APPLICATION OF BLUETOOTH TECHNOLOGY TO RURAL FREEWAY SPEED DATA COLLECTION

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16. Abstract

Bluetooth data collection devices are an innovative technique for measuring travel times and speeds on roadway segments. This project developed a system capable of recording Bluetooth MAC addresses with a timestamp and determining the space mean speed of vehicles between multiple nodes. Battery powered and solar powered nodes are developed for the project. Various deployments of the nodes are utilized to determine the ideal placements and distances. The nodes are utilized in determining capacity of work zones by using travel speeds and times as surrogate measures of congestion. Nodes are also used to detect incidents based on increased Bluetooth device hit counts. Recommendations for node spacing are made for rural and urban areas.

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Prepared in cooperation with the
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and the
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Customary Unit	SI Unit	Factor	SI Unit	Customary Unit	Factor
Length			Length		
inches	millimeters	25.4	millimeters	inches	0.039
inches	centimeters	2.54	centimeters	inches	0.394
feet	meters	0.305	meters	feet	3.281
yards	meters	0.914	meters	yards	1.094
miles	kilometers	1.61	kilometers	miles	0.621
Area			Area		
square inches	square millimeters	645.1	square millimeters	square inches	0.00155
square feet	square meters	0.093	square meters	square feet	10.764
square yards	square meters	0.836	square meters	square yards	1.196
acres	hectares	0.405	hectares	acres	2.471
square miles	square kilometers	2.59	square kilometers	square miles	0.386
Volume			Volume		
gallons	liters	3.785	liters	gallons	0.264
cubic feet	cubic meters	0.028	cubic meters	cubic feet	35.314
cubic yards	cubic meters	0.765	cubic meters	cubic yards	1.308
Mass			Mass		
ounces	grams	28.35	grams	ounces	0.035
pounds	kilograms	0.454	kilograms	pounds	2.205
short tons	megagrams	0.907	megagrams	short tons	1.102

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LIST OF ACRONYMS

3G – Third Generation
ADT – Average Daily Traffic
BTDCS – Bluetooth Data Collection System
GPS – Global Positioning System
I-270 – Interstate 270
I-70 – Interstate 70
I-71 – Interstate 71
ID – Identification
$LiFePO_4$ – Lithium Iron Phosphate
MAC – Media Access Control
MPH – Miles per Hour
NB – Northbound
NTP – Network Time Protocol
ODOT – Ohio Department of Transportation
SB – Southbound
SFTP – Secure File Transfer Protocol
SLA – Sealed Lead Acid
SR-13 – Ohio State Route 13
SR-95 – Ohio State Route 95
SR-97 – Ohio State Route 97
US-30 – United States Route 30
US-36 – United States Route 36
US-37 – United States Route 37
US-39 – United States Route 39
USB – Universal Serial Bus

CHAPTER I
INTRODUCTION

Bluetooth devices may be used in an innovative and relatively inexpensive data collection technique for measuring travel times and speeds by comparing two or more time-stamped positional measurements, which are recorded by detecting a Bluetooth device (such as a cell phone or a Bluetooth-enabled GPS) as it passes near a Bluetooth radio. When a local device is discovered by the Bluetooth scanning radio, a time-stamp of the event is recorded, along with the media access control (MAC) address of the target radio. The MAC address is a unique identifier assigned during manufacturing of each Bluetooth target radio and is not associated with any personal information of a passing motorist; because of this, collection of data poses no threat to personal privacy. When several radios are installed alongside a segment of roadway, one Bluetooth target radio may produce a unique time-stamp at multiple locations. Since the distance between each scanning radio is known *a priori*, the corresponding travel time and average speed of the vehicle containing the target radio may be obtained by using MAC address logs to calculate the change in time between the target radio stamps over the fixed distance. Successful demonstrations of the implementation of the Bluetooth system for collecting travel time estimates are found in Pasolini and Verdone 2002, Barceló et al. 2009, Ahmed et al. 2008, Haghani et al. 2010, Quayle et al. 2010, Wasson et al. 2008, and Schneider et al. 2010.

1.1 Purpose and Objectives

Four research objectives must be met in order to ensure that state job number 134567, "*Application of Bluetooth Technology to Rural Freeway Speed Data Collection,*" will be considered a success. These four objectives, which are described in the Ohio Department of Transportation (ODOT) request for proposal, include:

- **Objective One -** Develop a system which uses Bluetooth technology in roadside devices to capture and match signals from vehicle-based Bluetooth devices,
- **Objective Two -** Determine minimum required spacing of devices to produce accurate (95%) travel times,
- **Objective Three -** Deploy sensors along a designated roadway and collect data in real time, and
- **Objective Four -** Summarize the final results.

1.2 Benefits from this Research

The research described within this report will have both immediate as well as long-term benefits. The main immediate benefits of this project include the demonstration of the Bluetooth Data Collection System (BTDCS) at the "pilot level," highlighting the technologies and their capabilities, as well as lessons learned from various BTDCS configurations. Other immediate impacts from this research include training of key ODOT employees for future deployments as well as software updates, which will allow for a greater independence from outside contractors, a potential cost-saving benefit, and a preliminary statewide feasibility assessment for using Bluetooth technologies.

In addition to the immediate benefits, there are several longer-term benefits of this research. These benefits include hardware and software that will lead to a straightforward implementation and compatibility with current ODOT software and websites. The BTDCS may potentially include the adaptation onto *Buckeye Traffic* and may be an effective way of independently validating travel times and speeds provided by future data service vendors. Improved cost savings for both ODOT and motorists who require efficient travel time and speed estimates on interstate highways may be realized. The ultimate benefit of this research is to provide ODOT with a cost-effective solution for monitoring traffic along interstates in Ohio.

1.3 Organization of this Report

This report is divided into six chapters. Chapter 1 is the introduction of the topic and a statement of the research objectives. Chapter 2 presents a description of the Bluetooth hardware. Chapter 3 presents the research methodology used in collecting the appropriate data for use in the analysis. Chapter 4 summarizes the results from the data collection, which include the average speeds and travel times for the various segments of the highway and a comparison between various node placements. Chapter 5 provides conclusions and recommendations based on the final results. Chapter 6 provides suggestions on the best approach to implement the findings from this research.

CHAPTER II

DEVELOPMENT OF BLUETOOTH HARDWARE

This chapter discusses the development of the Bluetooth system and is divided into three sections:

- Section One – Node Hardware,
- Section Two – Node Software, and
- Section Three – Server Software.

2.1 Node Hardware

In this section, each hardware component of the Bluetooth system (nodes) is described. Figure 2.1 provides a block diagram of the nodes. As illustrated in this figure, the main hardware components include: the computer board, the 3G and Bluetooth adaptors, two external antennas, a power regulator, and a power supply.

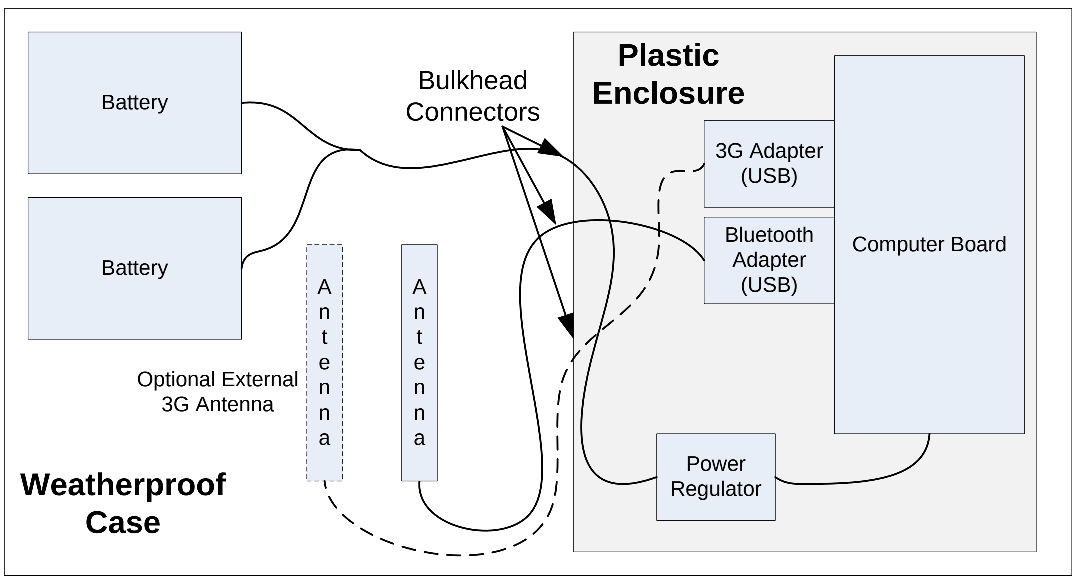


Figure 2.1: Block Diagram of Bluetooth Nodes.

2.1.1 Bluetooth Radio

For this application, the Bluetooth radio is the centerpiece of the node, and all other components are designed to support its operation in the field. The choice of radio strongly affects the performance of the system with respect to data return, especially with regard to the transmitter power and receiver sensitivity. A class 1 Bluetooth transmitter is a necessity because it maximizes the range at which the node may solicit responses (MAC addresses) from passing target devices. High receiver sensitivity increases the probability that the node will properly receive these responses. When considered together, these two device properties characterize the effective range of the node, and a large effective range means more MAC hits per node. The quantity of MAC hits is also dependent on the amount of vehicles with an active Bluetooth device; the proportion of vehicles with active devices is known as Bluetooth saturation rate and is discussed by Tarnoff et al. 2009 and Haghani et al. 2010. Additional information on Bluetooth radio antenna range may be found in Bakula et al. 2012.

The AirCable XR3 Bluetooth radio selected for use in the node is a class 1 device with the highest receiver sensitivity that is found by the research team. It also has the following desirable features: an external antenna port, support for open-source software, and adjustable transmitter power. The external antenna port provides the research team with the option to mount the Bluetooth antenna outside of the enclosure in a location that may provide a clear line-of-sight to the traffic flow. In addition, since the computing hardware runs open-source software, the Bluetooth radio must also support BlueZ, the open-source Bluetooth software suite. For research purposes and congested deployments, where nodes are spaced relatively close together, it may be useful to reduce the transmitter power, thus lowering the effective range of the devices so that the coverage zones for the nodes do not overlap.

2.1.2 Computer Processing

In order to operate the Bluetooth radio, a suite of software known as a “Bluetooth stack” must be installed on a computer platform. For a battery-powered field application such as this, a small, low-power, single-board computer is an ideal platform. The board must be powerful enough to run a full operating system (without a graphic interface), and it must contain USB interfaces for both the Bluetooth radio and the 3G cellular adapter.

The boards are expected to run for long periods of time in an outdoor environment without operator interaction, so they must be reliable and environmentally robust. The ARM9 processor-based computer board used in the nodes for this study is designed for operation over a wide range of temperatures, and it features an industrial-grade memory to decrease the possibility of memory failure that is prevalent with other types of memory devices, such as removable flash devices. The ARM9 is capable of running a full distribution of the open-source Linux operating system, yet it only consumes about 2W of electricity.

2.1.3 3G Cellular Communications

For the node to transfer data back to a central data processing server and maintain time synchronization with the other nodes, an Internet connection must be provided in the field. Currently, the most cost-effective way to achieve this is to use a cellular network. The nodes for this research use the USB760 3G adapter over the Verizon network, which is selected on the basis of cost, size, open-source support, and reliable coverage. An external antenna port on the device gives the research team the option to mount the 3G antenna outside of the enclosure, which provides a stronger signal in areas with poor 3G coverage.

One caveat here is that 3G communications are not completely reliable. During peak talk times, it is not uncommon for cellular phones to drop calls, even when stationary – and this holds true for the nodes as well. Hence, the node software used in this study is designed to maintain functionality during periods when there is no 3G link, by enabling the node to call out to the 3G network until it becomes available again. While no loss of data, i.e. MAC hits, will occur during these blackout periods, the data that is collected is delayed from being sent to the server for processing, and this will have ramifications on the real-time aspects of using the system.

2.1.4 Power

Two separate power systems are available for the node: battery power and solar power systems. Both are discussed briefly in this section. All hardware components for the nodes are selected with power consumption in mind, to reduce power consumption to the point where a battery may be used to power the node. The primary design criteria for the choice of battery are size, weight, capacity, safety, and cost. The selected battery must have sufficient capacity to run the node for several weeks in the field between recharges; this requires a battery with a capacity of about 80AH, which is achieved through the use of two 40AH batteries. The two principle battery chemistries that support batteries of this size are lithium iron phosphate ($LiFePO_4$) and sealed lead-acid (SLA). The $LiFePO_4$ battery is relatively new on the market and is showing signs of replacing the older SLA technology as manufacturing costs come down. The $LiFePO_4$ battery is about 60% lighter than SLA and will not leak toxic chemicals should the node become damaged by a vehicle, snowplow, or flooding. Although $LiFePO_4$ batteries are much more expensive, they provide cost advantages because their lower weight makes them less expensive to transport and because they have a longer battery life. For these reasons, the research team selected the $LiFePO_4$ battery to power the node.

The primary design of the node also incorporates a high-efficiency switching voltage regulator that decreases the 12-volt output of the battery down to the 5 volts required by the computer board. To increase safety, fuses are installed and industrial-grade power connectors are used to prevent loose connections.

With the installation of some additional hardware, the node may be configured to operate on solar power, eliminating the need to change batteries in the field. This configuration requires the addition of a solar panel, a solar power regulator, a sturdy post, and some hardware for mounting the panel and node to the post. Because power is being generated by the solar panel, only half of the battery storage is needed as compared to the battery-powered node, and this will help to offset some of the added expense of the solar power option.

