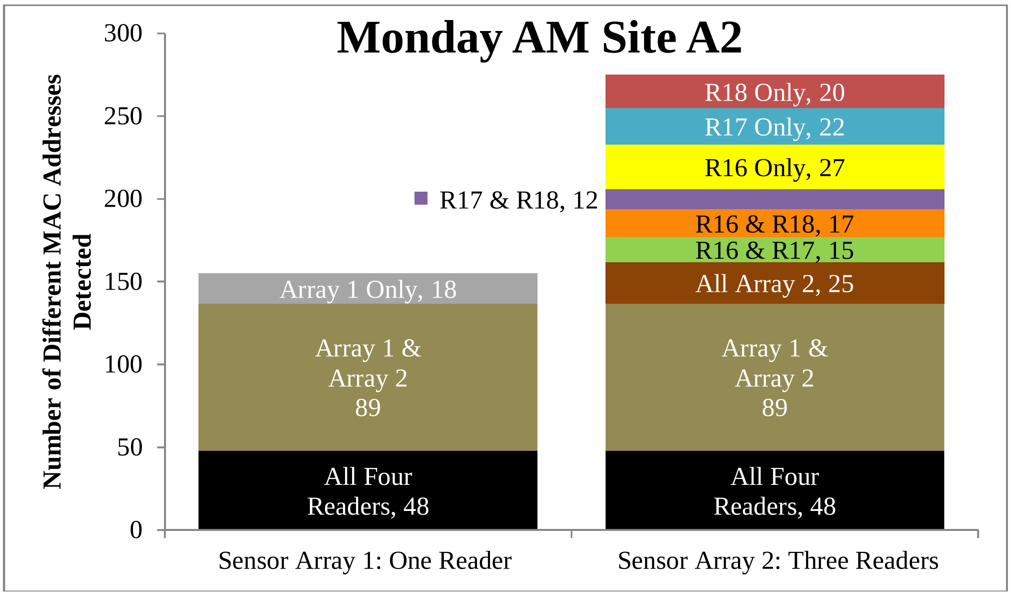


Figure 40: Unique Detection of Monday Site A2 MACs by Sensor Array and Reader

4.4.1.3 Site A4 Results

Similar results to those at Site A2 were found at Site A4. A total of 131 different MAC addresses were detected between the two arrays, with Sensor Array 1 identifying 73 devices and Sensor Array 2 discovering 124 devices. The added benefit from including the three reader array at the site was 58 detections. Using only the horizontally separated three reader array instead of the single-reader array results in a 70% increase in the number of devices detected. Figure 41 shows the number of detections uniquely identified by individual readers or by combinations of readers on one or both sensor arrays.

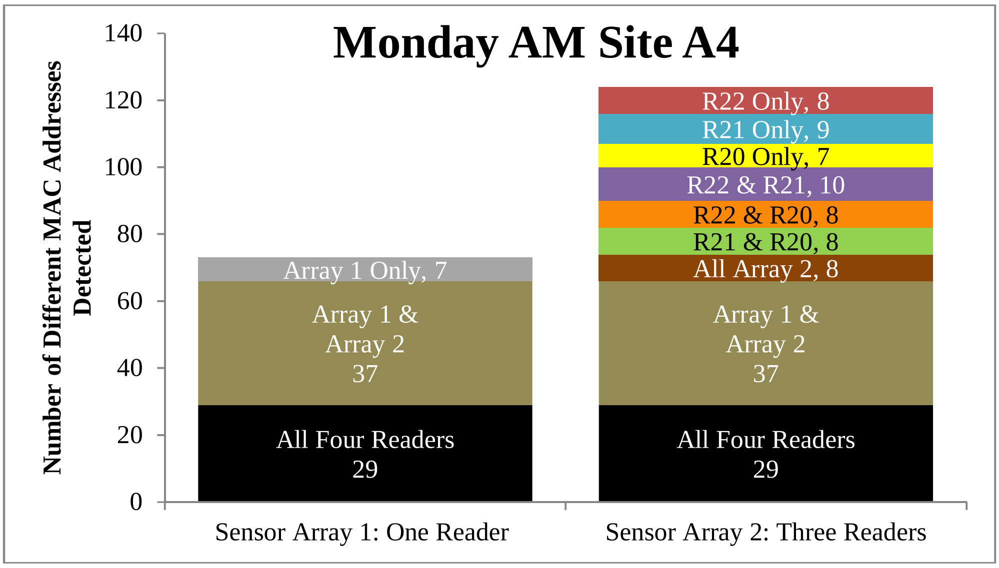


Figure 41: Unique Detection of Monday Site A4 MACs by Sensor Array and Reader

4.4.2 Monday PM Results

Data were collected on Monday evening between 4:45PM and 6:45PM. The variable sensor array configuration was the same as the morning test: three readers at 10 feet, each separated by three feet horizontally. Due to reader malfunctions and very low number of matched pairs at the two sites, no travel time results can be evaluated for this study period.

4.4.2.1 Site P1 Results

A total of 183 different MAC addresses were detected on Monday at Site P1. Sensor Array 1 detected 108 devices and Sensor Array 2 detected 160 devices, a 48% increase over the single-reader array. As seen in Figure 42, a majority of the single-reader detections (85 MAC addresses) were also detected by one or more readers on Sensor Array 2. Twenty-five devices were detected by all readers at the site. On Sensor Array 2, Reader 20 detected 32 devices that were not detected by any other device, 20% of all detections by the array.

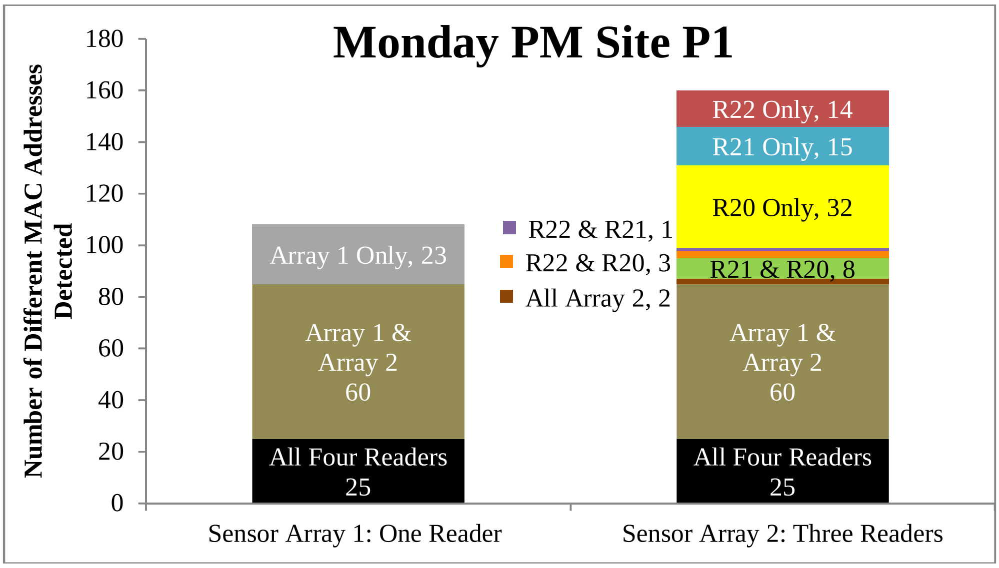


Figure 42: Unique Detection of Monday Site P1 MACs by Sensor Array and Reader

4.4.2.2 Site P3 Results

The control reader and one reader on the three-reader sensor array malfunctioned at Site P3 during the afternoon test, rendering the Monday P3 data set unusable.

4.4.3 Tuesday AM Results

During the Tuesday AM study period data were collected from 7:00AM to 9:00AM. Once again there were three readers on the variable sensor array; however, this time they were separated by three vertically with one reader at a height of 7 feet, another at 10 feet, and the last at a height of 13 feet.

4.4.3.1 Travel Time Results

Figure 43 shows the travel time data for the Tuesday morning study. Not including probe vehicles, 9 southbound and 5 northbound matched pairs were identified. Out of the total 355 MAC addresses that were identified, there were only 14 matched pairs. This may be a result of a combination of reasons, such as many passing MAC addresses not being detected or that a significant percentage of vehicles are not traveling through the entire corridor.

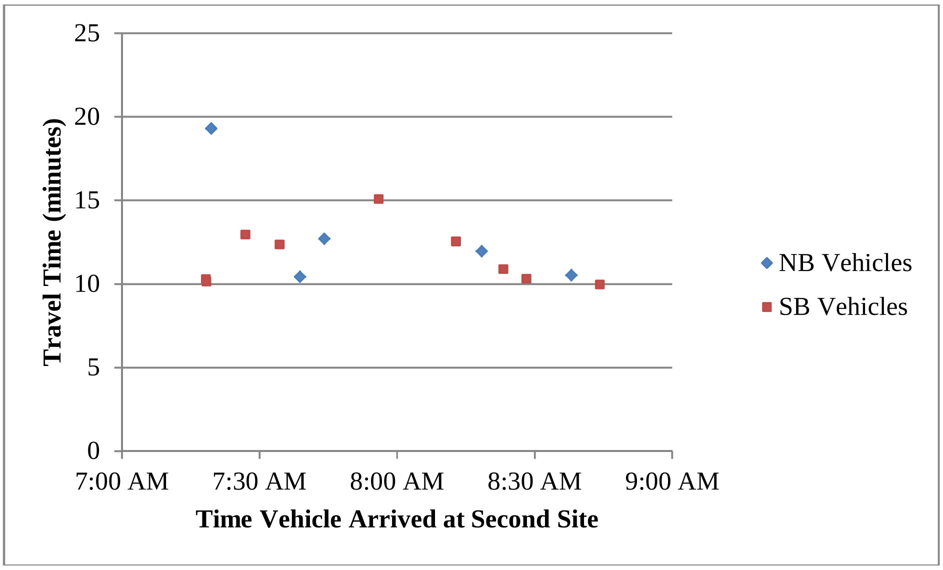


Figure 43: Tuesday AM Travel Times

4.4.3.2 Site A2 Results

On Tuesday morning, Sensor Array 1 at Site A2 identified 152 different MAC addresses and Sensor Array 2 identified 253 devices, with a total of 276 different MACs detected at the site. This results in a 66% increase in the number of different devices detected by the vertically separated multi-reader array over the control array. Figure 44 shows a visual representation of this increase, as well as how many MAC addresses were detected only by one reader, by all readers, or by any combination of readers on both arrays. Interestingly, nearly a third of the devices discovered by Sensor Array 2 were only identified by one of the three readers. This indicates that there may be significant added benefit to having multiple readers per sensor array.

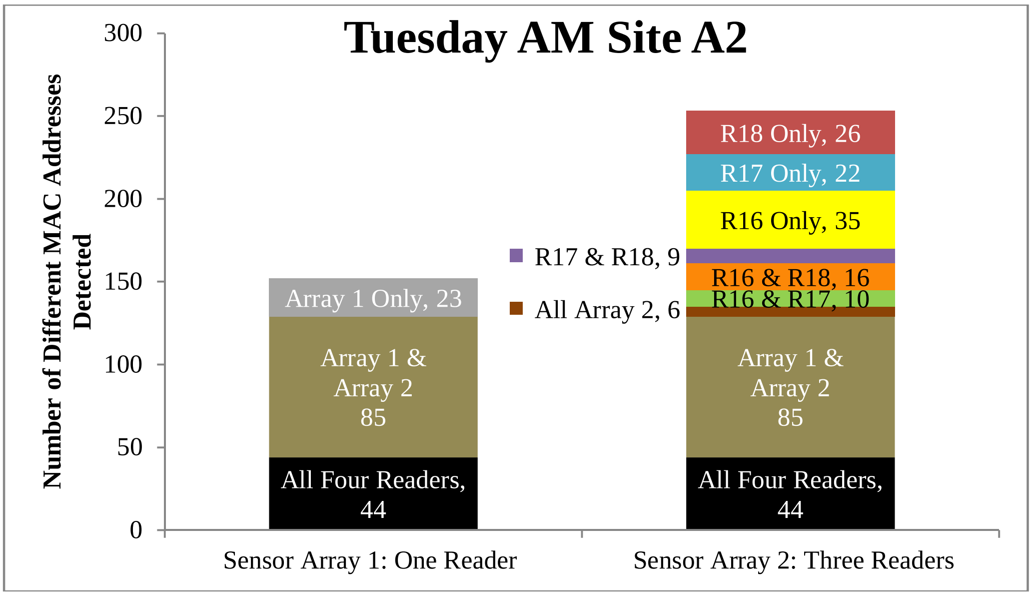


Figure 44: Unique Detection of Tuesday Site A2 MACs by Sensor Array and Reader

4.4.3.3 Site A4 Results

At Site A4, Sensor Array 1 gathered 78 MAC addresses and Sensor Array 2 detected 85 different MAC addresses. In total, 103 different devices were detected at the site. Figure 45 shows the number of detections by each possible combination of readers for Sensor Array 1 and Sensor Array 2. Contrary to the Monday data and Tuesday Site A2 data, there appears to be little added benefit to having multiple vertically separated readers on the array, with only a 9% increase in detections on the multi-reader array over the control array. Overall, the number of detections at the site was lower than during the other tests throughout the week.