2.1.5 Packaging

Outdoor roadside deployments require a lockable, weatherproof enclosure to house all of the components of the node. The enclosures for nodes used in this study are large enough to house all components, and each enclosure contains shapeable foam to minimize the movement of the node components as the devices are being transported and deployed. A smaller plastic enclosure is used to house and protect sensitive electronic components, e.g. radios, computer board, inside the node, as well as to reduce the risk of hardware damage during servicing.

2.2 Node Software

2.2.1 Operating System

The Linux open-source operating system is selected for this study on the basis of cost, it is free of charge, security, reliability, and the availability of extensive support for Bluetooth and 3G hardware. The Linux distribution that runs on the nodes contains only the libraries and modules necessary for the node to function. By eliminating all unnecessary software, the platform becomes more stable and secure, and more memory is available for data to be stored locally if the wireless connection is interrupted.

2.2.2 Bluetooth Software

The BlueZ Bluetooth stack is an open-source implementation of the interface required to operate Bluetooth radios. This stack is the only major open-source option that implements all of the functions required for the selected system.

2.2.3 3G Software

The Linux operating system supports the use of 3G adapters by employing point-to-point protocol. This module bridges the gap between the 3G hardware and the networking subsystem of the operating systems. When properly connected to the Verizon network, an Internet-connected network interface is made available to any software applications running on the computer board. In order for the adapter to properly communicate with a Verizon 3G cellular tower, a custom configuration script is developed by the research team.

2.2.4 Time Synchronization

Since the fundamental idea behind using Bluetooth scanners for interval speed measurements is dependent upon the timestamps of the MAC hits, a global time source must be made available to all nodes so that every node is operating from the same time base. The network time protocol (NTP) is used to achieve this. Because each node is equipped with an Internet connection, it is able to use the NTP to synchronize its system clock to an NTP server. With all nodes synchronized to the same server, the timestamps contained in the MAC hits will have the same time base, allowing for accurate computations of speed data.

2.2.5 Software/Image Updates

The research team developed a process to facilitate field updates of the software and quick node construction. In this process, the entire board's memory may be saved and restored as a single image file, which may then be restored on another node in a matter of minutes, essentially duplicating the first node. This process allows the research team to load the software for large numbers of nodes in a short period of time. In addition, if changes are made to the software and a new image is created with those changes included, the nodes in the field may be easily upgraded.

As the imaging progressed, the research team developed a system to image the nodes. The imaging process consists of the following steps:

- Remove the wireless card and all wires plugged into the motherboard.
- Disconnect the power to the node.
- Insert the flash drive with the image on it into the USB port and plug in the power cable.
- The red and green light on the motherboard will alternate 6 blinks, and then both lights will remain on. Once the lights turn off (after approximately 12 minutes) the image is complete.
- Remove the flash drive from the USB port in the node.
- Disconnect the power to the node.
- Plug in the wireless card and any other wires previously removed.
- Reconnect power to the node.

2.2.6 Operator Interface

An Ethernet port is available on the node for a laptop connection, which allows a field technician to verify that a node is working correctly. The nodes are designed to operate without any user intervention, so this capability is for user feedback only.

2.2.7 Field Hardening

The software suite running on the node is designed to work as long as power is connected and a 3G connection may be made, even if the connection is intermittent. Because large software deployments, such as the one used in this study, and all digital hardware components are subject to occasional errors, the software must be robust enough to self-diagnose and fix any issues that may occur during operation. A great deal of effort was put into the "field-hardening" of all of the software processes that run on the node, since the research team is unable to log into a node over a 3G connection without violating the usage terms of the 3G providers. Even if this were possible, it is still advantageous to minimize the amount of field maintenance of these devices, especially for large deployments.

2.3 Server Software

All of the data from the nodes are sent to a single server for processing. The functionality of this server is discussed in the following subsections.

2.3.1 Updating Node Positions

Nodes may be moved during the deployment, and these movements must be meticulously tracked to ensure that the speed measurements will be correct. The speed calculations are based on the road segment length, and if this value is changed after a node is moved, then the speed calculations may be totally inaccurate. To efficiently facilitate node movement, the road segments are defined in a simple database that contains information about which two nodes form a road segment and what the distance is between the two nodes. Timestamps are also recorded to keep track of when the nodes are moved. The data processing algorithms described earlier will read from this database every time speeds are computed; by simply updating the road segment database every time a node is moved, the integrity of the system will be maintained.

2.3.2 Maintenance of the Nodes

To ensure that the nodes are functioning correctly, each node will periodically send status data to the server, allowing the system administrator to diagnose any problems that are occurring. This feature facilitates the diagnosis and fixing of software and hardware issues and allows the research team to monitor conditions for each node, including the amount of free memory that is available.

2.3.3 Receiving and Processing Data from the Nodes

The primary role of the server is to provide a location for all of the nodes to send their MAC hit data for processing. Each node uses a secure file transfer protocol (SFTP) to periodically transfer files to the server, which then extracts the MAC hits from the files and places them into a database. Two stages of processing are needed to turn these hits into useful data: cleaning and matching.

2.3.4 Cleaning MAC Hits

As a target radio passes by a detector, the target may be discovered multiple times. Instead of using only one hit and discarding the rest, all of the hits for a single pass are grouped together into what the researchers refer to as a "cleaned" hit. This hit consists of a hit count, as well as the first, last, and average timestamps from the group of hits. An interval of time is specified that delineates between hits from a single pass of a target device and the hits from a future pass. This is important, because it is very common for a node to record two passes of a target radio each day as a driver commutes to a given destination and makes a return trip.

2.3.5 Matching the Cleaned Hits

Once the hits are cleaned, they must be matched up to produce speed measurements for each road segment. The matching algorithm processes the cleaned speed intervals from a "start" node and a "finish" node to produce a speed measurement consisting of three speeds: slow, fast, and average. A "slow" speed is computed using the first timestamp from the start node and the last timestamp of the finish node. A "fast" speed is computed using the last timestamp from the start node and the first timestamp from the finish node. An "average" speed is also computed using the average timestamps from both nodes. These speeds are shown in Figure 2.2 on page 11, which shows a case where a target device is detected multiple times, indicated by the black dots, from two nodes. The three time intervals that are derived from the matching algorithm are shown at the bottom of the figure. The distance between the nodes is divided by each time interval to obtain the three speeds. If each node only detects the target device once, then all three speeds would be equal. Depending on which speed is utilized, the resulting travel times may vary; accordingly, several studies have been conducted comparing the accuracy of Bluetooth segments speeds to probe vehicle speeds including Quayle et al. 2010, Kim et al. 2011, Schneider et al. 2010, Haghani et al. 2010.

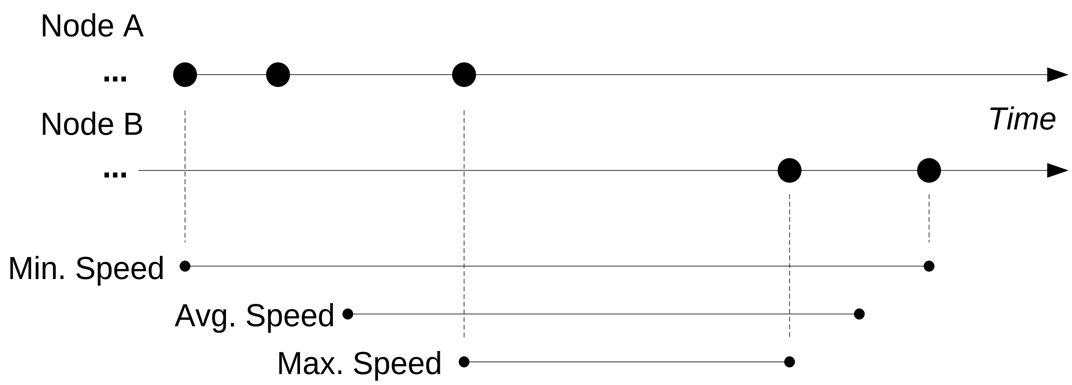


Figure 2.2: Diagram of Speeds Obtained between Two Nodes.

The rationale behind including first, last, and average timestamps for each cleaned hit and using them to compute three different speeds for each match is the preservation of information for analysis. The research team is interested in analyzing the following quantities for various node placement scenarios:

- Detection count statistics,
- The time distribution during multiple detection cases, and
- The distribution of the three speed measurements.

These statistics will vary quite a bit depending upon where the nodes are located, how they are placed near the road, and the traffic conditions. This additional information may enable the team to gather other information, such as detecting a traffic crash by sensing a spike in the hit counts for cleaned hits instead of a decrease in speed measurements. The advantage of this feature is that one does not need to wait until the traffic traverses the entire road segment, when the speeds would be computed, before being alerted about the incident.

2.3.6 Real-Time Processing

In order to produce speed data in real-time, the data processing algorithms described in the previous paragraph are repeated periodically in very short time intervals on the order of tens of seconds. An important metric for real-time data is the latency between the second target detection, i.e. the detection at the "finish" node, and the computation of the speed. The time that is elapsed from when a MAC hit appears at the finish node of a road segment to when a speed match is computed is dependent upon the following delays:

- The delay between the acquired MAC hit and when the node sends the hit to the server,
- The delay between when the hit arrives at the server and when the server processes the hit,
- The time it takes for the hit cleaning algorithm to be run, and
- The time it takes for the speed matching algorithm to be run.

Each of these delays is a quantity that maybe controlled up to a certain extent. The current software configuration has a worst-case delay of a little over two minutes for MAC hits that are *not* delayed from being sent to the server due to temporary loss of 3G service. By adjusting how often these server processes are run, the worst-case delay maybe decreased.

CHAPTER III

METHODOLOGY

3.1 Introduction

The objective of this study is to develop a sustainable Bluetooth system capable of measuring travel speeds and travel times on Interstate 71. This methodology chapter is comprised of four sections:

- Section One – Introduction,
- Section Two – Individual Node Setup,
- Section Three – Maintenance of the Bluetooth System, and
- Section Four – Deployment of the Nodes.

3.2 Individual Node Setup

The setup of each individual node is the same for the duration of the project. Each Bluetooth node is located within a small, waterproof, suitcase-sized Pelican case. These cases are then placed on the ground when deployed in the field. Since the antenna that records the Bluetooth hits is located inside the case, it is essentially at ground level, as shown in Figure 3.1.

Figure 3.1: Bluetooth Node Setup.

Although the idea of mounting the antennas to a structure above the roadway was discussed, the research team decided to keep the antennas within the Pelican case to avoid drilling a hole through the side of the node case. If a drilled hole is not properly sealed, the node will become susceptible to water damage. Also, by mounting the antennae to an external structure, the deployment time will increase as the nodes are relocated for the various deployment strategies. The research team is aware that this placement of the antennae is not the most efficient. However, the current design is more conservative when compared with one incorporating external antennas, and there is still a sufficient amount of data recorded in this study to have appropriate findings.

For this study, a typical node setup with the attachment to a guardrail is used, see Figure 3.2. Positioning the nodes behind a guardrail ensures that nodes and personnel are protected from traffic. During weekly visits to change batteries and deploy the nodes, the research team parks the vehicle and performs all work behind the guardrails. Also, nodes positioned behind the guardrails are less visible and are therefore less likely to distract a driver. Attaching nodes to guardrails does have a disadvantage: a guardrail may potentially shield the signal before it reaches the Bluetooth node. This setup is less efficient in terms of potential signal gain or loss than installing a new pole and mounting the equipment to that pole. The research team discussed moving the nodes to other locations, but the safety aspects for both the motorists and the research team are considered of greater importance than the optimization of the signal. The influence of vertical signal placement on data collection efficiency for Bluetooth MAC addresses is discussed by Brennan et al. 2010.

Figure 3.2: Typical Bluetooth Setup with Guardrail Attachment.

The second style for the deployment of Bluetooth nodes, as shown in Figure 3.3, is a more permanent structure that uses solar power. The solar powered node consists of a standard small traffic case which holds the node and battery and a solar panel located outside the case. This is the preferred setup if there is no desire to move the Bluetooth nodes from one location to another. A solar powered node takes several hours to install, while nodes in the Pelican cases only requires a few minutes. To reduce the time needed to train personnel and install nodes at Bluetooth deployment locations, the solar powered nodes are not used extensively in this project.

Figure 3.3: Solar Powered Node.

3.3 Maintenance of the Bluetooth System

In order to maintain the Bluetooth system, weekly visits are made to the field. During these visits, the batteries are replaced on each node and the nodes are moved to a new location along Interstate 71. Typically, the batteries have the capacity to be deployed for two weeks, but the research team replaces them weekly to guard against loss of data. While replacing the nodes, a visual inspection is performed to ensure that there is no damage to the node. Nodes are more likely to be damaged in the winter months than in the summer due to the harsh conditions, including both temperature as well as snow displaced by snow plows. In some cases during this study, the snow around the nodes is removed to ensure the nodes are able to record passing Bluetooth devices and to maintain cellular service for uploading the data.

The research team exercised great caution when working in the field. Safety vests are worn while performing work on the nodes on the highway, and a light bar is placed on top of the service vehicle to provide additional warning to approaching motorists. When stopping at a node location, the light bar and hazard lights are turned on before slowing the vehicle and moving to the shoulder of the roadway. When stopping at the nodes, the vehicle is pulled off the roadway and is parked behind a bend in the guardrail to prevent a wayward vehicle from striking the parked vehicle. Once they exit the service vehicle, the research team performs all work behind the guardrail.