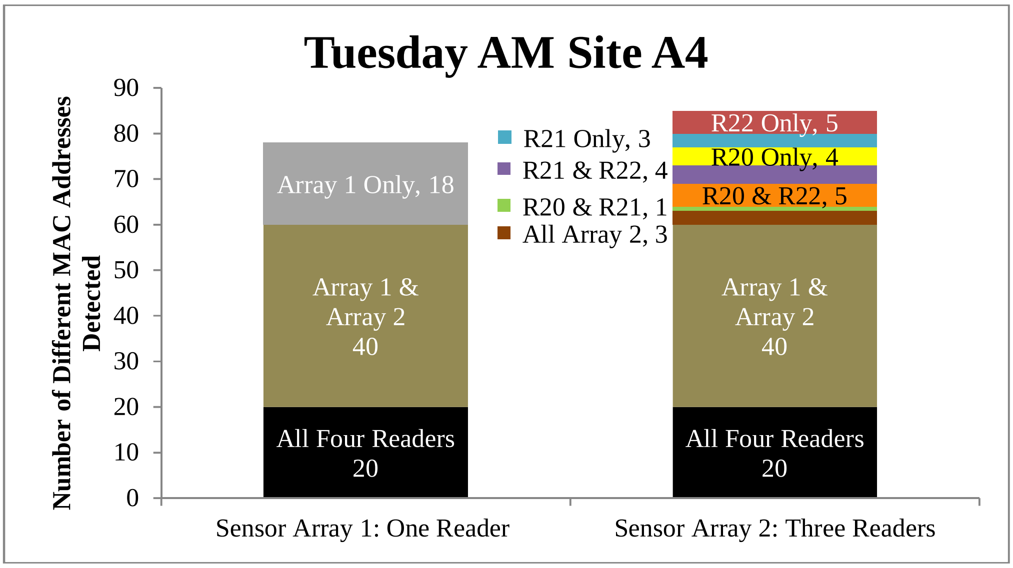


Figure 45: Unique Detection of Tuesday Site A4 MACs by Sensor Array and Reader

4.4.4 Tuesday PM Results

On Tuesday evening, data was collected between 4:35PM and 6:35PM. The variable reader configuration was the same as the morning configuration, with one reader at 7 feet, one at 10 feet, and the last at a height of 13 feet.

4.4.4.1 Site P1 Results

A total of 235 MAC addresses were detected at Site P1 during the Tuesday study. Of these, 157 were detected by the control sensor array while 192 of them were detected by Sensor Array 2. A total of 156 devices were detected by both arrays. The percent increase in detections from using the vertically separated three-reader array over the single-reader array is only 22% for these data.

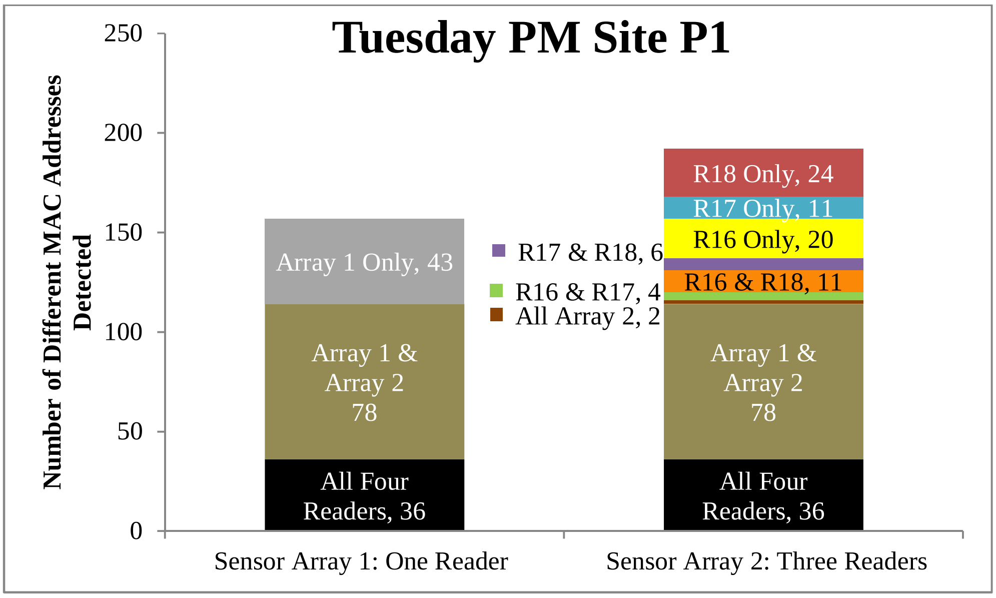


Figure 46: Unique Detection of Tuesday Site P1 MACs by Sensor Array and Reader

4.4.4.2 Site P3 Results

No conclusions can be drawn from the Site P3 sensor array data as one reader on the multi-reader array malfunctioned during the test.

4.4.5 Wednesday AM Results

Data were collected during the Wednesday AM study period from 7:30AM to 9:30AM. As with the previous days, the control sensor array consisted of one reader at a height of ten feet. The other sensor array was comprised of five Bluetooth adapters, all at a height of 10 feet, separated horizontally by a distance of 3 feet. Due to a reader malfunctioning at Site A2 and only 22 matched pairs from the remaining readers, conclusions about the travel time data cannot be drawn from this day’s results.

4.4.5.1 Site A2 Results

During the test, reader 12 malfunctioned and did not gather any data between the study hours, although it identified MAC addresses both before and after the 2-hour period. As a result, the Site A2 data is not usable for comparison between sensor arrays.

4.4.5.2 Site A4 Results

While there were too many possible combinations to show a visual representation of the number of detections uniquely identified by individual readers and combinations of readers, 82 devices were detected by Sensor Array 1, while 167 devices were detected by Sensor Array 2. In total, 170 MAC addresses were detected at Site A4. Using a five-reader horizontally separated sensor array over a single sensor array resulted in a percent increase of 104% in the number of different devices detected. This indicates that there is significant benefit to using this multi-reader array instead of one single reader per Bluetooth station.

4.4.6 Wednesday PM Results

The data from the Wednesday afternoon data collection session were not usable for this study, as the equipment is not weather hardened and the test was rained out after one hour. In addition, two readers malfunctioned at Site P3 prior to the end of the one hour.

4.4.7 Thursday PM Results

On Thursday June 16th, the evening travel time test was conducted between 4:35PM and 6:35PM. The reader configuration for the variable sensor array was four readers separated from one another by three feet vertically. The adapters were placed at heights of 5.5 feet, 8.5 feet, 11.5 feet, and 14.5 feet.

4.4.7.1 Travel Time Results

Figure 47 shows the limited number of matched pairs for the Thursday data. Not including the probe vehicles, only 12 MAC addresses were detected at both Site P1 and Site P3. All but one of these vehicles was traveling in the northbound direction. From observation of the data, it is evident that there were three outliers which had unusually slow travel times, each above 30 minutes. These could be due to vehicles leaving and re-entering the roadway somewhere along the 5-mile stretch between the two sites.

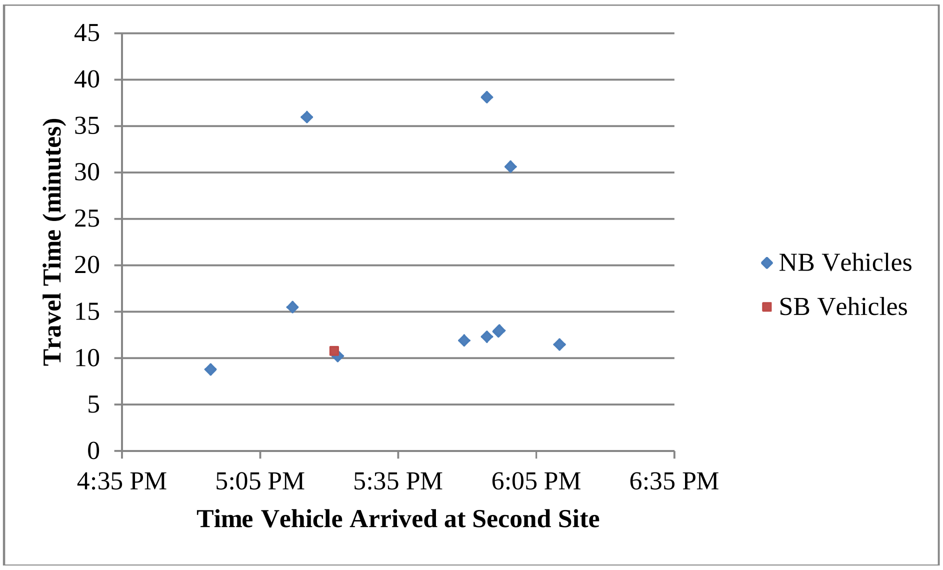


Figure 47: Thursday PM Travel Times

4.4.7.2 Site P1 Results

A total of 171 different Bluetooth devices were identified at Site P1 during the Thursday PM study period. Sensor Array 1 detected 94 of the 171 devices, while Sensor

Array 2 detected 155 devices. Installing the multi-reader vertical array resulted in a 65% increase in detections over the single-reader control array.

4.4.7.3 Site P3 Results

At Site P3 the control array, Sensor Array 1, detected 138 MAC addresses. Sensor Array 2 detected 230 different devices, a 67% increase over the control array. In total 250 MAC addresses were identified by either array.

4.4.8 Friday AM Results

On Friday June 17^{th}, 2011 the final morning travel time test was conducted from 7:00AM to 9:00AM. The sensor array configurations were identical to those during the Thursday PM session: four readers separated by three feet vertically at heights of 5.5 feet, 8.5 feet, 11.5 feet, and 14.5 feet.

4.4.8.1 Travel Time Results

The travel time results for Friday's study period are shown in Figure 48. It is immediately evident that the point with a travel time over 100 minutes is an outlying point that cannot be attributed to a Bluetooth device in a vehicle traveling directly from Site A2 to Site A4. A total of 13 matched pairs were found for this study period.

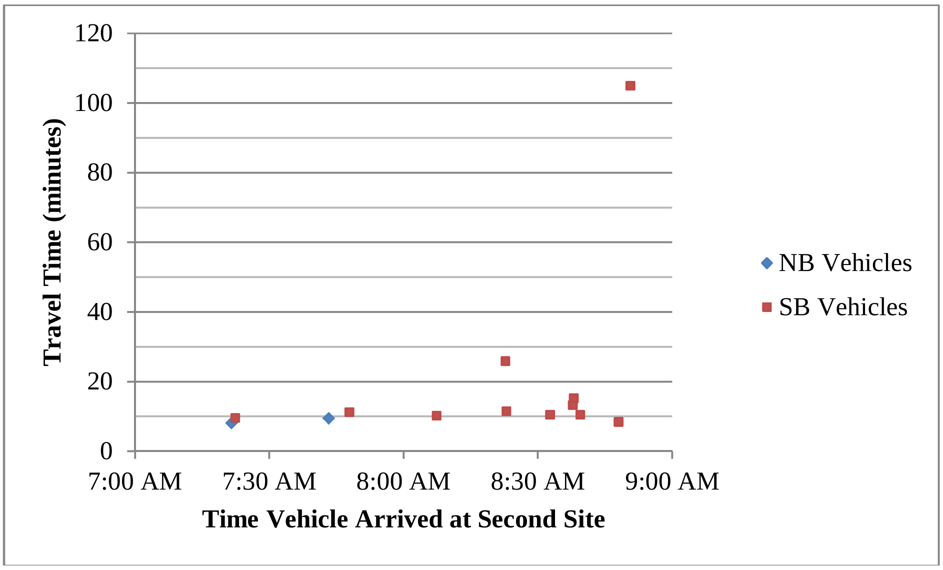


Figure 48: Friday AM Travel Times

4.4.8.2 Site A2 Results

Sensor Array 1 at Site A2 detected 130 different Bluetooth devices, while Sensor Array 2 detected 218 different devices, a percent increase of 68% over the control array. This suggests that a larger sample size of the passing vehicles can be gathered by using a 4-reader vertically separated sensor array rather than a Bluetooth station with only a single reader. In total 242 Bluetooth devices were detected at Site A2.

4.4.8.3 Site A4 Results

At Site A4 there were 113 Bluetooth devices detected by one or both of the arrays. The control reader identified 86 different MAC addresses and the variable sensor array identified 92 different MACs. The similar number of detections by both the single and multi-reader arrays results in a small percent increase of only 7% for the additional benefit gained from using Sensor Array 2 instead of Sensor Array 1. The large disparity between the results at Site A2 and Site A4 suggests that a large amount of variability can exist with regard to Bluetooth detections, even with the same array.

4.5 Combined Test Results

4.5.1 Bootstrap Analysis

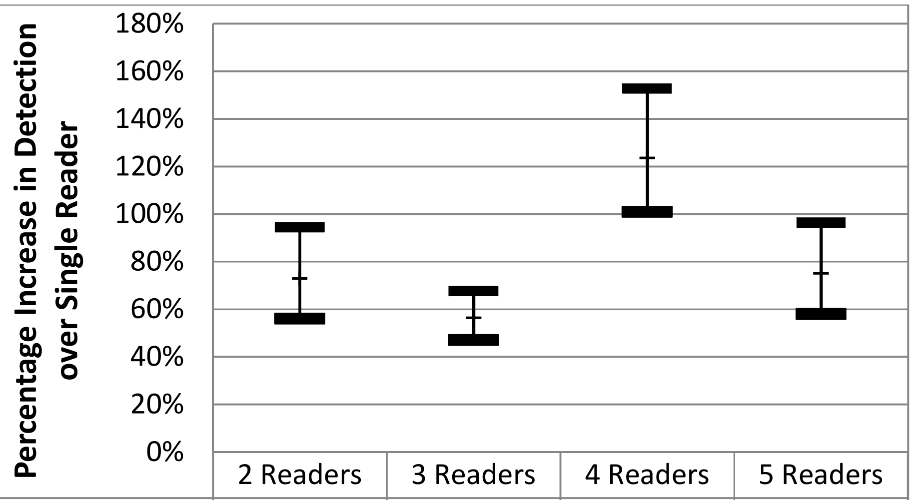
To establish confidence bounds around the relative detection efficiency of the different array configurations, a bootstrap statistical analysis was performed on the observed fractional increase in detection efficiency for each multi-reader array compared to the control array for the same site and day. The bootstrap approach helps account for the influence on the mean of potential outliers in the data and small sample size and can be used to produce a reasonable estimate for the confidence bounds of the resulting means [39]. The bootstrap approach employs a large number of randomly sampled data sets created from the original data set (random sampling of data, with replacement), and calculates the outcome (percent change) for each resample [40]. Only complete data sets for each array configuration and its corresponding control were evaluated and aggregated to produce a total of 1000 re-samples for each comparison. There were twelve complete comparison datasets for horizontal arrays and nine complete comparison datasets for vertical arrays. The percent increase for each of these data sets prior to the bootstrap analysis is shown in Table 19. The data were aggregated into 10 minute bins, yielding 12 ten-minute samples from each 2 hour data set. Data sets from different days but with the same number of readers and the same type of separation were merged for bootstrap re-sampling purposes.

Because the configuration comparisons indicate that horizontal configurations gather a larger sample size than vertically separated configurations (see Table 19), the discussion below focuses on the horizontally separated sensor array results.

Table 19: Overall Percent Increase in Detections by Multi-Reader Arrays over Control Array During Two-Hour Period

		2 Readers	3 Readers	4 Readers	5 Readers
Percent Increase in Detections over Single Reader	**Horizontally Separated Reader Trials**	55%	31%	123%	69%
		84%	38%	-	104%
		86%	77%	-	-
		-	70%	-	
		-	48%	-	-
		-	69%	-	-
	Average	**75%**	**56%**	**123%**	**87%**
	Vertically Separated Reader Trials	29%	66%	67%	-
		55%	9%	65%	-
		-	22%	68%	-
		-	-	7%	-
	Average	**42%**	**32%**	**52%**	**-**

The results of the bootstrap analysis coincide with the original results that indicate that the use of multiple readers per sensor array does significantly increase detection efficiency and that even and odd number reader configurations showed different trends, with even number configurations being more efficient. On average, the two and four reader configurations showed 73% and 124% improvement compared to the control respectively, while the three and five reader configurations showed improvements of 56% and 75%. This difference is potentially due to changes in multi-reader interference patterns associated with the mounting configuration. Figure 49 illustrates the median and 95% confidence interval (2.5 and 97.5 percentile results) for detection efficiency improvements based on the bootstrap analysis. Despite the relatively wide confidence bounds for this set of experiments, there is a clear improvement in detection efficiency of multiple reader configurations, although additional experiments with longer sample durations will be required to determine the most efficient configuration of the multiple reader arrays.



	2 Readers	3 Readers	4 Readers	5 Readers
− Upper 95% Confidence Bound	95%	68%	153%	96%
+ Median	73%	56%	124%	75%
− Lower 95% Confidence Bound	56%	47%	101%	58%

Figure 49: Increase of Multi-Reader Array Detection Efficiency Based on Bootstrap Analysis

CHAPTER 5: CONCLUSIONS

5.1 Discussion

The series of four field studies reported on in this thesis led to a number of important conclusions regarding the use of Bluetooth sensor arrays for gathering traffic data. Each result relates to the overall effectiveness of utilizing Bluetooth technology to gather traffic data along arterial roadways. To develop a sensor array that will reliably and efficiently gather the largest sample of passing vehicles, the trends observed over the course of these tests need to be considered both individually and cumulatively.

5.1.1 Bluetooth Detection Zone Observations

While Bluetooth does not require line-of-sight, it was observed in this study that the outer walls of the buildings around the study sites are thick enough to prevent detections of discoverable Bluetooth devices inside the buildings. Similarly, positioning the probe device behind the wall of a building from the reader eliminated the ability to detect the device. In addition, beyond the immediate vicinity of the Bluetooth reader, the human body appeared to be a sufficient barrier to limit the signal of the probe device from being detected by the master device.

Nonetheless, while these results indicate that devices inside adjacent buildings would not have influenced the results of the previous Bluetooth travel time test on Spring Street, the ability to identify probe devices 500 feet away at the pedestrian crosswalk at 5^{th} Street suggests that heavy pedestrian traffic may have falsely increased the detection rate, as the detection rate is based on the assumption that each different MAC address corresponds to one passing vehicle. The detection of pedestrian devices would not have influenced the travel time results, however, as the pedestrian device's MAC address either would not be identified at both Bluetooth stations or the significantly longer travel time of a pedestrian would classify the device as an outlier. These results highlight the importance of surveying a site before a Bluetooth implementation to determine if there are potential non-vehicle related Bluetooth signals and, if so, to determine their source to allow for development of appropriate filters.

5.1.2 Bluetooth Antenna Orientation and Configurations

The results of the antenna orientation test showed that the Bluetooth antenna with a flat orientation (i.e. parallel to the ground) had the longest detection range of approximately 360 feet compared to an on edge or vertically oriented antenna. If using similar antennas, future tests should incorporate this finding into their studies, positioning all antennas in a flat orientation to increase the detection zone and therefore the number of Bluetooth device detections. Otherwise, different antennas should be similarly tested to determine optimal orientation. Antennas should also be separated, as interference does occur when two readers are placed directly adjacent to one another with little or no separation. Further research is needed to assess the optimal antenna separation distance.

The use of multiple Bluetooth readers per sensor array is beneficial for increasing the fraction of discoverable Bluetooth devices that are detected in passing vehicles. The tests consistently showed detection rates below the anticipated 5-10% for all configurations; however, all of the multi-reader configurations evaluated during the bootstrap analysis showed statistically significant increases in detection efficiency with the largest noted detection increase (+124% compared to a co-located single Bluetooth detector) obtained from a four reader horizontal array. Although the vertically separated Bluetooth reader arrays showed more variability than the horizontally separated arrays and were somewhat less efficient, they also consistently and significantly out-performed the single reader.

In addition, identical sensor array configurations detected approximately the same number of Bluetooth devices when tested during the same time period. The similar detection rates obtained by these duplicated configurations indicate that the results are generally replicable and reliable. With the main cost of the Bluetooth installation coming from labor and the communications setup, the cost of additional readers and data collection systems is expected to be very cost effective. With perhaps only 5-10% of vehicles in the traffic stream currently carrying Bluetooth devices operating in discoverable mode, increasing the number of device detections and therefore vehicle detections using Bluetooth sensor arrays rather than single readers will yield more accurate origin-destination analyses, travel time studies, corridor performance assessments, etc.

5.2 Travel Time Tests

While reliable travel time results were not obtained from the limited set of travel-time experiments in this study, there were several lessons learned. The low number of matched pairs throughout the test emphasized the importance of site selection: for Bluetooth technology to be an effective method of collecting travel times, the stations need to be selected to ensure a sufficient volume of traffic that passes by both sites. The origin and destination of vehicles using the corridor needs to be assessed prior to choosing the installation site locations. One solution if major intersections are unavoidable is to shorten the segments or increase the number of Bluetooth stations collecting data in a manner that increases the potential for matches. However, while the shorter travel time segment may improve the number of matched pairs between the sites, one must still consider that the percentage errors in the measurements are larger when the size of the detection zone becomes comparable to the segment size.

5.3 Limitations of Bluetooth for Transportation Applications

Bluetooth has shown its viability as a methodology for collecting travel time and origin destination data along arterials; however, there are several limitations that must be addressed and considered when using this method. At the basic level, the maximum amount of data that can be gathered through Bluetooth technology is limited by the percent of passing vehicles that contain Bluetooth devices in discoverable mode, currently believed to be only 5-10% [1, 4, 8, 13, 19]. The method also assumes that each device MAC address corresponds to one vehicle, when in fact there may be multiple Bluetooth devices per vehicle or the discovered device may belong to a pedestrian or bicyclist. The impact of pedestrian and other low speed transportation means can be mitigated during travel time calculations with outlier filters to discard the longer times. When considering a single site, the detection rate must consider pedestrian and other transportation modes as well as other potential source of extraneous signals.

The assumption of one Bluetooth device per vehicle may create a bias toward higher occupancy vehicles such as buses and carpools, as it may be more likely that there are multiple Bluetooth enabled devices in a vehicle with multiple people. This was not a major factor on Buford Highway as there was a minimal number of higher occupancy vehicles, but could play a factor on freeways or arterials with HOV or bus only lanes.

Increasing technology in new vehicles may also lead to multiple detections from a single vehicle. In addition, there may be a bias towards slower vehicles, as they stay within range of the Bluetooth sensors for a longer period of time and therefore have a higher probability of being detected. Newer vehicles with integrated Bluetooth systems may also have a higher probability of being detected.

Finally, a reliable filtering method must be developed to screen outliers during travel time data calculations. For instance, vehicles with discoverable devices may pass the first site, divert from the route for any amount of time, then pass by the second site later. While this will result in a matched pair, the travel time will not be representative of the corridor; however, filtering of data must be done with caution as it is similarly possible that a long travel time is due to an incident or significant congestion. In addition, if a vehicle makes multiple passes by one site, it will only be recorded once when a first-to-first or last-to-last detection filtering method is used unless the filter is limited to a certain time frame. This can affect the detection rate as well as the number of matched pairs that are calculated.

5.4 Further Research

Further research is needed to fully understand how the Bluetooth sensors interact with one another and to design an efficient, portable, and cost-effective system. First, the Bluetooth reader setup utilized for this research project was only designed for temporary deployments in the field. To use this method to gather real-time Bluetooth traffic data with permanent installations, weather hardened equipment that can withstand both the heat and the rain needs to be developed. Most of the readers that malfunctioned did so during the evening data collections sessions in June, when temperatures reached upward of 90 degrees Fahrenheit and potentially significantly greater inside the Bluetooth device case. In addition, for multi-reader sensor arrays, a method needs to be developed to enable multiple readers to function off of only one computer to decrease the bulk of equipment and simplify the setup. For real-time data, communications systems that connect the field units to a central computation server would also need to be installed.

Identifying the source, or sources, for the different trends observed in even and odd reader arrays and obtaining a better understanding of Bluetooth reader interference are also topics that warrant further research. Understanding these issues is important to determining the ideal number of readers and reader geometry to implement on multi-reader sensor arrays for various applications. For example, a vertical array might prove to be more efficient on a multilane highway whereas a horizontal configuration may perform better on a two lane facility. These optimal configurations are also likely to depend on device acquisition characteristics, handoff times, cycle time required to acquire and release IDs etc. and will require an improved understanding of their contributions to overall detection system efficiency. Further tests will need to be performed to gain a better understanding of the interactions between adjacent and nearby Bluetooth readers and to determine at what point the additional cost of multiple readers and potential interference outweighs the benefits of additional device detections due to the use of multiple readers.

The small number of matched pairs gathered from the travel time tests in spite of the much larger number of detections overall showed the need for a replication of the travel time test at better sites. To ensure a large overlap of vehicles that pass by both sites, the origin and destination characteristics of the roadway should be evaluated prior to the Bluetooth test. In addition, major intersections in between the corridor should be avoided to minimize the number of vehicles leaving and entering the corridor. While a shorter segment would increase the likelihood of vehicles passing by both sites, it also increases measurement errors since the detection zone is large; therefore, distance traveled between detections can vary and will have a more significant impact when stations are closer together.

Finally, analyzing data obtained from probe vehicle GPS data and video license plate data is important to establish ground truth travel times, detection rates, and number of matched pairs. An analysis can be done to compare the number of times the probe was detected by each sensor array configuration to provide a controlled detection rate. Probe vehicle data can also be used to assess whether there is a trend in number of detections based on where the probe devices are placed within the vehicle. For the last week of tests with two sites along Buford Highway, license plate data at both sites can be compared to evaluate the actual number of vehicles that passed by both locations. These data can also be used to determine the number of unique vehicles that traversed the entire corridor and the ground truth travel times for comparison to the Bluetooth data.

APPENDIX A: 771 SPRING STREET DETECTION ZONE DEPLOYMENT PLAN

Overview

The ideal range for a class 1 Bluetooth adapter is 330 feet. However, physical obstacles and other wireless devices may decrease this range. This field test seeks to evaluate the extents of the detection zone of a Bluetooth station deployed in front of the Crum and Forster Building at 771 Spring Street, Atlanta, Georgia.

On Friday, April 15, 2011, from 3:00 PM to 4:00 PM, a sensor array equipped with a Bluetooth reader at 10 feet will be deployed at 771 Spring Street to collect MAC address data using a netbook running PERL scripts on a Ubuntu operating system, a Bluetooth adapter, and an extended USB cable. Discoverable Bluetooth devices with known MAC addresses will be carried by a member of the research team who will walk around the area, recording their time-stamped location data.

Site Location

The study site is the area surrounding the intersection of Spring Street and Armstead Place in Atlanta, Georgia, shown in Figure 50.