3.4 Deployment of the Nodes

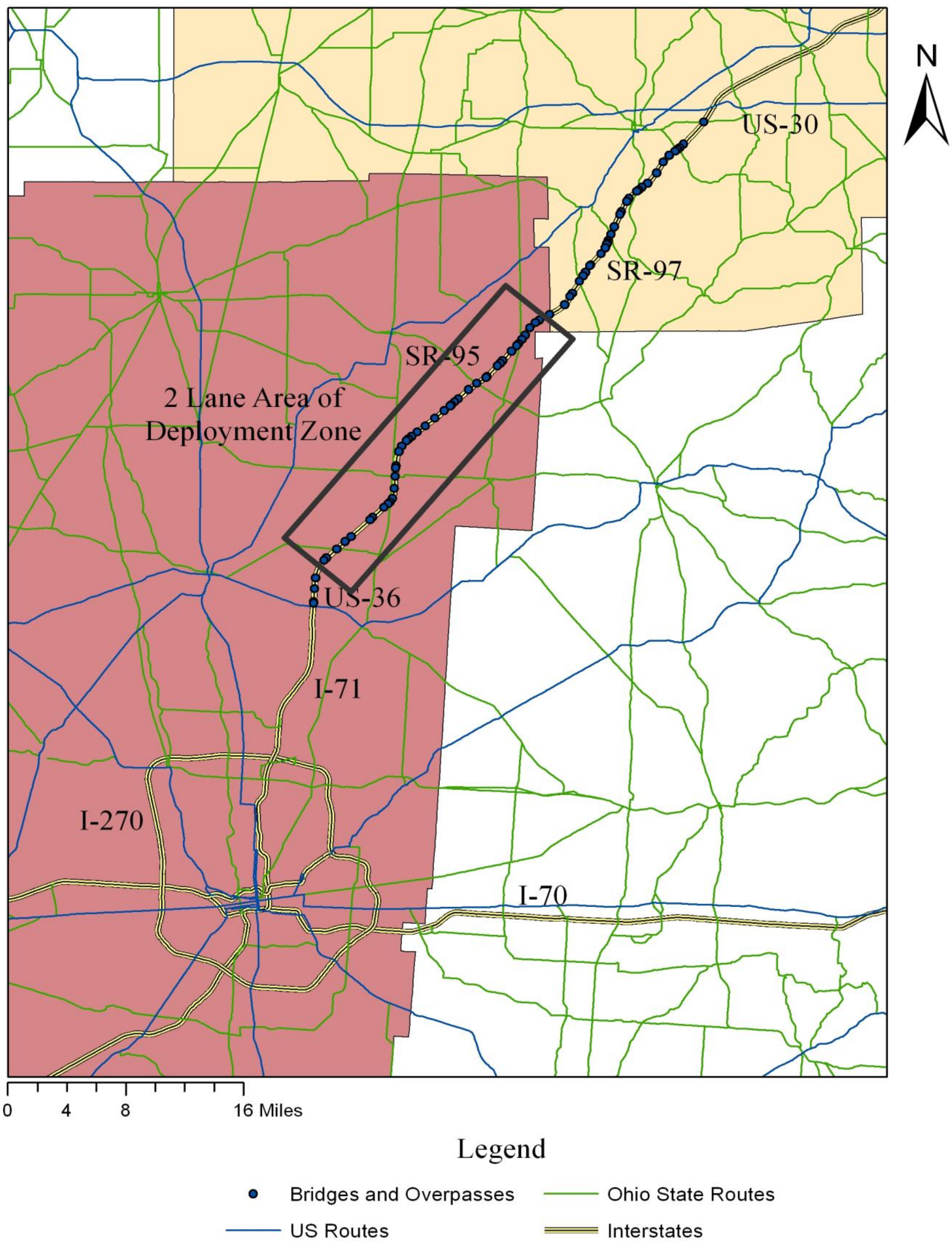
After the Bluetooth nodes are installed, the next task is to evaluate the deployment of these nodes along a segment of Interstate 71. Several strategies are developed to optimize the deployment of the Bluetooth nodes. This section is comprised of three sub sections detailing the tactics used in deploying the nodes:

- Section One – Initial Inventory of the Project,
- Section Two – Timeline of the Deployment Locations, and
- Section Three – Summary of Bluetooth Deployments.

3.4.1 Initial Inventory

Initially the research team created a roadway inventory using Google Maps. Unfortunately, Google Maps does not provide the level of resolution required for this research, since the maps are missing several key pieces of the roadway inventory: guardrails, signs, and the exact mile markers of bridges and overpasses. In order to create a more accurate database of landmarks and become familiar with the deployment area, the research team traveled throughout the boundaries of this study, from mile marker 180 to mile marker 121 on Interstate 71. While on this trip, the research team recorded the mile marker of every bridge, overpass, sign, and guardrail. The locations of bridges, signs, and guardrails are necessary for helping the research team to decide where future deployments will be located. Guardrails are the best structure to lock the nodes to, so the locations of these were recorded. Once the research team identified these locations, the actual coordinates were loaded into ArcGIS, a complete software system for incorporating geographic information.

The overall map of the deployment area is shown in Figure 3.4. The points on this map represent all bridge and overpass locations within the deployment area. The locations of the bridges and overpasses are typically accompanied by guardrails. As stated previously, the guardrails provide protection from traffic to the nodes and the research team when working on the nodes, provide a structure to which the nodes are locked, and make the nodes less visible and thus less likely to distract a passing motorist. Within the boundaries of this research project are roadway segments that consist of either two or three lanes in each direction. The two-lane area is indicated on the map; the remaining portions of Interstate 71 in the deployment area consist of three lanes.



Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.

Figure 3.4: Overall Deployment Zone with Bridge and Overpass Locations.

By traveling the route and recording this data, the research team is able to familiarize themselves with the project area. Also, the team is able to identify the location of any ODOT projects so as to not negatively impact traffic as well as avoid interfering with or interrupting any ODOT projects. While traveling the route, the research team is also able to identify potential areas of danger such as a reduction in shoulder width in the two-lane section of the highway, or an overpass with a node deployment location that has poor sight line for merging back onto the highway, as shown in Figure 3.5.

Figure 3.5: Overpass with Poor Sight Lines for Merging onto Highway.

3.4.2 Timeline of Bluetooth Node Deployments

The following section is the progression of the node deployments. Several node configurations are considered to identify the best possible deployment strategies. Ten deployment strategies are considered in this research project, and the deployment methods are divided into two categories. In category one, the research team focuses primarily on the development of the Bluetooth technology including the hardware, software, and data processing of the nodes. Category two is developed for the optimization of the nodes with respect to estimating travel times. Table 3.1 shows the deployments in each category and gives a brief description of each.

Table 3.1: Description of Each Node Deployment.

	Deployment Description	Rationale	Dates of Deployment
		Category 1	
Deployment 1	Technology Development	Optimize hardware, software, data processing of nodes and begin collecting data	8/19/11 - 9/16/11
Deployment 2	Technology Development	Optimize hardware, software, data processing of nodes and begin collecting data	9/16/11 - 11/11/11
Deployment 3	Technology Development	Optimize hardware, software, data processing of nodes and begin collecting data	11/11/11 - 11/22/11
Deployment 4	Technology Development	Optimize hardware, software, data processing of nodes and begin collecting data	11/22/11 - 12/22/11
		Category 2	
Deployment 5	Winter hardening and system sustainability.	Maintained locations for winter months to ensure optimal working conditions of nodes.	12/22/11 - 3/9/11
Deployment 6	Compare nodes spaced 2 to 3 miles with nodes spaced 5 to 9 miles. Then placed 3 or 4 nodes in clusters as close together as possible.	Analyze overlapping coverage areas of antennas and resolution of data based on node spacing.	3/9/12 - 3/23/12
Deployment 7	Compare Bluetooth speeds to side fire radar speeds.	Compare results of Bluetooth travel times based on space mean speed to ODOTs current method of measuring travel times based on space mean speed.	3/23/12 - 4/13/12
Deployment 8	Nodes placed on either side of interchanges, node placed on each shoulder and median in rural and urban areas.	Determine amount of Bluetooth hits lost at interchanges and evaluate the difference in quantity of hits from nodes in the median to nodes on the shoulders.	4/13/12 - 4/27/12
Deployment 9	Gather speeds before, during, and after construction zone.	Identify areas of queuing in or before the construction zone, determine travel speeds in construction zone, and compare speeds to same segment before construction zone.	4/27/12 - 5/8/12 5/24/12 - 7/20/12
Deployment 10	Node concentrated in the southern end of deployment zone and placed on or just outside of I-270 loop.	Compare travel speeds in urban area to rural area and quantify hits traveling around Columbus and along I-71.	5/8/12 - 5/24/12

Note: Nodes remain in the field as of July 2012.

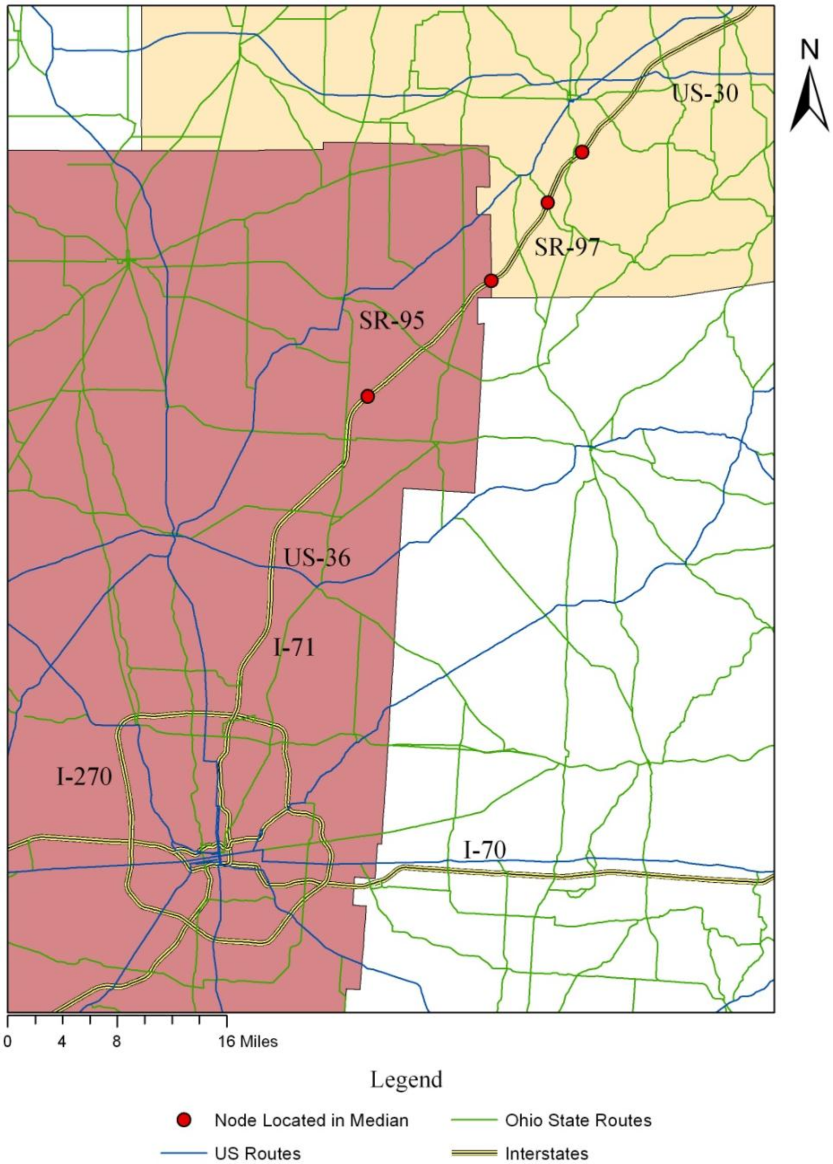
In Deployments 1 through 4, nodes are added as the Bluetooth technology is developed, and the nodes are moved farther south to determine the coverage area. In Deployment 5, the nodes ran continuously to ensure their working condition during the harsh winter months. Deployment 6 is used to determine if any issues arise from having overlapping coverage areas of the antennas. In Deployment 7, as a result of a software error, seven of the nodes would not upload data to the server. Once the research team discovered this error, the software is updated and the seven nodes came back on line. The research team is comparing the results of the Bluetooth travel times to ODOT’s current method of measuring travel times using side fire speed radars. In Deployment 8, nodes are placed north and south of several interchanges to analyze the number of Bluetooth hits lost and a node is placed in the median with nodes on each right shoulder in rural and urban areas. In Deployment 9, nodes are placed before, in, and after a construction zone to analyze travel speeds in the work zone and to identify any queues created. In addition, a deployment from before the construction zone is in place is recreated to compare speeds over the same road segment. In Deployment 10, nodes are spaced closely in the southern end of the research zone, and additional nodes are placed on Interstate 270, or just outside of Interstate 270 on Interstate 71.

Category 1: Deployments 1 through 4, Development of Bluetooth Technology

The main focus of Deployments 1 through 4 is to develop the Bluetooth nodes as well as to optimize the hardware, software, and data processing of the nodes. Simply stated, as the number of nodes increases, so too does the demand on the entire system. Throughout the initial phase of this research, the software and hardware are continuously updated with the goal of improving their efficiency.

Deployment 1

The first node deployment, as shown in Figure 3.6, consists of four nodes and is utilized from August 19, 2011, until September 16, 2011.