Tripod Setup

The tripod will be positioned on the south end of the brick area in front of the building. Two of the legs will be parallel to Spring Street, with one of the two flush against the southern wall of the brick area as shown in Figure 51.

Figure 50: Map of the Bluetooth Reader Location ***(Background image from [36])***


Figure 51: Bluetooth Reader Setup

Equipment

The equipment that should be brought to the site includes:

- 1 heavy-duty tripod
- 1 Bluetooth reader
- 1 netbook
- 1 Bluetooth adapter
- 1 USB cable
- 3 sandbags
- 3 orange safety cones
- 2 Velcro ties
- 1 plastic rolling bin

Probe Devices

While one researcher monitors the Bluetooth station, the second researcher carrying several discoverable Bluetooth devices will walk around the area. Specifically, the second researcher will walk to the following locations and stay stationary for at least 20 seconds:

- The southeast corner of the Spring Street and Armstead Place intersection
- The northeast corner of the Spring Street and Armstead Place intersection
- The west end of the Spring Street crosswalk
- Inside the southwest glass entryway of Barnes & Noble
- The northeast corner of the Spring Street and 4th Street intersection
- The northwest corner of the Spring Street and 4th Street intersection
- Inside the second floor of the Georgia Tech parking garage
- The entryway of the Georgia Tech Hotel and Conference Center
- The taxi-stands outside of the Georgia Tech Hotel and Conference Center
- The 4th Street exit to the Georgia Tech parking garage

- Inside the entrance to the Georgia Tech Economic Development Building

The researchers should be in communication throughout the test. In order to obtain the limits of the Bluetooth reader range, the researcher with the Bluetooth devices should also walk slowly past each test point that is farthest from the Bluetooth reader until the devices are no longer detected.

Notes should also be taken as to the MAC address of each Bluetooth device, where the Bluetooth devices are located on the person, where the researcher traveled, the locations where the researcher remained stationary and the direction that they were facing, and the start and end times that the researcher stayed in those locations. All movements will also be recorded on a map of the area to easily display the range covered during the test.

APPENDIX B: BLUETOOTH CONFIGURATION TESTS DEPLOYMENT PLAN

Overview

The use of Bluetooth technology in monitoring travel times has been developed substantially in recent years. Many vendor applications and research studies have only used single Bluetooth readers at each site to avoid potential interference between two Bluetooth readers. However, a previous Bluetooth study conducted on January 21, 2011, yielded results that suggest that multiple readers at one site may increase the likelihood of detection of discoverable Bluetooth devices in vehicles traveling past the site. The major issue with equipping one site with multiple readers is Bluetooth radio interference. The interference caused between two Bluetooth readers with overlapping piconets is further investigated in this field deployment.

On May 10th-13th from 7:00 AM to 9:00 AM, field tests will be conducted where three to four Bluetooth-equipped tripods will be deployed on Buford Highway between Pittman Circle and Smith Ridge Trace to collect MAC address data of Bluetooth devices in passing vehicles using netbooks running PERL scripts on a Ubuntu operating system and Bluetooth adapters. The tripods will have varying configurations of Bluetooth readers attached to them each day. Similarly, on June 3rd and June 6th four tripods will be deployed in the same location on Buford Highway. Probe vehicles equipped with GPS data loggers and Bluetooth emitters with known MAC addresses will travel past the site in order to provide ground-truth data. The number of unique MAC addresses detected by each tripod will be compared in order to analyze the effect of the proximity of a

Bluetooth reader to another reader on its ability to detect Bluetooth devices in passing vehicles.

Study Segment and Tripod Sites

This field test requires one roadway segment which has sufficient space for four tripods separated by at least 50 feet to minimize interference between tripods. A 0.5-mile segment of Buford Highway between Pittman Circle and Smith Ridge Trace is an ideal location for this study because it is characterized as an arterial road which experiences high traffic volumes (24,220 AADT, Source: GDOT STARS) but has no cross-streets and no high-volume driveways. A map of the segment is shown in Figure 52.

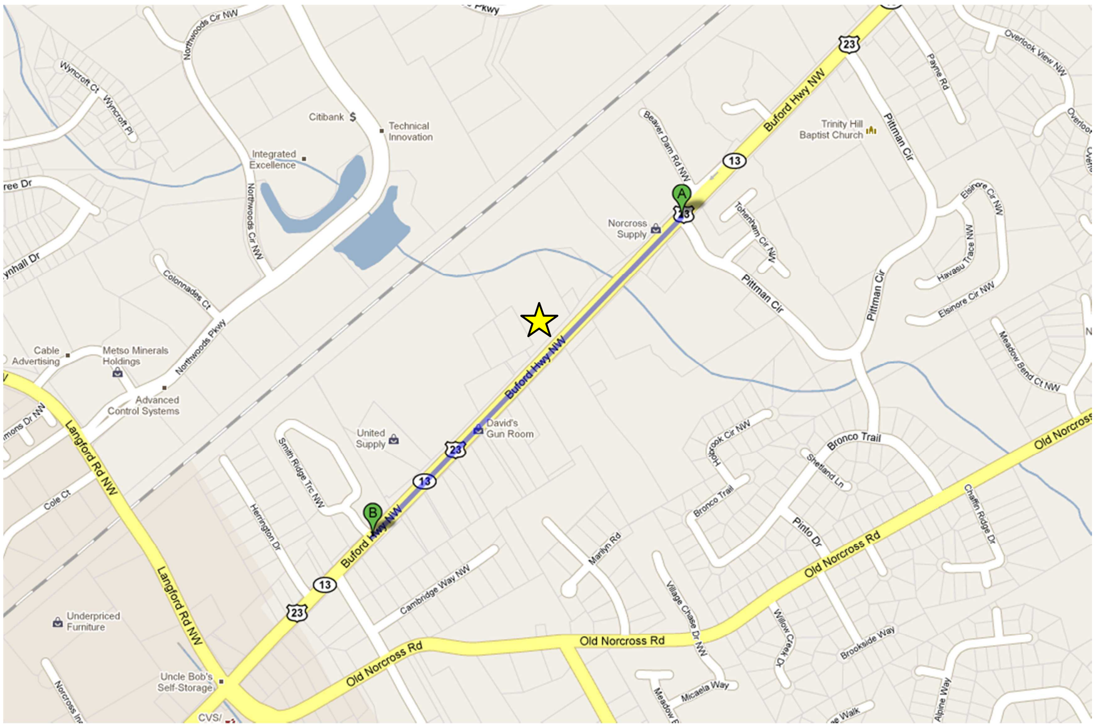


Figure 52: Map of Buford Highway Study Segment [36]

Locations for the four tripods were selected based on consistent setback from the closest travel lane, level ground, distance between tripods, and safety for the graduate students in the field. All four tripod locations are on the northwest side of the study segment and are set back 25 feet from the outer edge of the nearest travel lane (including turn bays). The overall site is located outside Atlas Furniture Wholesalers at 5015 Buford Highway. Permission was given by the owner to use the site for this study. The four tripods will be placed on the grassy areas on either side of the driveway shown in Figure 53. The site’s coordinates are 33.955642, -84.191292.

Figure 53: Configuration Test Site on Buford Highway

The three or four tripods will be placed with 85 feet in between each. The tripods are shown in Figure 54 as yellow triangles.

Figure 54: Tripod Sites on Buford Highway ***(Background image from [36])***

Study Period

This field test will take place from 7:00 AM to 9:00 AM on Tuesday May 10th through Friday May 13th and on Friday June 2nd and Monday June 6th. The time period was chosen to monitor the commute hours of traffic flow traveling southbound in the lanes closest to the tripod sites. It is expected that Bluetooth devices in vehicles traveling northbound in the lanes farthest from the tripod will also be detected; however, previous studies have shown that the likelihood of a Bluetooth reader detecting a Bluetooth device decreases as the separation distance increases.

Site Equipment and Setup

The equipment vehicle will park in the Atlas Furniture Wholesalers parking lot. Permission has been obtained from the owner to use the site during this study. The equipment that must be taken to the site includes:

- 4 heavy-duty tripods
- 10 to 12 Bluetooth readers (dependent on the day's configurations)
- 10 to 12 netbooks
- 10 to 12 USB cables
- 10 to 12 Bluetooth adapters
- 4 plastic rolling bins
- 9 sandbags
- 4 safety cones
- 1 allen wrench
- 10 to 12 Velcro ties
- 3 high-definition video cameras
- 3 SD cards for video cameras
- video camera batteries
- 2 camera tripods
- GPS device
- 1 measuring tape
- 4 safety vests
- 1 information packet containing a copy of the deployment plan, emergency contacts, and a signed letter explaining the project

A different Bluetooth adapter configuration will be deployed at each tripod location on each day. At each tripod there will be a plastic rolling bin which will house the netbooks. Bluetooth adapters, attached to the netbooks via USB cables, will be attached to the tripods using Velcro ties. A sandbag will be placed on each leg of each tripod to ensure stability, and orange safety cones will be placed on top of the sandbags for increased visibility. Two students will be stationed at the site to monitor the tripods.

Tuesday May 10th

- Tripod 1 will have one reader at 10’ placed “flat”
- Tripod 2 will have two readers at 8.5’ and 11.5’ placed “flat”
- Tripod 3 will have two readers at 10’ separated by 3’ and placed “flat”

Wednesday May 11th

- Tripod 1 will have one reader at 10 feet placed “on edge”
- Tripod 2 will have two readers at 8.5’ and 11.5’ placed “on edge”
- Tripod 3 will have two readers at 10’ separated by 3’ and placed “on edge”
- Tripod 4 will have two readers at 10’ with no separation placed “flat”

Thursday May 12th

- Tripod 1 will have three readers at 10’ separated by 3’ placed “flat”
- Tripod 2 will have three readers at 10’ separated by 3’ placed “flat”
- Tripod 3 will have five readers at 10’ separated by 3’ placed “flat”
- Tripod 4 will have one reader at 10’ placed “flat”

Friday May 13th

- Tripod 1 will have two readers at 10’ separated by 3’ placed “flat”
- Tripod 2 will have four readers at 10’ separated by 3’ placed “flat”
- Tripod 3 will have one reader at 10’ separated by 3’ placed “flat”
- Tripod 4 will have three readers at 10’ separated by 3’ placed “flat”

Friday, June 3rd

- Tripod 1 will have one reader at 10’ placed “flat”
- Tripod 2 will have two readers at 8.5’ and 11.5’ placed “flat”
- Tripod 3 will have four readers at 5.5’, 8.5’, 11.5’, and 14.5’ placed “flat”
- Tripod 4 will have three readers at 7’, 10’, and 13’ placed “flat”

Monday, June 6th

- Tripod 1 will have three readers at 7’, 10’, and 13’ placed “flat”
- Tripod 2 will have three readers at 10’ separated by 3’ placed “flat”
- Tripod 3 will have three readers at 7’, 10’, and 13’ placed “flat”
- Tripod 4 will have three readers at 10’ separated by 3’ placed “flat”

Video Data Collection

Two video cameras will collect data during the study period. The first will record a wide-angle view of the traffic passing through the study segment in order for post-processing of traffic volume counts. The second camera will be directed southbound to collect license plate data of vehicles traveling in the peak direction.

Probe Vehicles

Two probe vehicles will be equipped with a Bluetooth enabled BT-335 GPS data logger and three IOGEAR class 1 Bluetooth adapters attached to netbooks. Each probe vehicle will be operated by one driver. The first probe vehicle will drive northeast in the right lane through the study segment, completing a clockwise loop by utilizing Pittman Circle, Bronco Trail, Old Norcross Road, and Cambridge Street. The second probe vehicle will travel southwest in the left lane through the study segment, completing a counter-clockwise loop via Old Norcross Rd and Simpson Circle. The clockwise route is shown in Figure 55.

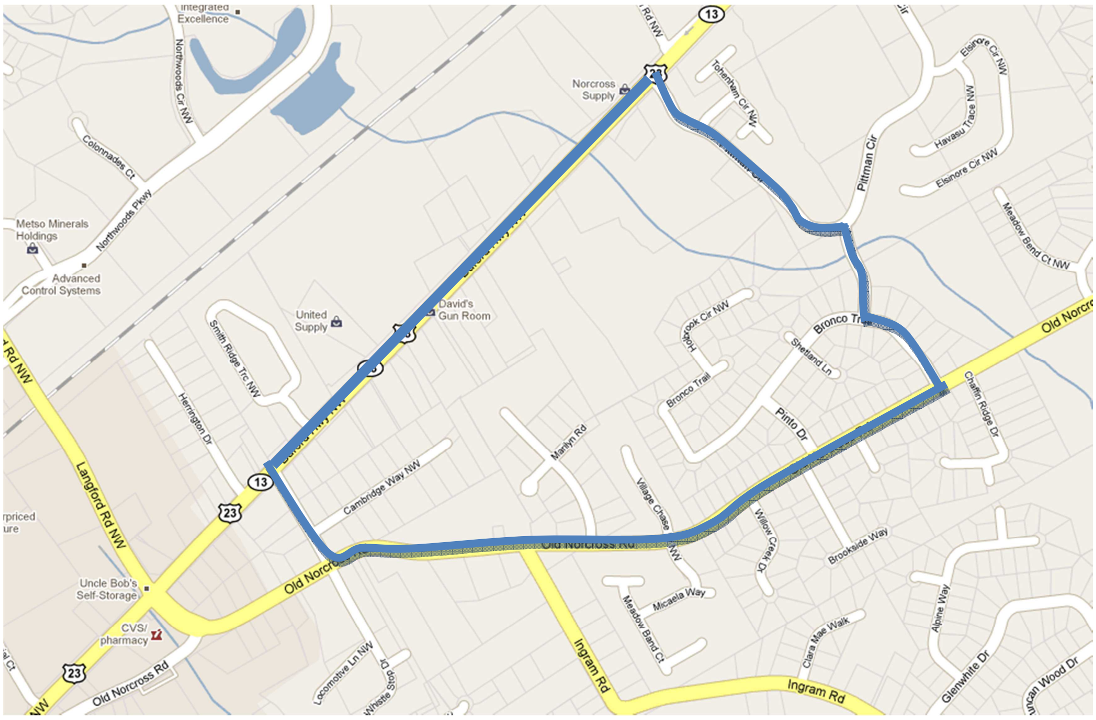


Figure 55: Probe Vehicle Travel Route ***(Background image from [36])***

Within each vehicle the GPS data logger will be attached to the dashboards. The three Bluetooth adapters will be attached to the dashboard, to the front passenger seat, and to the floor in front of the front passenger seat. All of these devices will be in discovery mode and will be able to be detected by the Bluetooth readers. The MAC address and location of each reader will be recorded prior to the field test.

The equipment for each probe vehicle is listed below:

- 1 BT-335 GPS data logger
- 3 Bluetooth emitters
- 3 netbooks
- 3 Bluetooth adapters
- 3 USB cables
- Adhesive tape

Pre-Deployment Procedure

The probe vehicles will be outfitted with the GPS data loggers and Bluetooth devices before leaving Georgia Tech's campus. Additionally, the Gwinnett County Police

Department will be contacted at 770-513-5911. The following is the message that should be relayed to the dispatcher:

"This is a non-emergency notification call. Georgia Tech will have a transportation data collection crew located on Buford Highway between Pittman Circle and Smith Ridge Trace from 7:00 AM to 9:00 AM this morning. This is part of a Georgia DOT project. There will be students collecting data outside of Atlas Furniture Wholesales."

The dispatcher will also ask that you provide your name and cell phone number. Additionally, Dr. Guensler's name and number (404-894-0405) may be provided as a secondary contact.

Data Output

The data collected from this field study will include the detection logs from each Bluetooth reader (detections of both probe vehicle devices and non-probe vehicle devices) and the GPS data. The detection logs will allow for comparison across the three Bluetooth station configurations, and the GPS data will be used to determine the times at which the probe vehicles passed each tripod. The results of this study will aid in determining the best configuration of Bluetooth readers to yield the greatest detection rates. The traffic volumes which will be processed from the recorded video will allow for the calculation of detection rates for each Bluetooth reader and for each Bluetooth tripod.

APPENDIX C: BUFORD HIGHWAY TRAVEL TIME AND LICENSE PLATE CAPTURE PLAN

Overview

The goal of this study is to collect travel time data along the SR-13 (Buford Highway) between Chamblee Tucker Rd and Old Peachtree Rd corridor using Bluetooth technology. During the study license plate video data will also be collected in order to identify regular commuters for future studies. As shown in Figure 56, this segment of Buford Hwy is roughly parallel to the section of HOV lanes that will be converted to HOT lanes along Interstate 85. SR-13 has been divided into four segments between the major intersections along the corridor: Chamblee Tucker Road to Interstate 285, Interstate 285 to Jimmy Carter Boulevard, Jimmy Carter Boulevard to Beaver Ruin Road, and Beaver Ruin Road to Old Peachtree Road. The initial data collection will consist of license plate captures and Bluetooth reads at two of the segments: 1. Between Chamblee Tucker Rd to I-285 and 2. Between Jimmy Carter Blvd and Beaver Ruin Rd. The Bluetooth and license plate data will then be matched to assess travel times between the two segments.

Five days of Bluetooth travel time and video license plate data will be collected. Cameras will be focused in the commute direction, southbound to Atlanta in the morning and northbound out of Atlanta in the evening. Camera clocks will be coordinated prior to field deployment in order to obtain reliable travel time data. Southbound vehicle license plates will be recorded at sites A2 and A4 during the AM peak hours of 7:00-9:00am. Northbound vehicle license plates will be recorded at sites P1 and P3 during the PM peak hours of 4:30-6:30pm. Detailed information about each site, including camera placements and access is included in the Site Descriptions section of this report. A probe vehicle with Bluetooth emitting devices and a GPS unit installed in it will also be driven continuously past the site throughout the two-hour study period.

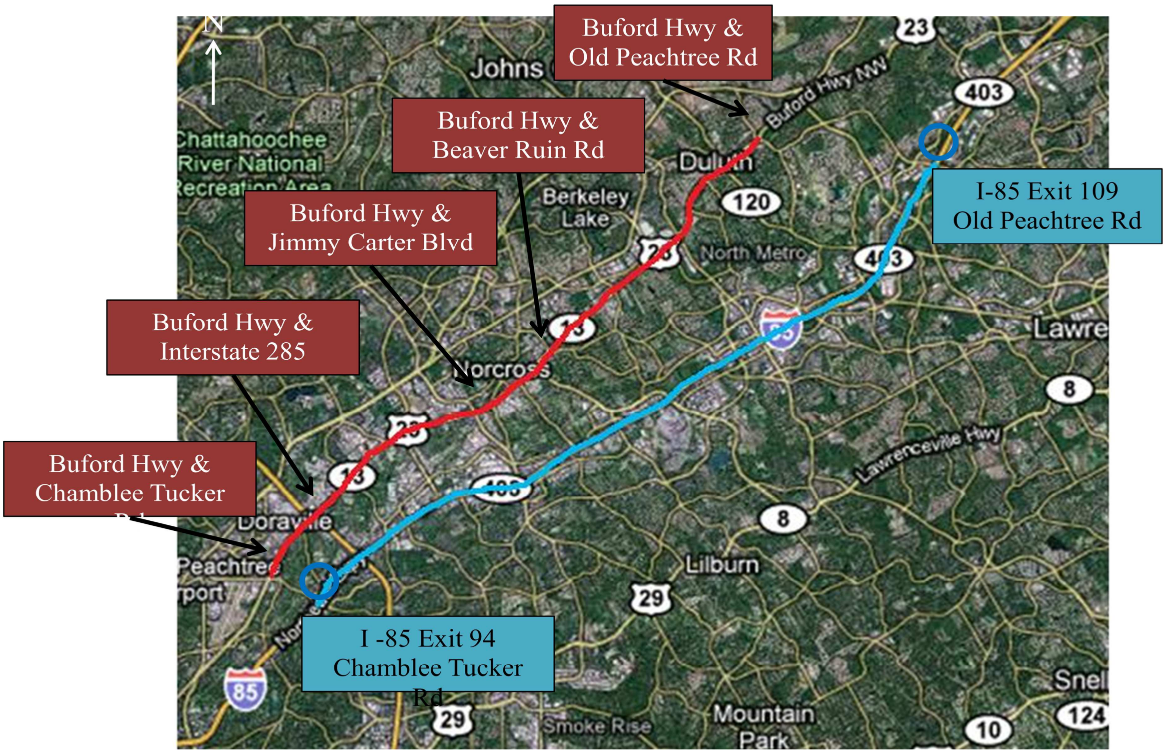


Figure 56: Map of study corridor and parallel segment of I-85 (*Background image from [36])*

Data collection teams will consist of undergraduate and graduate students. Four undergraduate team members will collect license plate data, two per site. A graduate research assistant (GRA) will supervise the data collection and be responsible for deploying the teams and equipment at each location. Safety vests, long pants, and closed-toed shoes will be worn at all times while in the field.

Once all teams have been dropped off at their data collection sites, the GRA will serve as the probe vehicle driver. Probe vehicle drivers are only to use their cell phones or other electronic devices when the car is safely parked. The probe vehicle will begin at site A4 in the morning and site P3 in the evening. Full descriptions of the routes are described below and maps of the turnarounds for the routes are shown in Figure 58 and Figure 59. At the end of the data collection period, the team members will be picked up in the same order in which they were deployed. Each site will have a set of safety gear, letters explaining the team's activities, and telephone contact information for project managers, GDOT staff, and local police.

Probe Vehicles

Configured inside the probe vehicle will be a Bluetooth GPS device and three discoverable Bluetooth adapters connected to netbooks. Figure 57 shows the setup of the probe vehicle. Within the vehicle the GPS data logger will be attached to the dashboard. The three Bluetooth adapters will be attached to the dashboard, to the front passenger seat, and to the floor in front of the front passenger seat. The MAC address and location of each adapter and GPS logger will be recorded prior to the study.

AM Probe Vehicle Route

Begin at site A4. Turn right to proceed south on Buford Hwy and begin the route. Turn left at the third signal onto Shallowford Rd. Take the first right (no stop sign or signal) onto Chamblee Dunwoody Rd and then turn right again at the next signal onto Buford Hwy. Proceed on Buford Hwy for more than 5 miles, past the intersection with I-285, the railroad tracks, and site A2. After the signal at Mitchell Rd move into the right turn lane and take the channelized right onto Summerour St. At the stop sign, turn right onto Price Place, then right again onto Mitchell Rd at the signal. At the next signal turn left onto Buford Hwy and repeat the loop.

Figure 57: Probe Vehicle Bluetooth Adapter & GPS Configuration

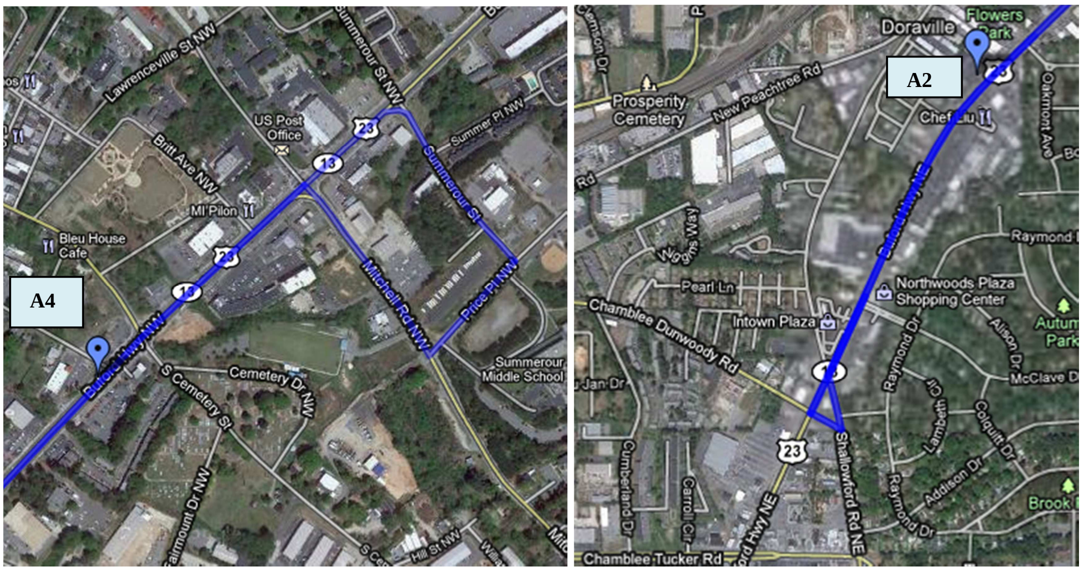


Figure 58: AM Probe Vehicle Turnarounds (*Background images from [36]*)

PM Probe Vehicle Route

Begin at site P3. Turn right to proceed north on Buford Hwy and begin the route. At the first signal turn left onto N Norcross Tucker Rd. Take the first right onto Lively Ave (no stop sign or signal). If you reach Carlyle St, you have gone too far, but can turn right on Carlyle St to get back to Buford Hwy. Turn right at the stop sign onto Buford Hwy. Proceed on Buford Hwy for more than 5 miles, past the railroad tracks, the intersection with I-285, site P1, and Chamblee Tucker Rd. Turn left at the signal onto Beverly Hills Dr. Take the first left onto Ortega Way, then turn right on Shallowford Rd. At the first signal turn right back on to Beverly Hills Dr. At the signal turn right onto Buford Hwy and repeat the loop.