Node ID	Mile Marker
1	170
2	165
3	158
4	146

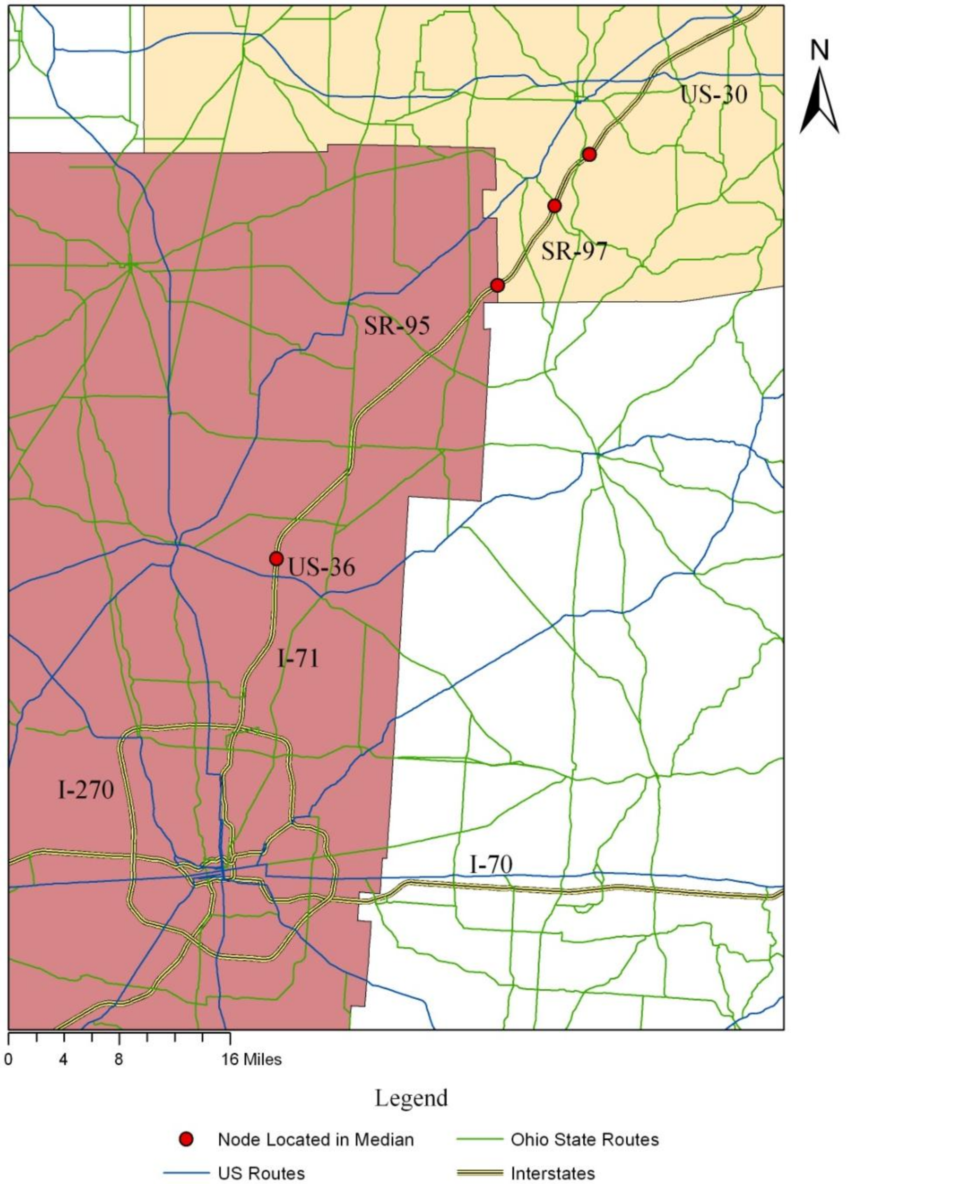
Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.6: August 19, 2011, Bluetooth Node Deployment.

The first node is located at mile marker 170 and the last node is located at mile marker 146. All four nodes are installed in the median and are attached to a guardrail. While this deployment is not optimal, the research team is able to collect information from sensor spacing ranging from 4.5 miles to 12.5 miles in length.

Deployment 2

The second node deployment, as shown in Figure 3.7, consists of four nodes and is utilized from September 16, 2011, until November 11, 2011.



Node ID	Mile Marker
1	170
2	165
3	158
4	132

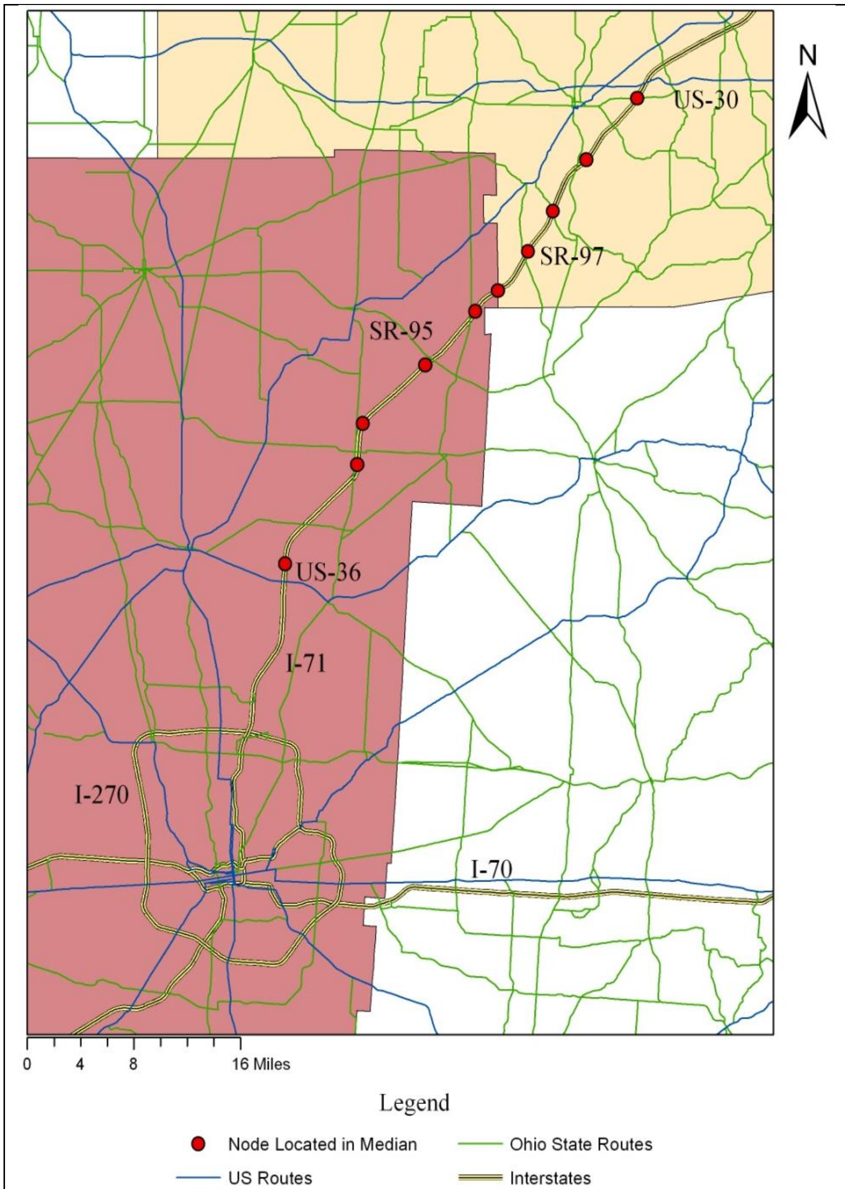
Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.7: September 16, 2011, Bluetooth Node Deployment.

In this deployment, the first three nodes remain in the same location as Deployment 1, while the last node is moved farther south, from mile marker 146 to mile marker 132. By relocating the fourth node, the coverage area of the deployment zone is increased. This is especially important, since the coverage area is greatly dependent on the quantity of matching hits between nodes. In addition, the final node is moved past the location where the highway widens from two lanes to three.

<u>Deployment 3</u>

The third node deployment, as shown in Figure 3.8, consists of ten nodes and is utilized from November 11, 2011, until November 22, 2011.



Node ID	Mile Marker
1	176
2	170
3	165
4	162
5	158
6	156
7	151
8	145
9	140
10	132

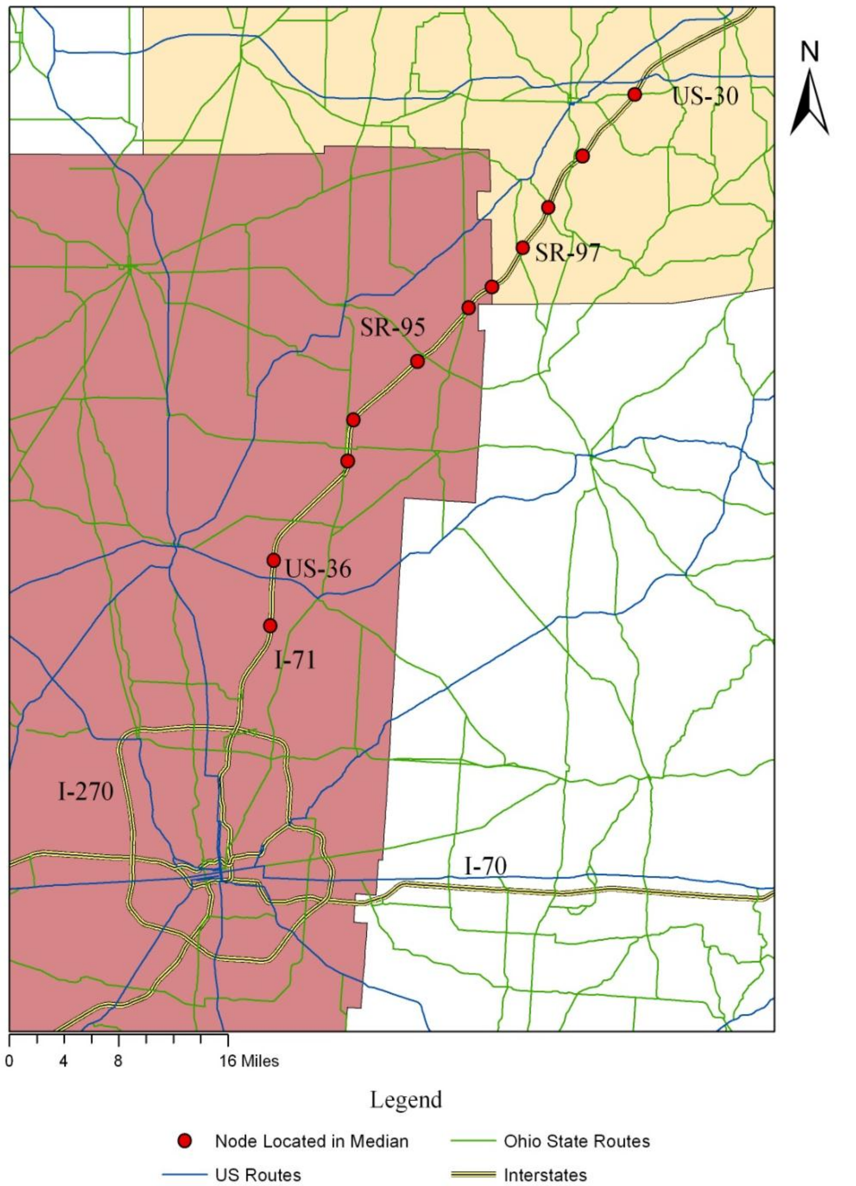
Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.8: November 11, 2011, Bluetooth Node Deployment.

By adding more nodes to the deployment zone, the research team enhances the resolution of the speed data obtained from the vehicles traveling on Interstate 71. Unfortunately, because of the large gaps between nodes, there is an increase in the probability that a vehicle will enter or exit the highway. A vehicle that exits and later reenters the highway will appear to the system to be traveling much more slowly than its actual rate of speed. A second concern with large distances between nodes is the temporal duration required to detect an incident along the highway.

Deployment 4

The fourth node deployment, as shown in Figure 3.9, consists of 11 nodes and is utilized from November 22, 2011, until December 22, 2011.



Node ID	Mile Marker
1	176
2	170
3	165
4	162
5	158
6	156
7	151
8	145
9	142
10	132
11	128

Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.9: November 22, 2011, Bluetooth Node Deployment.

With this deployment, the first node is located at mile marker 176 and the final node is positioned at mile marker 128. The majority of the nodes have the same locations as in Deployment 3, with the addition of another node to the south of the tenth node. Adding another node farther south enables the research team to collect data in a more urban area and to compare the amount of Bluetooth hits being recorded in the rural, north end with the number of hits in the urban, south end of the study. Based on the difference in hit rates, alternative deployment strategies for urban and rural areas may be developed. In addition, the research team is now able to compare speeds in both areas with three lanes of travel on Interstate 71, as well as the area where there are only two lanes of travel. A photograph showing an area where the highway widens from two lanes to three lanes is presented in Figure 3.10.