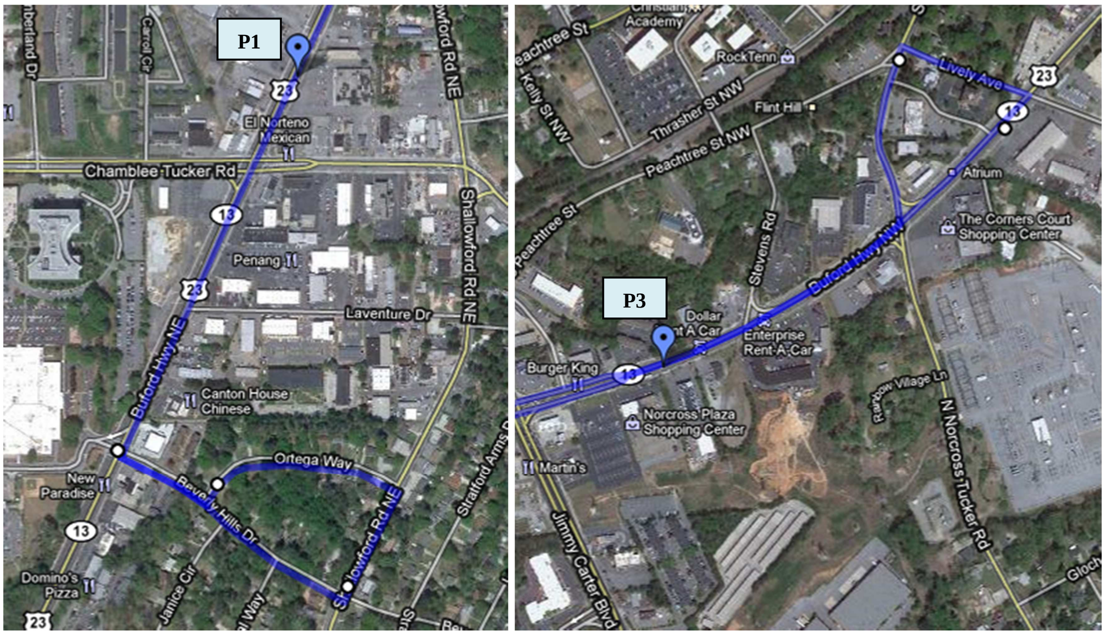


Figure 59: PM Probe Vehicle Turnarounds (*Background images from [36]*)

Police Notification

Prior to deployment, the police department for the jurisdictions where the sites are located should be contacted. The morning sites are located in the City of Doraville (police non-emergency phone number: 770-455-1000) and the City of Norcross (770-448-2111). The afternoon sites are located in located in the City of Chamblee (770-986-

5005) and the City of Norcross (770-448-2111). The following is the message that should be relayed to the dispatcher:

"This is a non-emergency notification call. Georgia Tech will have a transportation data collection crew located on Buford Highway from [7:00 AM to 9:00 AM/4:30 PM to 6:30 PM] this [morning/afternoon]. This is part of a Georgia DOT project. There will be three students collecting data outside of [location name]."

The dispatcher will also ask that you provide the address of the site, your name, and cell phone number. Dr. Guensler's name and number (404-894-0405) may also be provided as a secondary contact.

Video Quality

License plate data collection will be taken with high resolution (1080/60p) video cameras mounted on tripods. Each camera will collect data from two lanes simultaneously. Two cameras will be used at sites A4 and P1, as SR-13 has three lanes in each direction at these locations. For all sites, all parts of the camera tripod(s) should be fully extended and the camera(s) should be zoomed in to the full extent. Figure 60 gives an example of the video quality necessary in order to obtain legible license plate data. It is important that the cameras are set up exactly as shown in Appendix B1 and Appendix B2 so that legible license plate video is collected in this study.

Figure 60: Sample Frame of High Resolution Video Required to Read License Plates

Site Descriptions

AM Data Collection Sites

An overview of the AM data collection Sites A1 through A4 are shown in Figure 61. As this deployment will involve only sites A2 and A4, these locations are described in detail on the following pages.

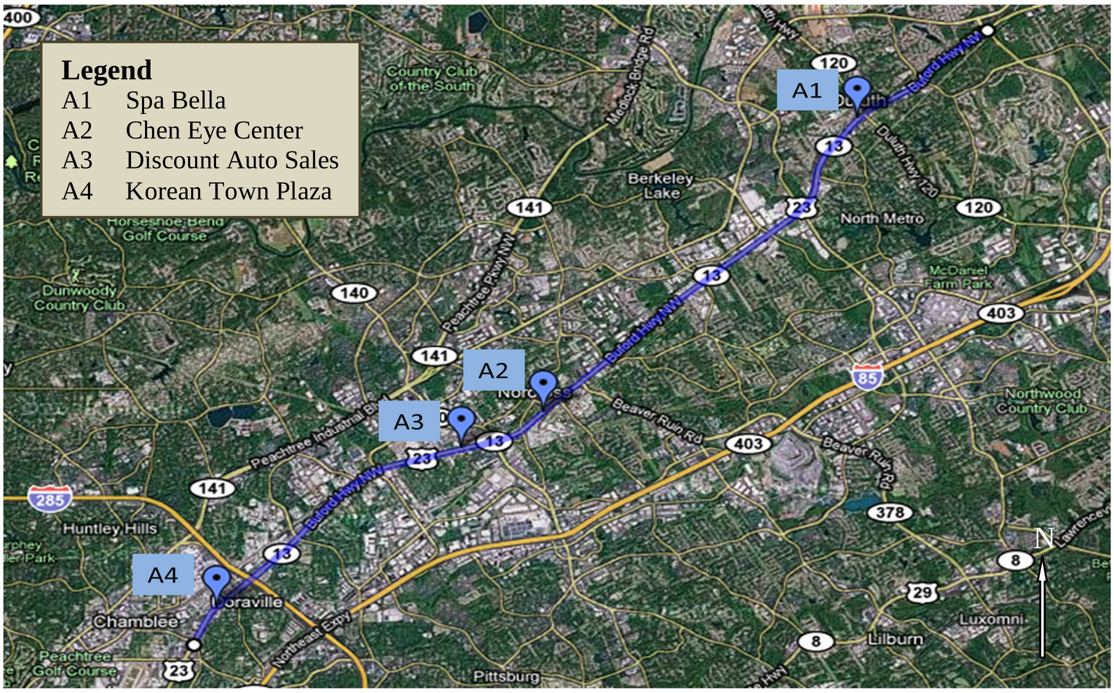


Figure 61: AM data collection sites along Buford Hwy (*Background image from [36]*)

Site A2: Southbound between Beaver Ruin Road and Jimmy Carter Boulevard

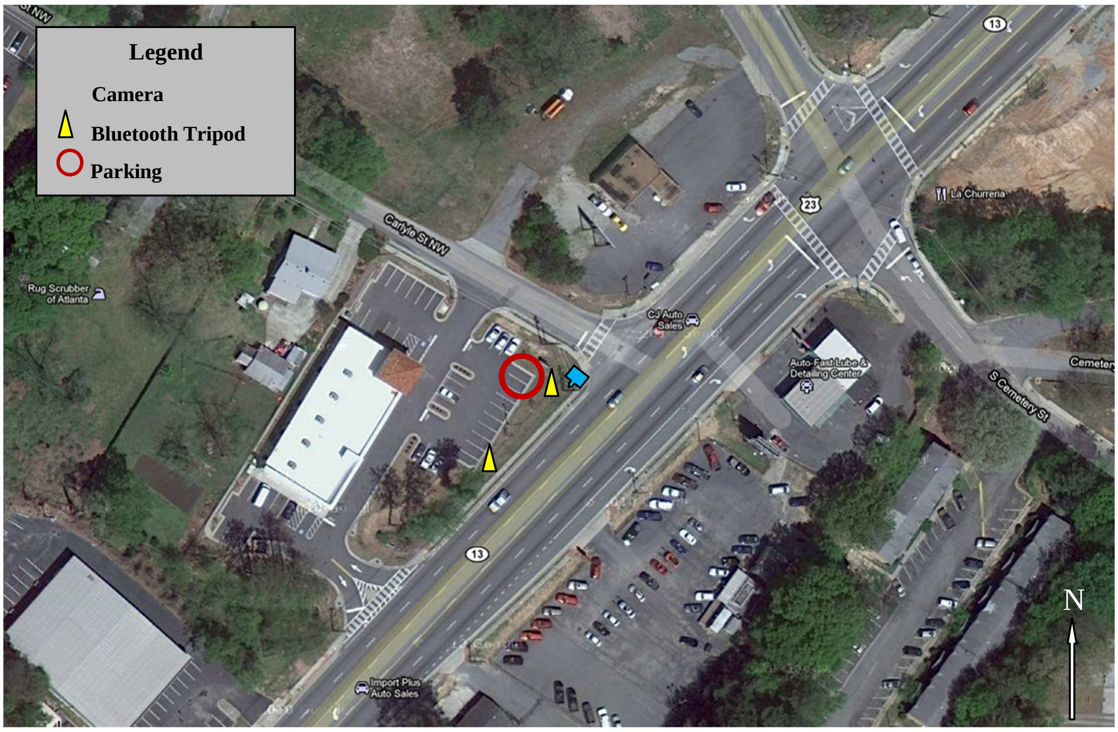


Figure 62: Map of Site A2 (*Background image from [36]*)

Site A2 is located immediately south of Carlyle St outside of Chen Eye Center at 5825 Buford Highway, shown in Figure 62. The GPS coordinates are 33.93869°N, 84.21210°W. Parking for this site is located in the Chen Eye Center parking lot. Permission has been obtained from the owner to use this site for the study.

The camera should be set up next to the sidewalk as shown in Figure 63. A rope should be tied around the top part of the tripod where the legs meet and tightly secured at the other end to a sandbag on the ground in order to ensure that the camera does not fall over. All parts of the camera tripod should be fully extended and the camera should be zoomed in to the full extent. A detailed view of the camera focus is shown in Appendix 1. Note the striping in the bottom right of the screen.

Figure 63: Camera location for Site A2.

The Bluetooth tripods will be set up 50 feet apart. Figure 64 shows the location of Tripod 1 and Figure 65 shows the location of Tripod 2. A sandbag will be placed under the leg of the tripod closest to the road in order to provide a level ground. Sandbags will also be placed on the other two legs of the tripods to ensure stability. An orange cone will be placed at the base of each tripod to warn pedestrians of the potential obstacle.

Figure 64: Location of Site A2 Bluetooth Tripod 1

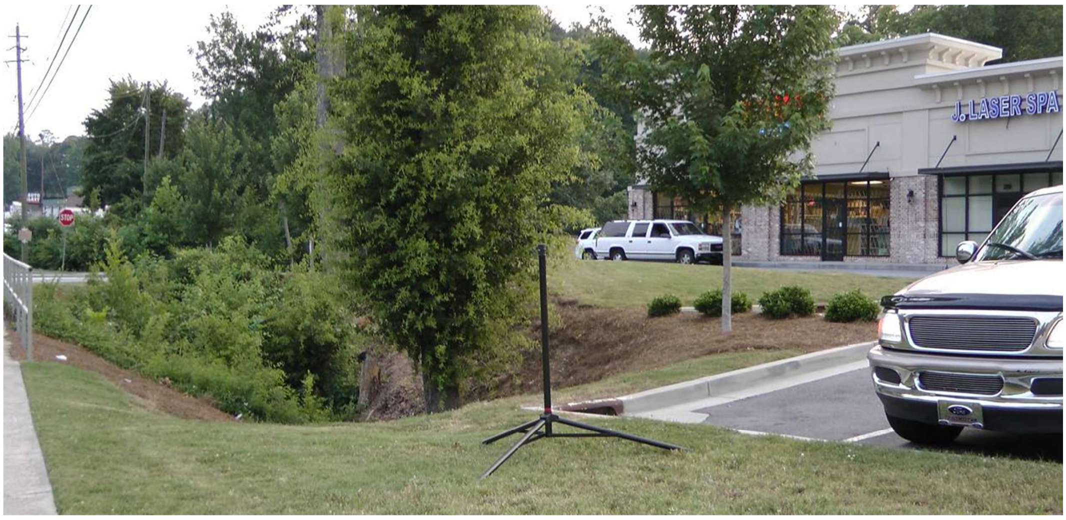


Figure 65: Location of Site A2 Bluetooth Tripod 2

Site A4: Southbound between I-285 and Chamblee-Tucker Road

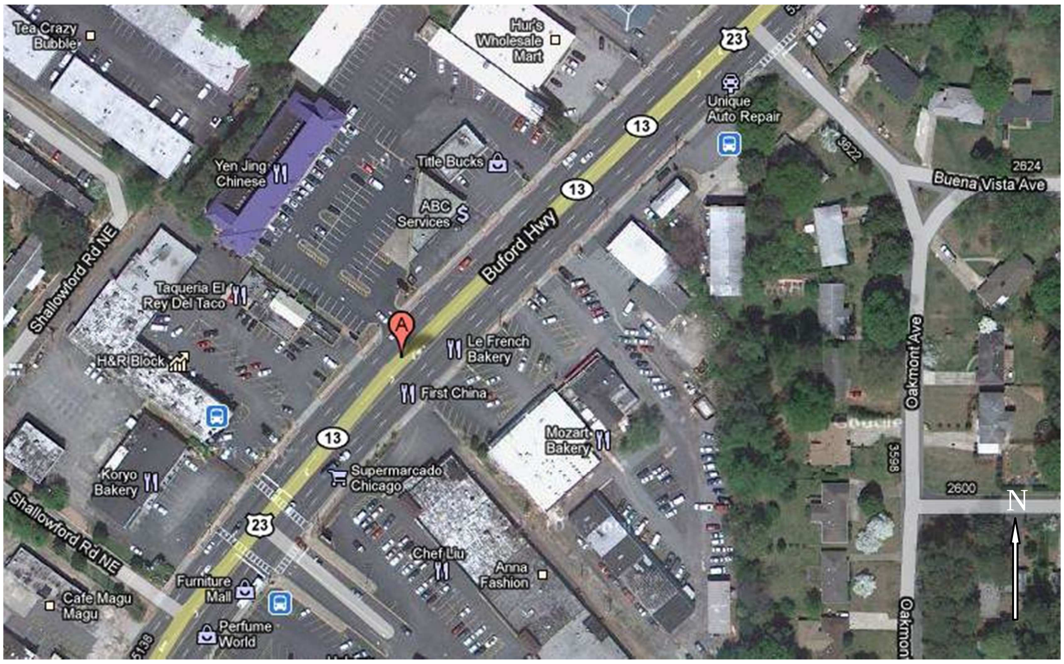


Figure 66: Map of Site A4 [36]

Site A4 is located south of Park Avenue, between El Rey del Taco and the Korean Town plaza at 5302 Buford Highway shown in Figure 66 and Figure 67. The GPS coordinates are 33.89709°N, 84.28163°W. Parking for the site is in the large Korean

Town parking lot located after the white Title Bucks Title Pawn building. Permission has been obtained to use the site for this study.