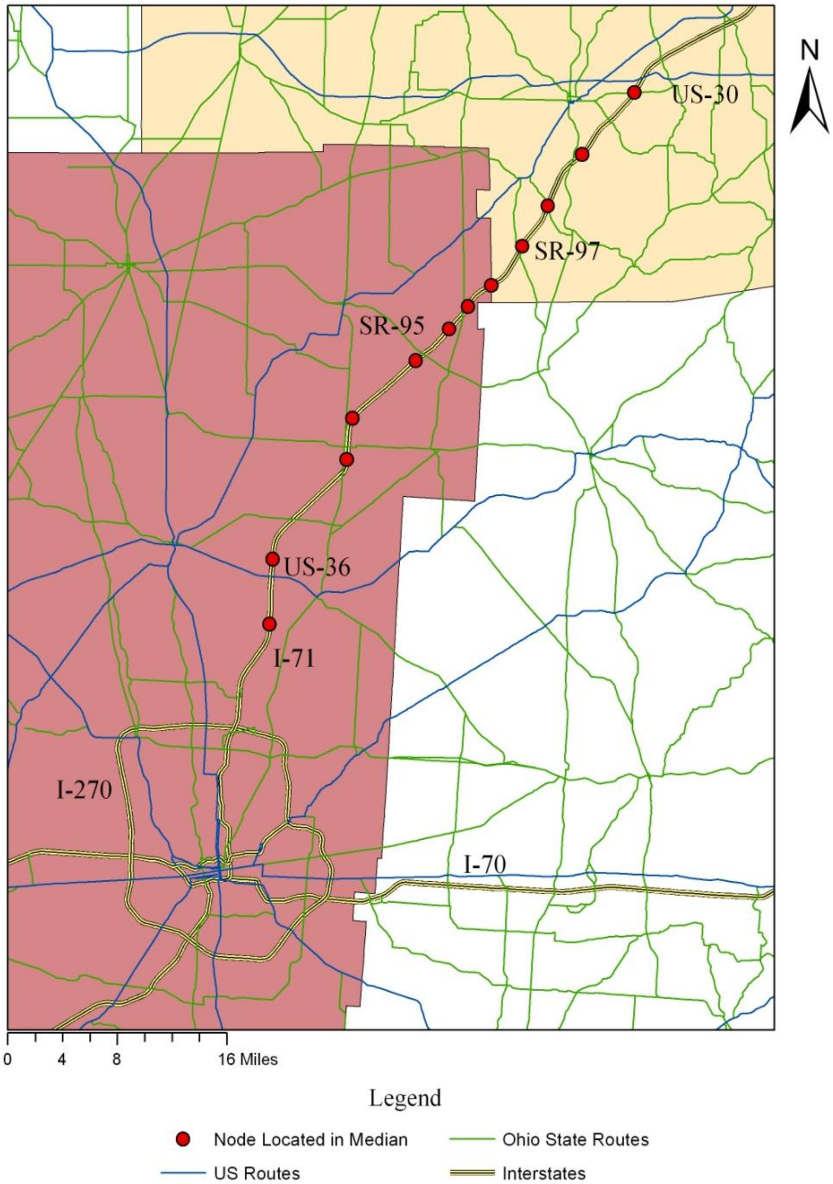
Figure 3.10: Interstate 71 Widening From Two Lanes to Three Lanes.

Category 2: Deployments 5 through 10, Optimization of Deployment Strategies

After the initial development of the Bluetooth nodes, the research team is now ready to evaluate multiple deployment strategies in order to optimize the implementation of the nodes.

Deployment 5

The fifth node deployment, as shown in Figure 3.11, consists of 12 nodes and is utilized from December 22, 2011, until March 9, 2012.



Node ID	Mile Marker
1	176
2	170
3	165
4	162
5	158
6	156
7	154
8	151
9	145
10	142
11	132
12	128

Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.11: December 22, 2011, Bluetooth Node Deployment.

In Deployment 5, the first node is located at mile marker 176 and the final node is located at mile marker 128. The difference between this deployment and the previous one is the addition of a node at mile marker 154. The added node provides better resolution of any activities occurring in the two-lane area of Interstate 71. With the reduction of the number of lanes, traffic speeds are likely to be slower as a result of congestion from the decreased capacity of the dropped lane. Figure 3.12 is a photograph of the location where the number of lanes is decreased from three lanes to two.

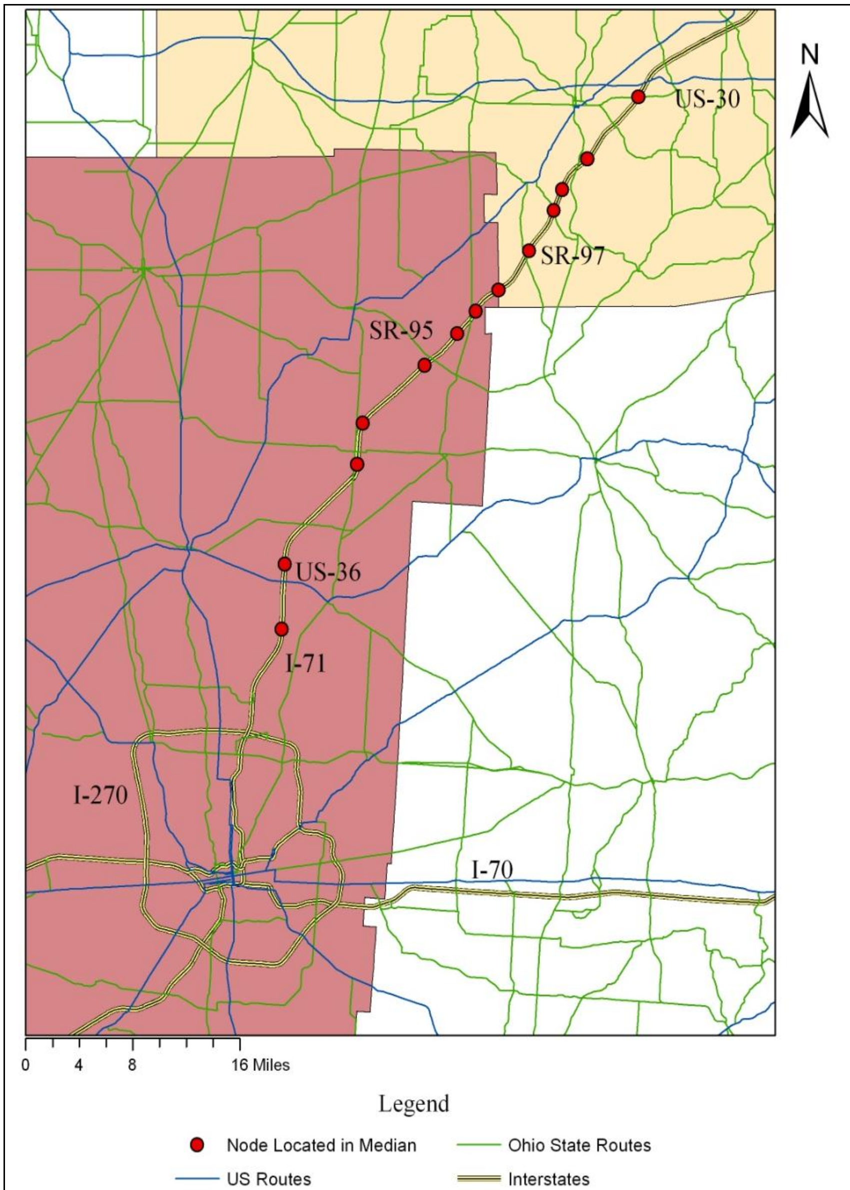
Figure 3.12: Interstate 71 Decreasing From Three Lanes to Two Lanes.

A key factor in Deployment 5 is the weather at this time of the year, as winter presents the harshest environmental conditions the nodes will face. Consequently, the research team is monitoring not only the traffic patterns but also the impact of weather on the equipment. Several interesting findings are noted during winter monitoring, including fatigue to the connectors and a decrease in battery capacity. In response to the wear and tear observed in the monitoring of the equipment, the research team used this time to upgrade the connections, shorten the connecting cables, and build the charging boards to ensure the cells of the batteries are evenly charged.

Using the roadway inventory created in the initial survey of the deployment area, suitable locations are identified for deployment of all the remaining nodes. The shortest distance between nodes is approximately two miles, and the longest is approximately nine miles. The varied spacing allows for a sensitivity comparison: too small of a distance between nodes will lead to overlapping of the signals, while too large of a distance will increase the possibility of losing a large number of matches from vehicles exiting or entering the highway.

Deployment 6

The sixth node deployment occurs in two phases. The first phase of this node deployment, as shown in Figure 3.13, consists of 13 nodes and is utilized from March 9, 2012, until March 16, 2012. The second phase, as shown in Figure 3.14, consists of 14 nodes and is utilized from March 16, 2012, until March 23, 2012.



Node ID	Mile Marker
1	176
2	170
3	167
4	165
5	162
6	158
7	156
8	154
9	151
10	145
11	142
12	132
13	128

Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.13: March 9, 2012, Bluetooth Node Deployment.

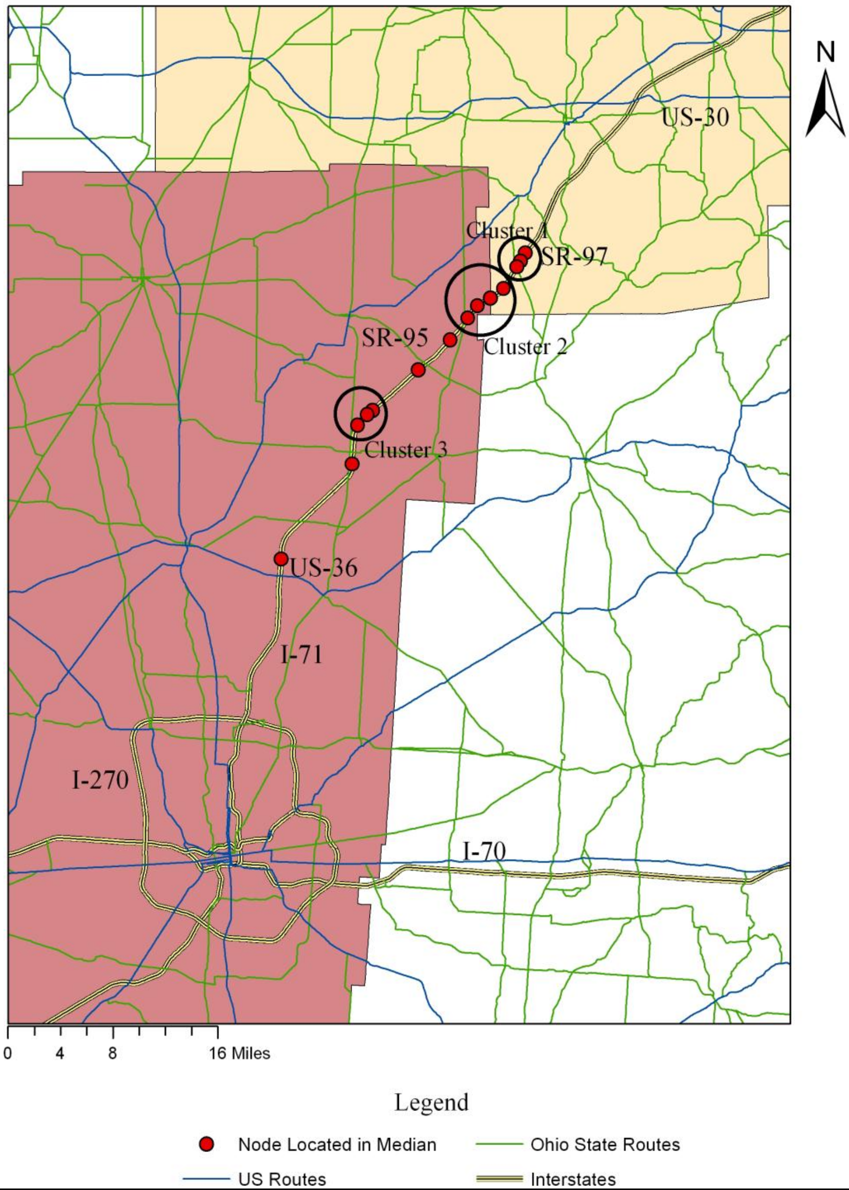
In the first phase of this deployment, the first node is located at mile marker 176 and the final node is located at mile marker 128. The nodes are grouped so that several nodes are within two to three miles of each other. Where the locations of bridges and overpasses did not allow for the nodes to be grouped closely, gaps of five to nine miles are left between the nodes. This layout is selected by the research team to evaluate any differences in having the nodes spaced close together versus far apart.

By placing some nodes in close proximity to each other while leaving other nodes farther apart, the research team is able to determine the effect of spacing on the quantity of Bluetooth hits obtained. With larger distances between nodes, it is possible to record fewer hits at one node than the next one; this may occur when a Bluetooth device is switched off or a vehicle exits the highway between two nodes. The rationale for leaving gaps of different lengths is to allow the research team to determine the optimal distance between nodes based on the amount of Bluetooth device hits between nodes. Within this configuration, the research team is able to evaluate the impact of spatial proximity of the nodes with respect to adequate estimation of travel speeds.

In the second phase of this deployment, the research team groups several nodes as close together as possible into clusters consisting of three or four nodes. The shortest distance between nodes is ½ mile, which occurs between Nodes 2 and 3. The research team spaces the nodes closely to determine if any overlap occurs in the coverage areas of the Bluetooth antennas. The research team wants to determine the effects of having overlapping coverage areas for example, to find if more or fewer hits are recorded by spacing the nodes so closely. The team will analyze the data to see if one or more nodes in a cluster fail to record a Bluetooth device that other nodes in the cluster were able to capture. By placing the nodes close together, the segment lengths will be short. Issues with short segment lengths for Bluetooth data collection are discussed by Malinovskiy et al. 2011.

Large gaps between the clusters typically occur in more rural areas, where there are few exits between the nodes and vehicles are unlikely to exit the interstate. Furthermore, gaps are left in areas where nodes cannot be safely secured. The large gaps are used to determine the amount of hits lost from one node to the next over a large span. If a significant amount of hits are lost, it may justify spacing nodes more closely in the optimal deployment strategy.

When placing nodes in the field, the research team discovered a trade-off in the spacing of the nodes. When nodes are spaced closely, the resolution of the speed data is higher, but more nodes must be built and maintained – which results in higher costs for a transportation agency. When nodes are spaced farther apart, fewer nodes are required, but the speed resolution will be lower.



Node ID	Mile Marker	Cluster Number
1	163	1
2	162	1
3	162	1
4	160	2
5	158	2
6	157	2
7	156	2
8	154	
9	151	
10	146	3
11	146	3
12	145	3
13	142	
14	132	

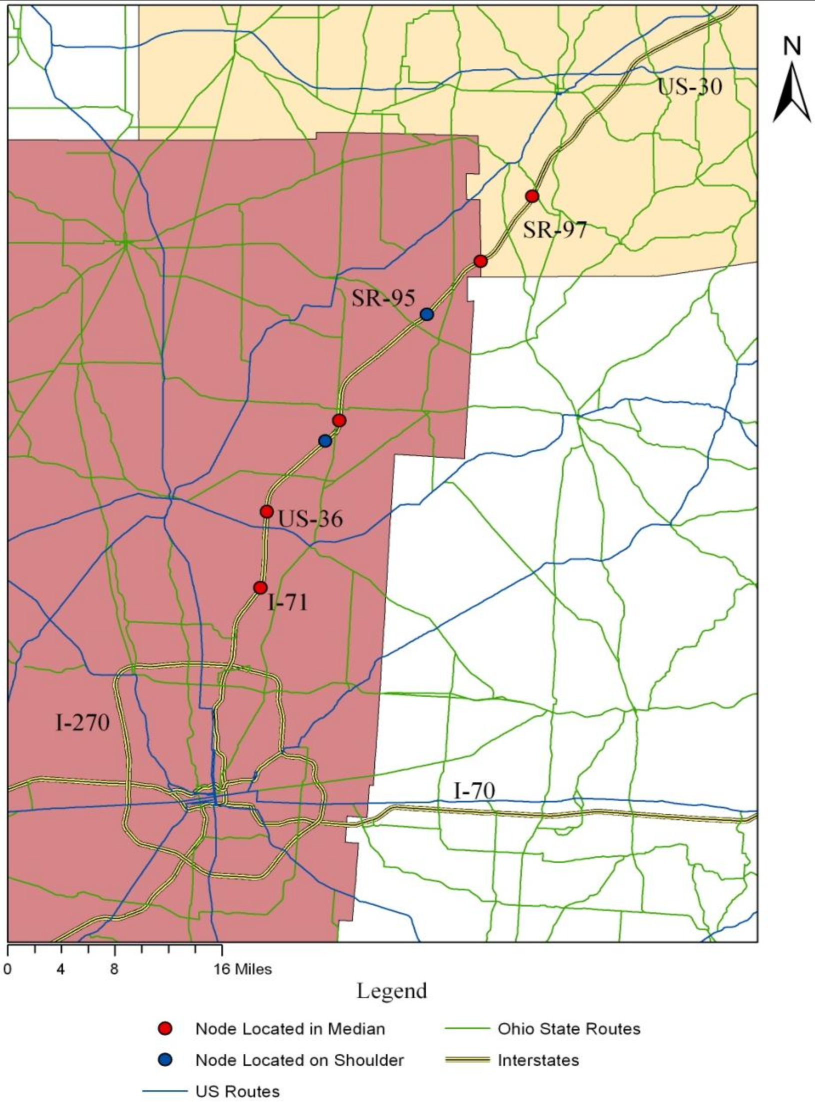
Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.14: March 16, 2012, Bluetooth Node Deployment.

In the second phase of the deployment, the first node is placed at mile marker 163, and the final node is placed at mile marker 132. The first four nodes are moved farther south in order to place them in clusters – ideally, at a distance of one mile between nodes. However, some clusters in the deployment include nodes that are spaced as far as two miles apart. In this phase, Nodes 1, 2, and 3 are considered as a cluster; Nodes 4, 5, 6, and 7 are considered as a cluster; and Nodes 10, 11, and 12 are considered as a cluster.

Deployment 7

Deployment 7 also occurs in two phases. The first phase of this node deployment, as shown in Figure 3.15, consists of seven nodes and is utilized from March 23, 2012, until March 29, 2012. The second phase of this node deployment, as shown in Figure 3.16, consists of 14 nodes and is utilized from March 29, 2012, until April 13, 2012.



Node ID	Mile Marker	Node Location
1	165	Median
2	158	Median
3	152	Shoulder
4	142	Median
5	140	Shoulder
6	132	Median
7	126	Median

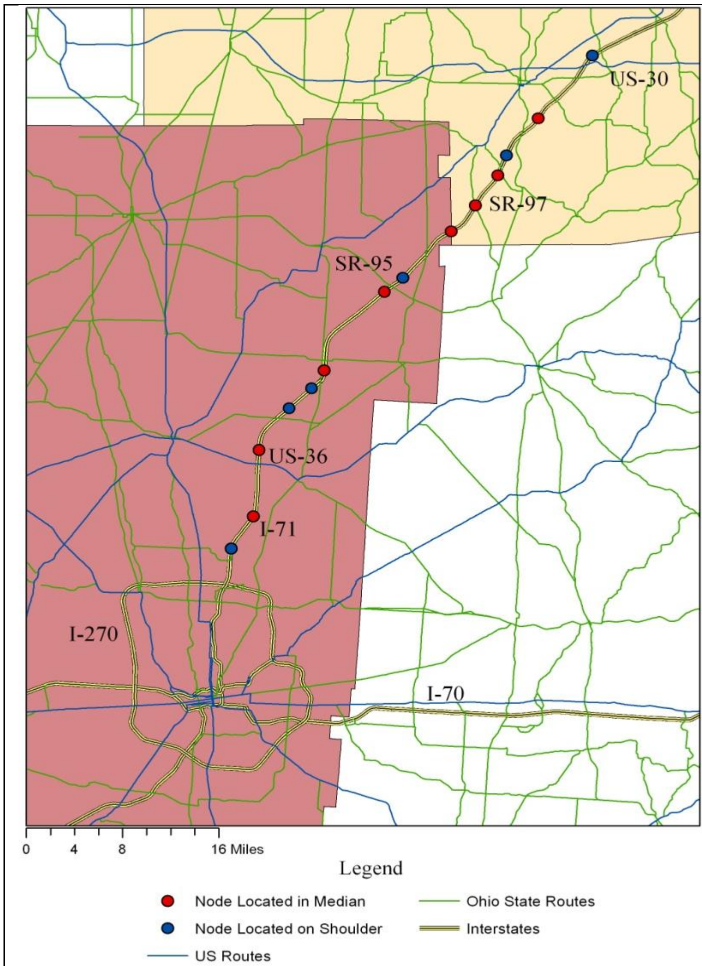
Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.

Figure 3.15: March 23, 2012, Bluetooth Node Deployment.

In the first phase of this node deployment, the research team uses seven nodes in the field. Three of the nodes in this deployment are located on the right shoulder rather than in the median, which makes it different from the previous deployments. The nodes located on the shoulder are shown as the blue points in Figures 3.14 and also in Figures 3.15 through 3.21. The first node is located at mile marker 165, and the final node is located at mile marker 126. Fourteen nodes are originally deployed in this phase; however, seven of these nodes are not able to upload data to the server.

In this phase of the deployment, all nodes are located in close proximity to the side-fire speed radar devices currently used by ODOT on Interstate 71 in order to compare the effectiveness of the two different technologies. The side-fire radar devices record time mean speeds i.e. the instantaneous speed of a vehicle, while the Bluetooth nodes record a vehicle's space mean speed, which is the speed calculated from the time it takes a vehicle to pass a known distance between two Bluetooth nodes. With the nodes deployed near the side-fire radars, the researchers are able to compare the speeds from the Bluetooth nodes to the speeds from the side-fire radars and validate the results of the Bluetooth nodes. In addition, by placing several of the nodes on the right shoulder, the team is able to determine what impacts the right shoulder spacing has on the operation of the nodes. Furthermore, the team is able to ascertain whether a substantial amount of data is lost or if no data at all is lost; this information will aid in developing an optimal deployment strategy.

In the next phase of this deployment, the research team places one node in the median and another just off the right shoulder, directly across from the node in the median, in order to determine the quantity of hits that are recorded by one node but not the other.

	Node ID	Mile Marker	Node Location
	1	179	Shoulder
	2	171	Median
	3	167	Shoulder
	4	165	Median
	5	162	Median
	6	158	Median
	7	152	Shoulder
	8	151	Median
	9	142	Median
	10	140	Shoulder
	11	136	Shoulder
	12	132	Median
	13	126	Median
	14	122	Shoulder

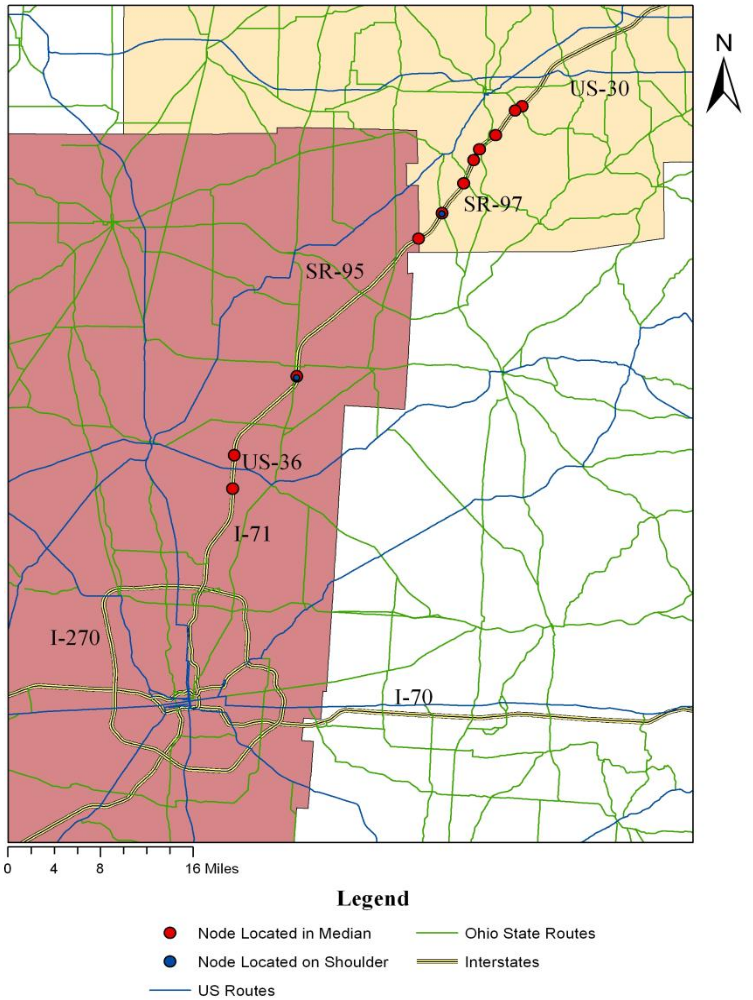
Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.

Figure 3.16: March 29, 2012, Bluetooth Node Deployment.

In the second phase of Deployment 7, six of the nodes are located on the right shoulder while the remaining eight are placed in the median. The nodes in the median are all located near a bridge or an overpass. The first node is located at mile marker 179, and the final node is located at mile marker 122.

<u>Deployment 8</u>

Deployment 8 also occurred in two phases. The first phase, as shown in Figure 3.17, consists of 14 nodes and is utilized from April 13, 2012, until April 19, 2012. The second phase of this node deployment, as shown in Figure 3.20 on page 41, consists of 14 nodes and is utilized from April 19, 2012, until April 27, 2012.



Node ID	Mile Marker	Node Location
1	174	Median
2	173	Median
3	170	Median
4	168	Median
5	166	Median
6	165	Median
7	162	Shoulder
8	162	Median
9	162	Shoulder
10	158	Median
11	142	Median
12	141	Shoulder
13	132	Median
14	129	Median

Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.

Figure 3.17: April 13, 2012, Bluetooth Node Deployment.