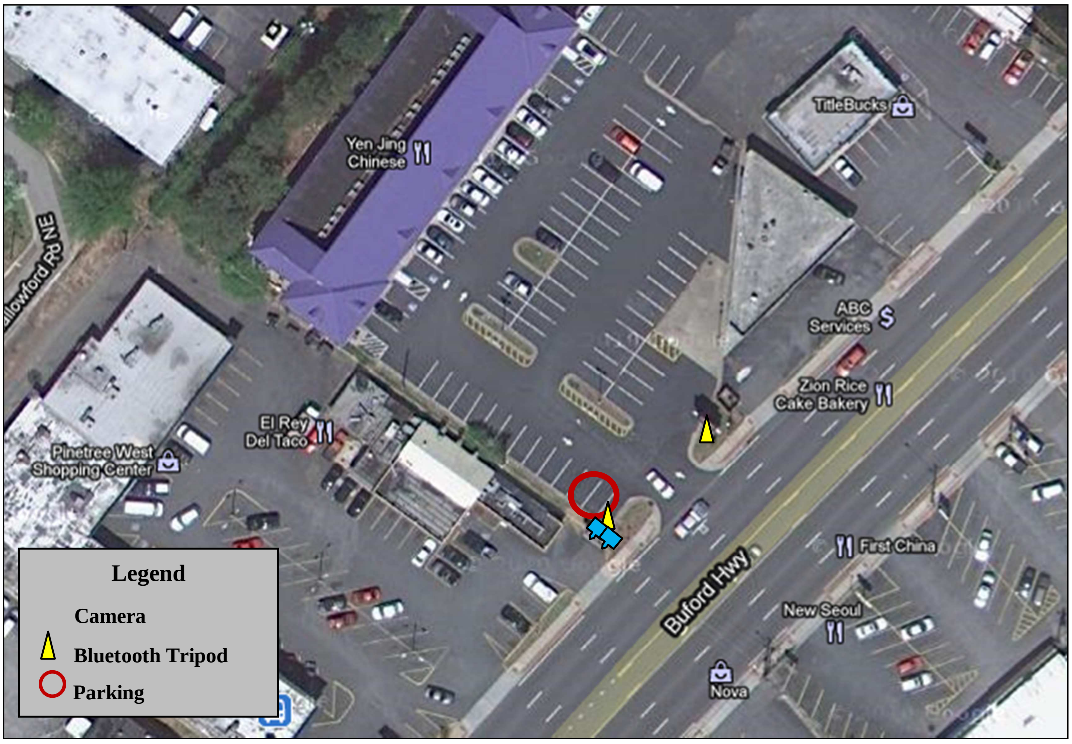


Figure 67: Setup for Site A4 (*Background image from [36]*)

Due to the three lanes of southbound traffic at this location, two cameras will be used to collect license plate data at Site A4. The two cameras should be set up as shown in Figure 68. A cable should be tied around the top part of the tripods where the legs meet and tightly secured at the other end to either the Bluetooth tripod or a sandbag on the ground in order to ensure that the camera does not fall over. Camera 1 will capture the inside and middle lane and camera 2 will capture the middle and outside lane. All parts of the tripods should be fully extended and the cameras should be zoomed in to the full extent. Detailed pictures of the camera views for camera 1 and camera 2 are shown in Appendix B1.

Figure 68: Camera location for Site A4.

The Bluetooth tripods will be set up 65 feet apart. Figure 69 shows the location of Tripod 1, and Figure 70 shows the location of Tripod 2, which will be the control tripod with only one reader at 10 feet. Sandbags will be placed on the legs of the tripods to ensure stability. An orange cone will be placed at the base of each tripod to warn pedestrians of the potential obstacle.

Figure 69: Location of Site A4 Bluetooth Tripod 1

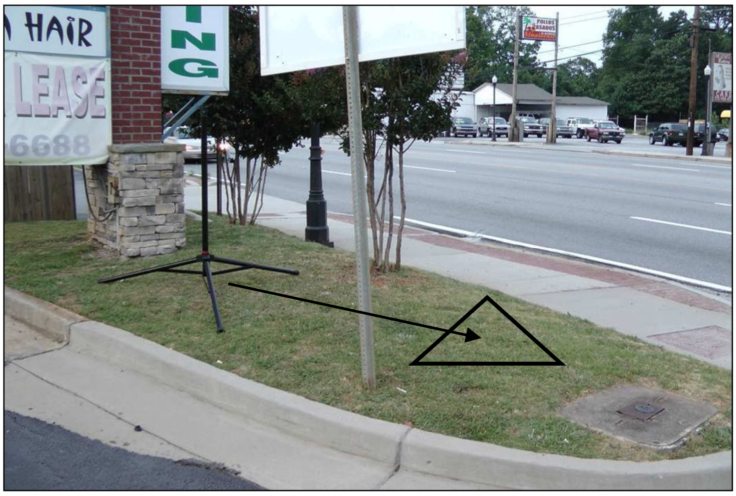


Figure 70: Location of Site A4 Bluetooth Tripod 2

PM Data Collection Sites

A map of the PM data collection sites P1 through P4 are shown in Figure 71. As only sites P1 and P3 will be used for this deployment, detailed information about these locations is included below.

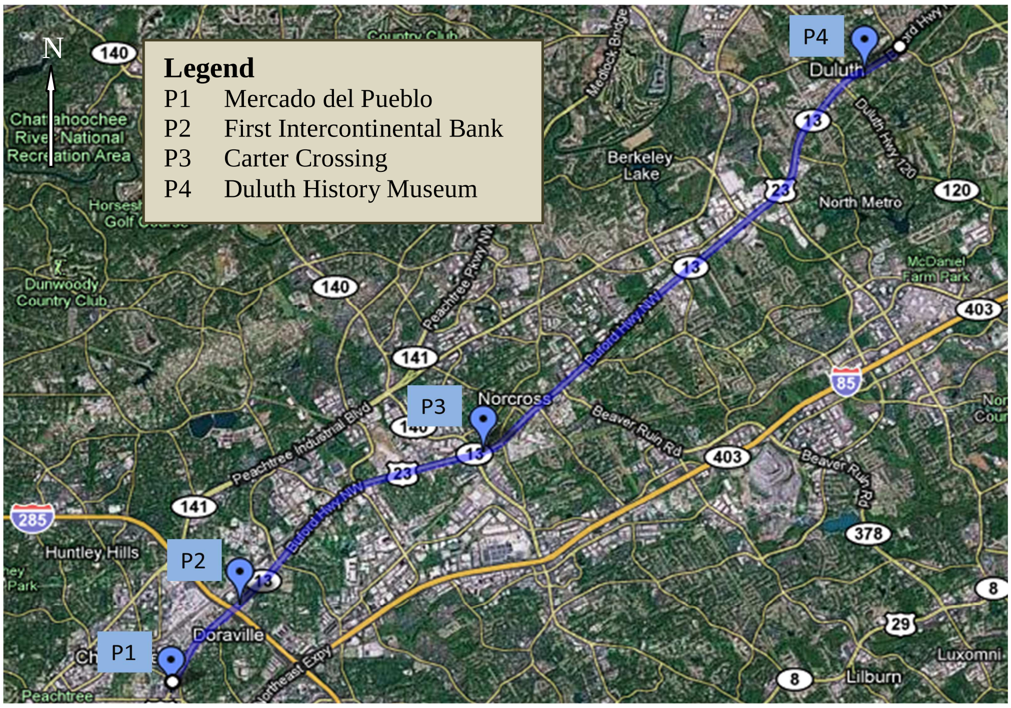


Figure 71: PM data collection sites along Buford Hwy (*Background image from [36]*)

Site P1: Northbound between Chamblee Tucker Road and I-285

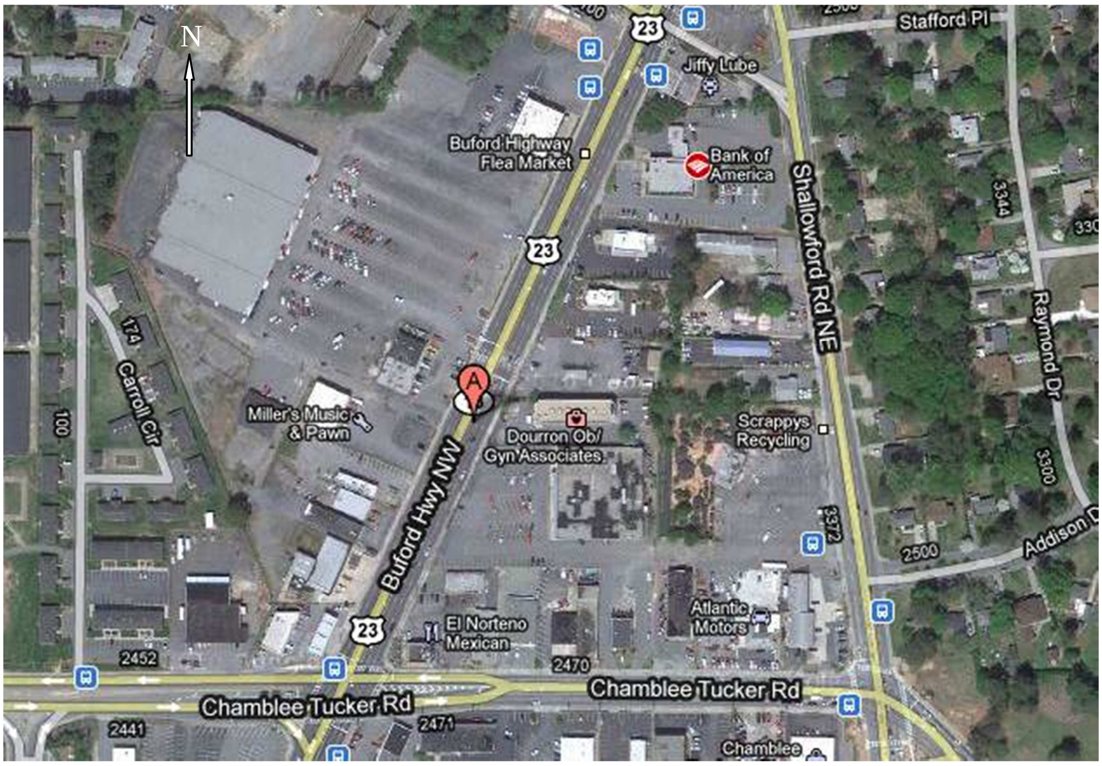


Figure 72: Map of Site P1 ***[36]***

Site P1 is located to the north of Chamblee Tucker Road outside Mercado del Pueblo at 4949 Buford Hwy, shown in Figure 72 and Figure 73. The GPS coordinates are 33.88683°N, 84.28738°W. Parking for this site is in the Mercado del Pueblo parking lot. Permission has been obtained to use the site for this study.

The camera location is on the northwest corner of the parking lot between the sidewalk and the stone wall, as shown in Figure 74. A rope should be tied around the top part of the tripods where the legs meet and tightly secured at the other end to the Bluetooth tripod, the fence, or a sandbag on the ground in order to ensure that the camera does not fall over. All parts of the tripod should be fully extended and the camera should be zoomed in to the full extent. A detailed view of the camera focus is shown in Appendix B2.

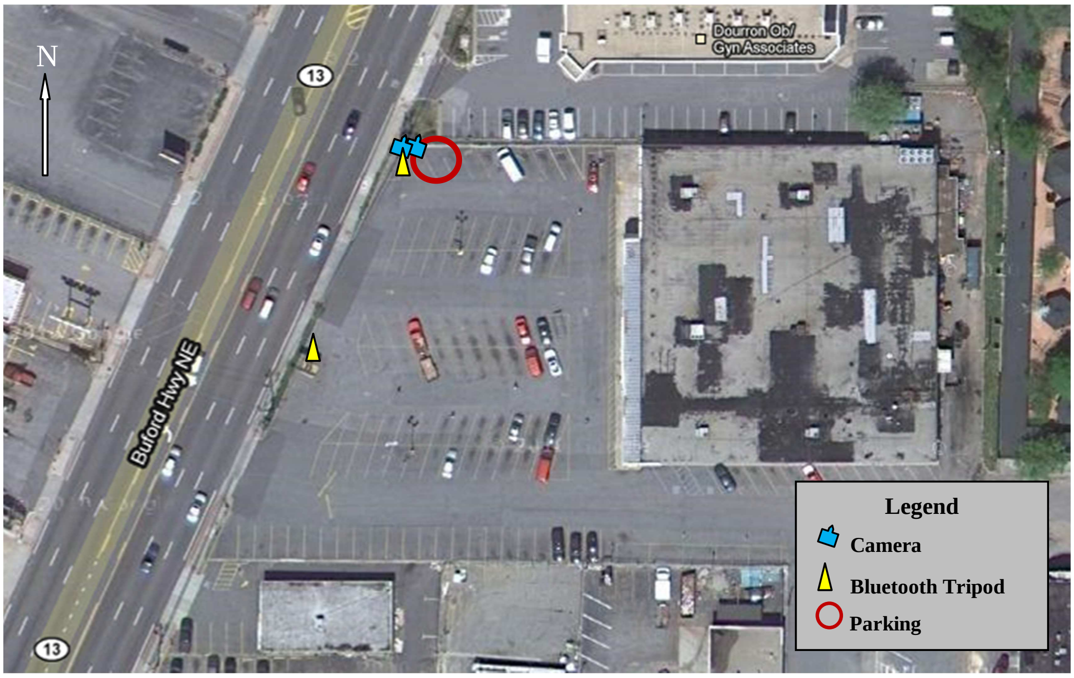


Figure 73: Setup for Site P1 (*Background image from [36]*)

Figure 74: Camera location for site P1

The Bluetooth tripods will be set up 120 feet apart. Figure 75 shows the location of Tripod 1, and Figure 76 shows the location of Tripod 2, which will be the control tripod with only one reader at 10 feet. Sandbags will be placed on the legs of the tripods to ensure stability. An orange cone will be placed at the base of each tripod to warn pedestrians of the potential obstacle.