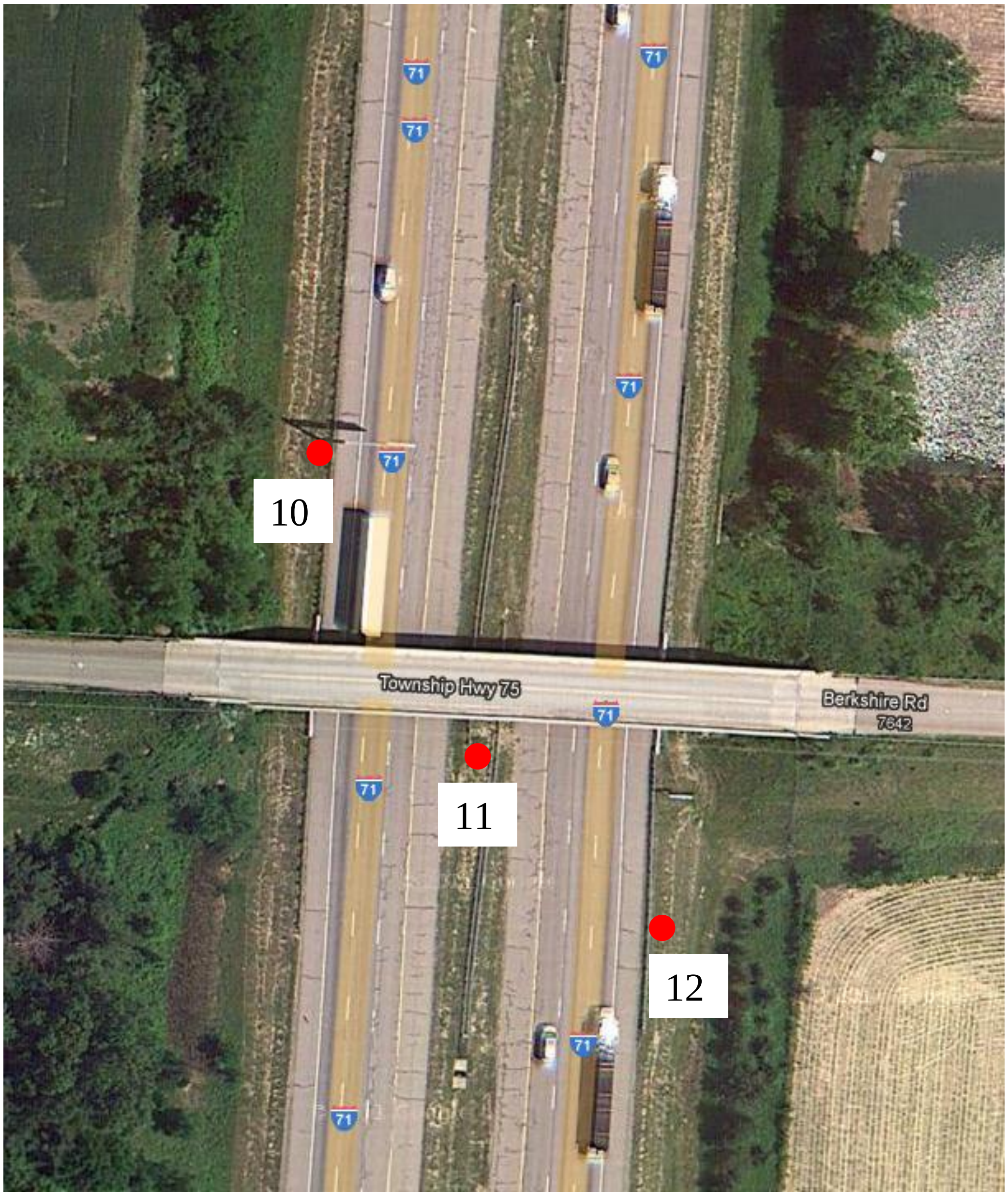
In the first phase of this deployment, three of the nodes are located on the shoulder while the remaining eleven are located in the median. The nodes that are located in the median are all placed near a bridge or an overpass. The first node is located at mile marker 174, and the final node is located at mile marker 129.

The nodes are placed at locations north and south of several interchanges on Interstate 71. This placement strategy enables the researchers to evaluate the number of Bluetooth hits lost when vehicles exit at the interchanges. Bluetooth hits are lost when a vehicle containing a device is recorded on one node then exits the highway or enters the highway and is only recorded by one node; in this case, the hit will appear only on one node and no travel speed may be calculated from the Bluetooth device. When a device is only recorded on one node, its corresponding Bluetooth hit must be removed from the dataset.

As part of this deployment, one location, at mile marker 162, in a rural area has a node placed on the northbound right shoulder, another on the southbound right shoulder, and a third node placed in the median, Figure 3.18 shows the area where the nodes are placed. This node configuration allows the research team to determine the difference in the number of hits received by nodes located on the shoulders compared to the number recorded by the node in the median. This information will aid in developing the optimal deployment strategy for the Bluetooth nodes.

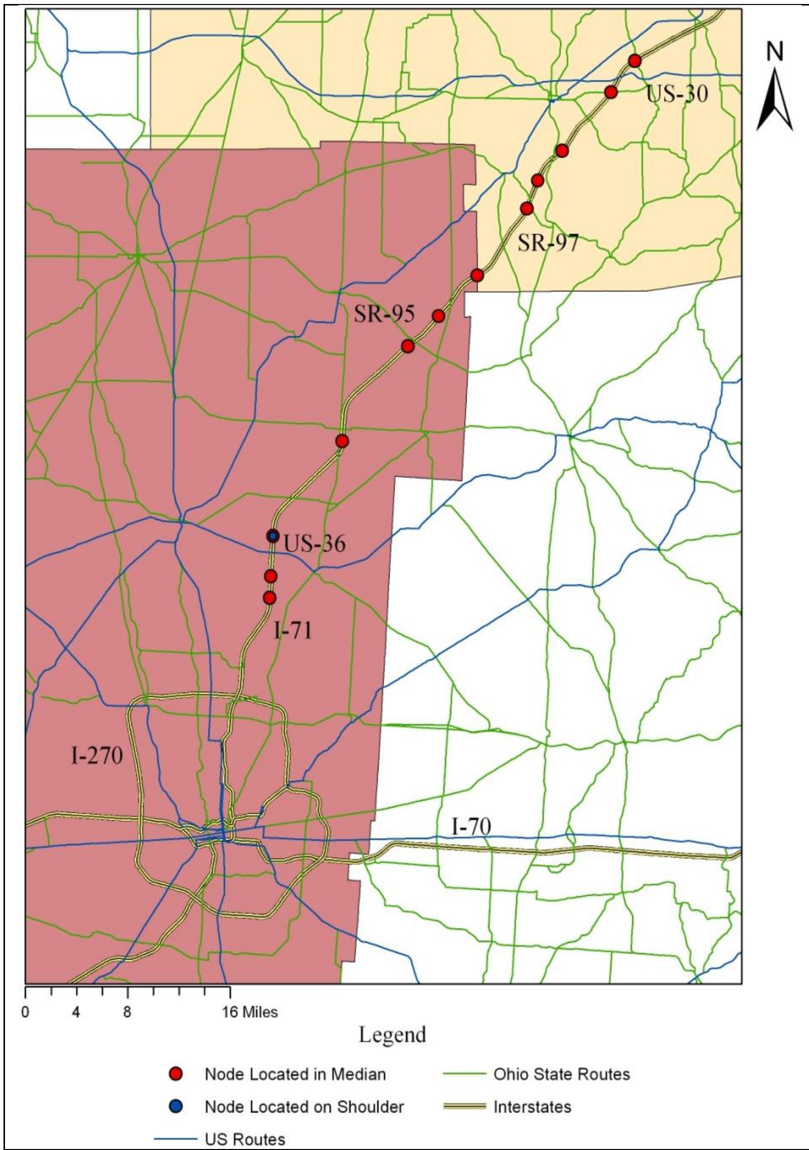
Note: This image was retrieved from Google Maps on 5/23/2012 and was edited to show the node locations, the numbers depict the node number.
Figure 3.18: Node Setup at Mile Marker 162 with Node in Median and Node on Each Shoulder.

In the second phase of this deployment, one node is placed in the median while two other nodes are placed on the shoulders, one on the southbound shoulder and another on the northbound shoulder, at mile marker 132 as shown in Figure 3.19.



Note: This image was retrieved from Google Maps on 5/23/2012 and edited to show the node locations, the numbers represent the node numbers.
Figure 3.19: Node Setup at Mile Marker 132 with Node in Median and Node on Each Shoulder.

The setup in the second phase is similar to that used in the first phase; however, the three nodes are placed in a more urban area that is closer to Columbus. The research team selected this deployment configuration to increase the number of Bluetooth device hits recorded by the nodes. The research team is able to compare the quantity of hits from the nodes on the shoulder to the node in the median as with the previous setup. The research team expects that a larger number of data points may be gathered in this more urban environment and a more accurate comparison may be produced.



Node ID	Mile Marker	Node Location
1	179	Median
2	176	Median
3	170	Median
4	167	Median
5	165	Median
6	158	Median
7	154	Median
8	151	Median
9	142	Median
10	132	Shoulder
11	132	Median
12	132	Shoulder
13	129	Median
14	128	Median

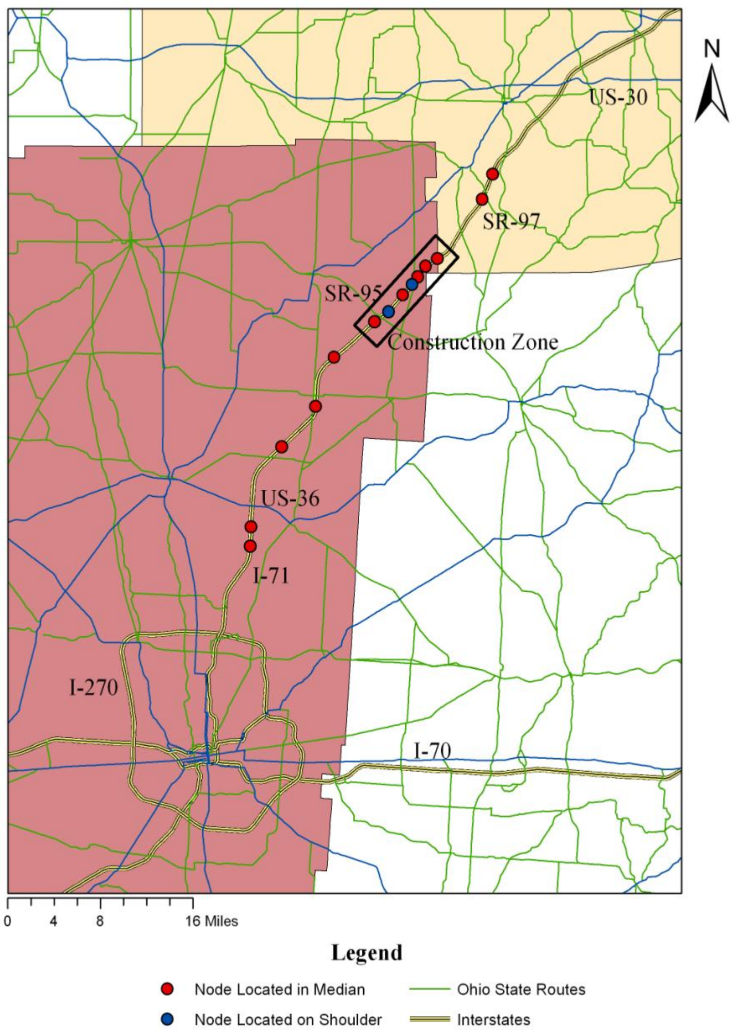
Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.

Figure 3.20: April 19, 2012, Bluetooth Node Deployment.

In this deployment configuration, two nodes are located on the shoulders while the remaining nodes are located in the median. The first node is located at mile marker 179 and the final node is located at mile marker 128.

Deployment 9

Deployment 9, as shown in Figure 3.21, consists of 14 nodes and is utilized from April 27, 2012, until May 8, 2012. The second phase of this node deployment, as shown in Figure 3.23 on page 44, consists of 14 nodes and is utilized from May 24, 2012, until the nodes are removed from the field in mid-July.



Node ID	Mile Marker	Node Location
1	167	Median
2	165	Median
3	158	Median
4	157	Median
5	156	Median
6	155	Shoulder
7	154	Median
8	152	Shoulder
9	151	Median
10	146	Median
11	142	Median
12	132	Median
13	129	Median
14	128	Median

Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.

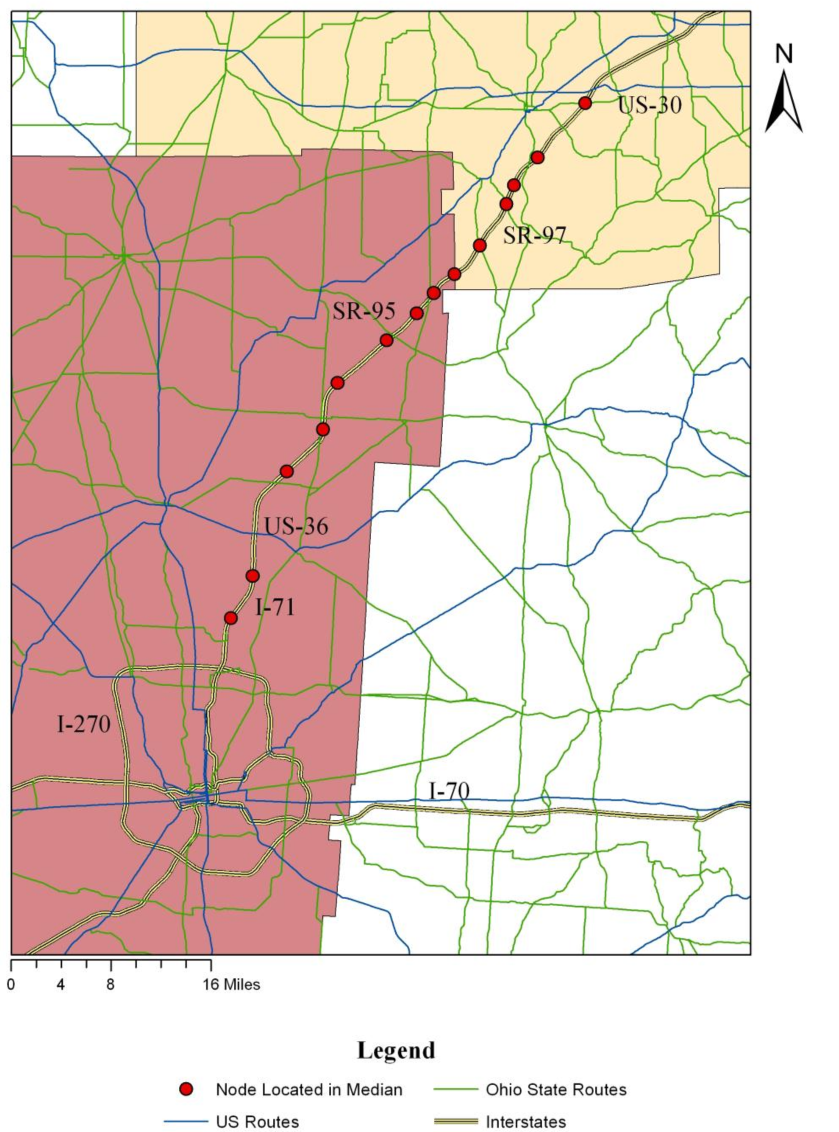
Figure 3.21: April 27, 2012, Bluetooth Node Deployment.