Figure 75: Location of Site P1 Bluetooth Tripod 1

Figure 76: Location of Site P1 Bluetooth Tripod 2

Site P3: Northbound between Jimmy Carter Boulevard and Beaver Ruin Road

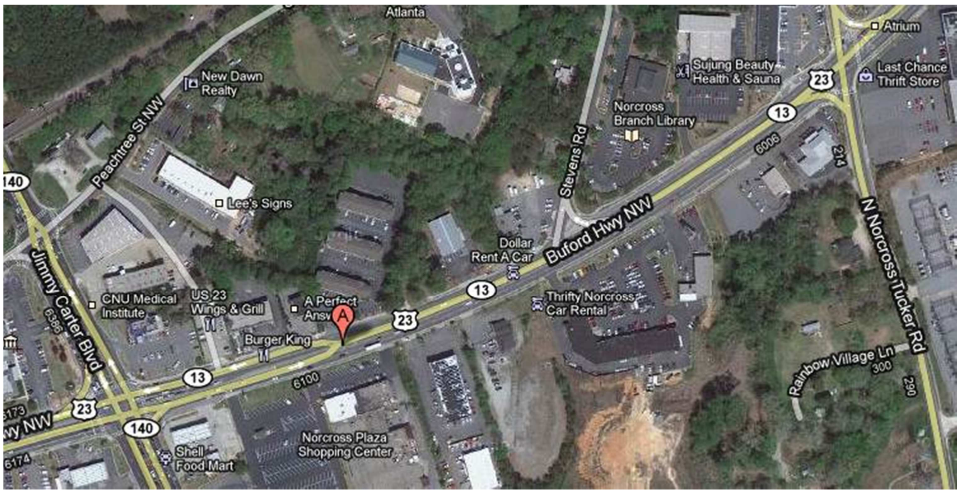


Figure 77: Map of Site P3 ***[36]***

Site P3 is located north of Jimmy Carter Blvd in front of Global Brokers in the Carter Crossing Shopping Center at 6355 Buford Hwy. The GPS coordinates are 33.93258°N, 84.22022°W. Parking for the site is in the shopping center lot. Permission has been obtained to use the site for this study.

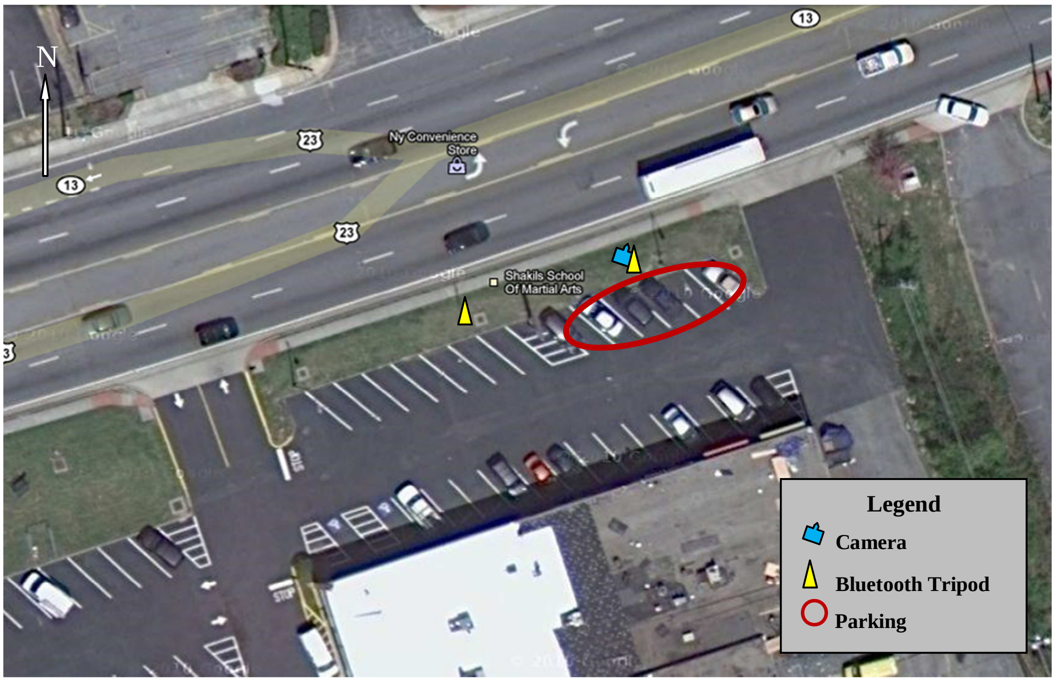


Figure 78: Setup for Site P3 (*Background image from [36])*

The camera location is in the grass between the sidewalk and the parking lot near the north end of the shopping center. A rope should be tied around the top part of the tripods where the legs meet and tightly secured at the other end to the Bluetooth tripod in order to ensure that the camera does not fall over. The tripod should be positioned above the manhole as seen in Figure 79. All parts of the tripod should be fully extended and the camera should be zoomed in to the full extent. A detailed view of the camera focus is shown in Appendix B2.

Figure 79: Camera location for site P3.

The Bluetooth tripods will be set up 60 feet apart. Figure 80 shows the location of Tripod 1, and Figure 81 shows the location of Tripod 2, which will be the control tripod with only one reader at 10 feet. Sandbags will be placed on the legs of the tripods to ensure stability. An orange cone will be placed at the base of each tripod to warn pedestrians of the potential obstacle. Due to the steep slope, the camera tripod will be secured to the weighted Bluetooth tripod using a cable.

Figure 80: Location of Site P3 Bluetooth Tripod 1

Figure 81: Location of Site P3 Bluetooth Tripod 2

Bluetooth Configurations

Various Bluetooth configurations will be implemented each day of the study. One tripod will always be the control, with one reader placed at 10 feet. The other tripod will vary as follows, with the same configuration implemented during the morning and evening data collection.

Day 1: Monday June 13th

- 3 readers placed horizontally at 10’, spaced 3’ apart
- Each site will require 4 total readers

Day 2: Tuesday June 14th

- 3 readers placed vertically at 7’, 10’, and 13’
- Each site will require 4 total readers

Day 3: Wednesday June 15th

- 5 readers placed horizontally at 10’, spaced 3’ apart
- Each site will require 6 total readers

Day 4: Thursday June 16th

- 4 readers placed vertically at 5.5’, 8.5’, 11.5’, and 14.5’
- Each site will require 5 total readers

Day 5: Friday June 17th

- To be determined based on earlier results

Equipment

Each site will require the following equipment. ‘X’ refers to the number required for the specific day’s Bluetooth configurations as stated in the Bluetooth Configurations section.

Site A2

- 1 high resolution camera & SD card
- 2 batteries
- 1 camera tripod
- 1 measuring wheel
- 2 Bluetooth tripods
- X Bluetooth readers & USB extension cables
- X netbooks
- X Velcro ties
- 1 field bin
- 1 netbook bag
- 1 packet with letter explaining the project
- 3 safety vests
- 4 sandbags
- 3 orange cones
- 1 rope/cable

All other sites

- 1 high resolution camera & SD card
- 2 batteries
- 1 camera tripod
- 1 measuring wheel
- 2 Bluetooth tripods
- X Bluetooth readers & USB extension cables
- X netbooks
- X Velcro ties
- 1 field bin
- 1 netbook bag
- 1 packet with letter explaining the project
- 3 safety vests
- 2 sandbags
- 3 orange cones
- 1 rope/cable

Sites A4 and P1

- 2 high resolution cameras & SD cards
- 4 batteries
- 2 camera tripods
- 1 measuring wheel
- 2 Bluetooth tripods
- X Bluetooth readers & USB extension cables
- X netbooks
- X Velcro ties
- 1 field bin
- 1 netbook bag
- 1 packet with letter explaining the project
- 3 safety vests
- 2 sandbags
- 3 orange cones
- 2 ropes/cables

Probe Vehicle

- 3 netbooks
- 3 Bluetooth readers & USB extension cables
- 1 GPS device
- 1 packet with letter explaining the project

Appendix B1: AM Camera Views

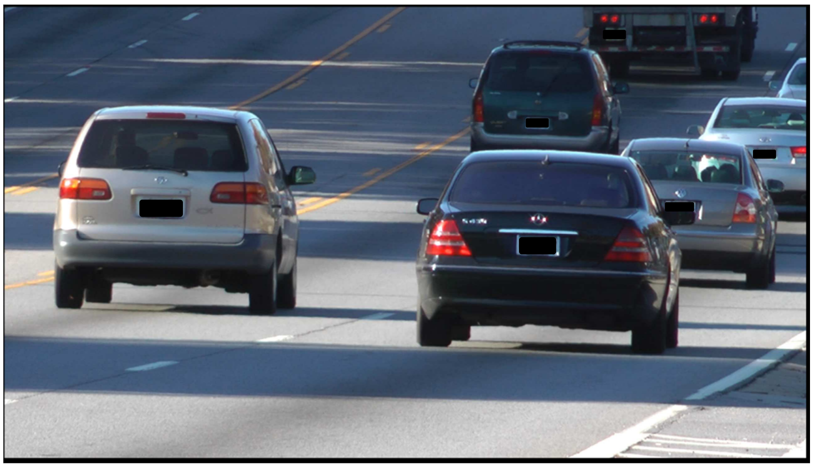


Figure 82: Camera View for Site A2

Figure 83: Camera View for Camera 1 (Inside Lanes) of Site A4

Figure 84: Camera View for Camera 2 (Outside Lanes) of Site A4

Appendix B2: PM Camera Views

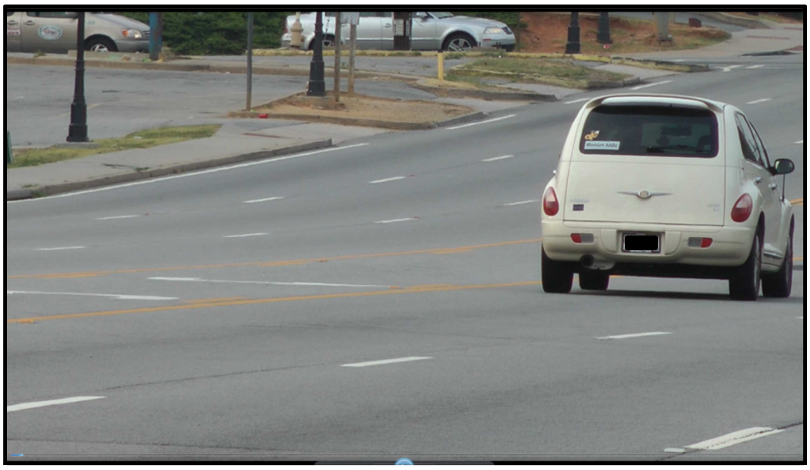


Figure 85: Camera View for Camera 1 (Inside Lanes) of Site P1

Figure 86: Camera View for Camera 2 (Outside Lanes) of Site P1

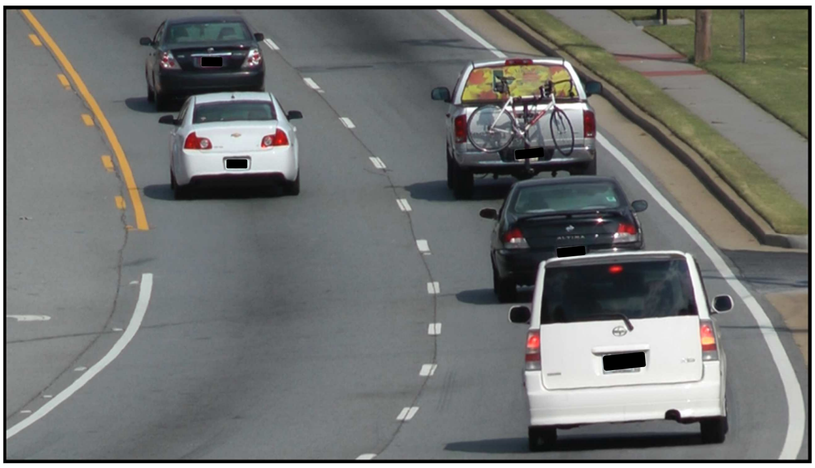


Figure 87: Camera View for Site P3

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