At the time of deployment, a construction project has been established on Interstate 71 from mile marker 159 to mile marker 150; seven nodes are placed in this zone. The remaining nodes are placed to the north and south of the construction zone. The team will evaluate speeds of vehicles in the approach area, in the construction zone, and in the area after the construction zone. A photograph taken at the beginning of the construction zone is shown in Figure 3.22.

Figure 3.22: Beginning of Construction Zone on Interstate 71 at Mile Markers 159 to 150.

The construction zone is located in the two-lane area of Interstate 71. Although two driving lanes are maintained through the construction zone, the shoulder width is decreased. The nodes are placed in close proximity to one another in the construction zone in order to provide a higher resolution of the vehicle activity along this stretch of Interstate 71. A small traffic backup is more likely to show up in the data if more nodes are located in this area. Capacity and travel times in work zones are explored at in depth by Wasson et al. 2010.

In the second phase of Deployment 9, the researchers place nodes in the same locations as the nodes in the first phase of Deployment 6. This placement helps the research team to compare speeds in the construction zone to speeds over the same segment of roadway prior to the creation of the construction zone. In addition, by keeping nodes in the construction zone in place for the duration of the construction project, the research team will find if speeds increase with the amount of time the construction zone is in place. The concept of using Bluetooth nodes to measure compliance with work zone speed limits is evaluated by Wasson et al. 2011.



Node ID	Mile Marker
1	176
2	170
3	167
4	165
5	162
6	158
7	156
8	154
9	151
10	146
11	142
12	132
13	128
14	124

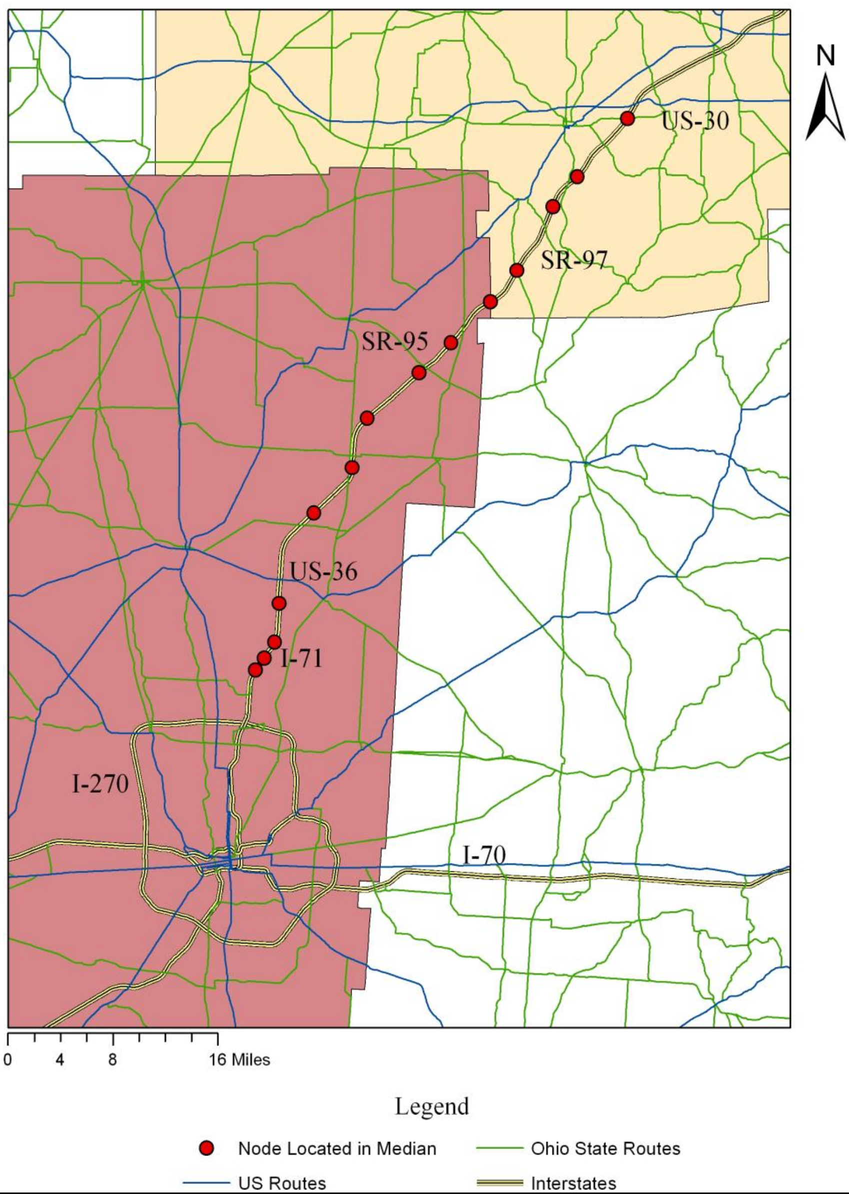
Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.23: May 24, 2012, Bluetooth Node Deployment.

In this deployment, 14 nodes are placed in the median of the highway. The first node is located at mile marker 176 and the final node is located at mile marker 124. The nodes are placed in the same locations as phase one of Deployment 6; however, one additional node is placed at mile marker 124 in order to gather speeds in the southern end of the area and the node at mile marker 145 is moved to mile marker 146 due to limited sightlines for merging onto the highway.

Deployment 10

Deployment 10 occurs in two phases. The first phase, as shown in Figure 3.24, consists of 14 nodes and is utilized from May 8, 2012, until May 16, 2012. The second phase of this node deployment, as shown in Figure 3.25, consists of 14 nodes and is utilized from May 16, 2012, until May 24, 2012.



Node ID	Mile Marker
1	176
2	170
3	167
4	162
5	158
6	154
7	151
8	146
9	142
10	132
11	129
12	126
13	125
14	124

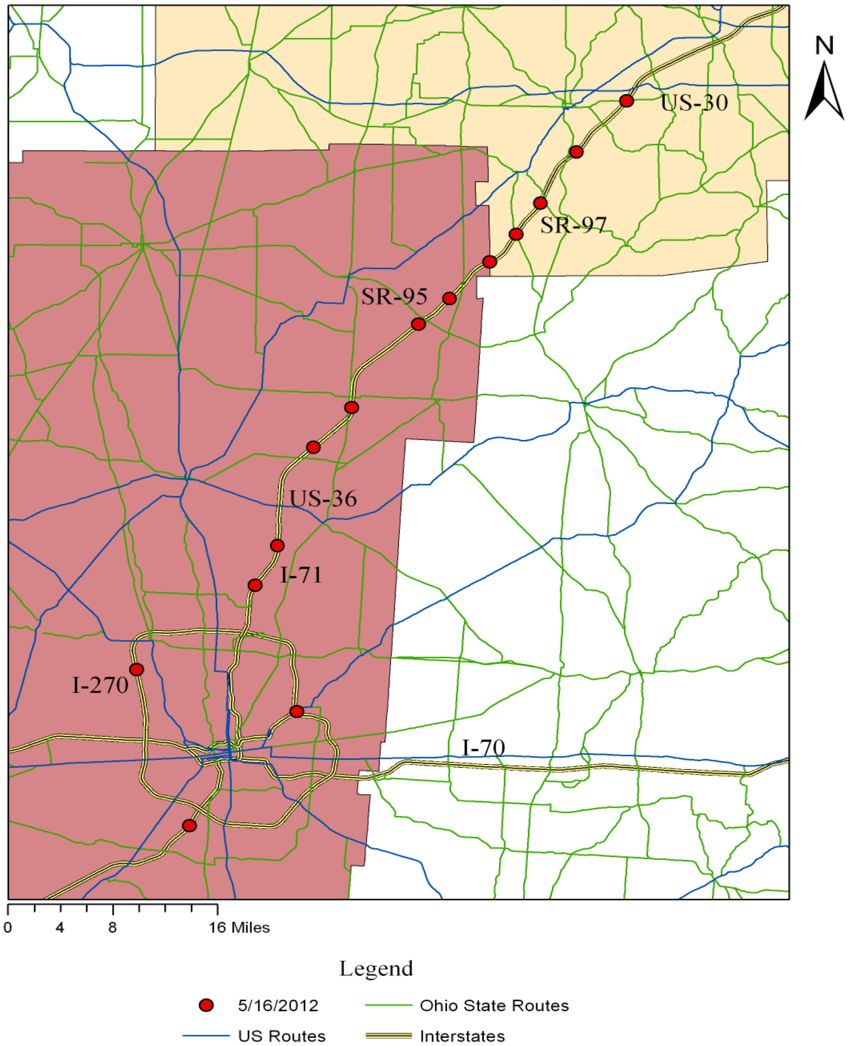
Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.24: May 8, 2012, Bluetooth Node Deployment.

In this deployment, 14 nodes are located in the median of the highway. The first node is located at mile marker 176, while the final node is located at mile marker 124. In this setup, the research team placed a larger number of nodes in the southern end of the deployment area

The research team placed several nodes at the southern end of the deployment area in order to obtain a better resolution for activities occurring there. This southern end is closer to Columbus and is a more urban area, and collecting data in this area will enable the research team to evaluate differences in speeds in urban and rural areas. By placing several nodes in the southern end, the research team is able to identify small areas of congestion that may occur during peak volume hours.

In the second phase of this deployment, nodes are placed on Interstate 270 east and west of Columbus, and nodes are placed on Interstate 71 north and south of the outer Interstate 270 loop. The research team placed the nodes to aid in quantifying the amount of matching Bluetooth hits gathered from vehicles traveling around Columbus on Interstate 270 and through Columbus on Interstate 71. With the large amount of space between the nodes placed around Columbus, the research team is evaluating the feasibility of using a low number of nodes for coverage in an urban area.



Node ID	Mile Marker
1	176
2	170
3	165
4	162
5	158
6	154
7	151
8	142
9	132
10	127
11	124
12	15 on I-270
13	100 on I-71
14	35 on I-270

Note: Mile markers decrease from North to South and all nodes are located in the median. All GIS maps are developed by the research team.

Figure 3.25: May 16, 2012, Bluetooth Node Deployment.

3.4.3 Summary of Bluetooth Deployments

Corresponding to the deployments in this chapter, Table 3.2 depicts the dates when a deployment is in use, number of nodes deployed, minimum spacing, maximum spacing, average spacing, minimum mile marker, and maximum mile marker for the nodes deployed.

Table 3.2: Summary of Bluetooth Node Deployments

Deployment	1	2	3	4	5	6		7		8		9		10	
Date	8/19/11 - 9/16/11	9/16/11 - 11/11/11	11/11/11 - 11/22/11	11/22/11 - 12/22/11	12/22/11 - 3/9/11	3/9/12 - 3/16/12	3/16/12 - 3/23/12	3/23/12 - 3/30/12	3/30/12 - 4/13/12	4/13/12 - 4/19/12	4/19/12 - 4/27/12	4/27/12 - 5/8/12	5/24/12 - 7/20/12	5/8/12 - 5/16/12	5/16/12 - 5/24/12
No. of Nodes	4	4	10	11	12	13	14	14	14	14	14	14	14	14	14
Min. Spacing (miles)	4.5	4.5	2.3	2.3	2.1	1.6	0.5	2.0	1.9	0.7	1.6	0.8	1.6	1.1	3.2
Max. Spacing (miles)	12.4	26.2	9.3	9.3	9.3	9.3	9.3	11.1	9.1	16.9	9.3	7.7	9.3	7.7	21.2
Avg. Spacing (miles)	8.0	12.6	4.9	4.8	4.4	4.0	2.4	6.4	4.3	4.4	5.4	3.0	4.0	4.0	8.0
Min. Mile Marker	146	132	132	128	128	128	132	126	122	129	128	128	124	124	100
Max. Mile Marker	170	170	176	176	176	176	163	165	179	174	179	167	176	176	176

As the project progressed, the number of nodes in the field is increased, so as to provide better resolution of the speed data from Interstate 71. From the deployments utilized in this project, the research team will be able to compare speeds from the two-lane sections to the three-lane sections of Interstate 71. Nodes are concentrated in the rural northern end of the project area as well as the urban southern end, and speed comparisons will be made between these two areas.

It should be noted that in the three deployments with the lowest number of nodes, Deployments 1 and 2, the average spacing between the nodes is the greatest. Also having one of the highest average spacing between nodes is the first phase of Deployment 7, which originally has 14 nodes but only seven are able to upload data. In the second phase of Deployment 10, nodes are placed on or near the Interstate 270 loop, causing the average spacing to be greater. These four deployments have the four greatest maximum spacing distances, and the resolution of the data will be less than for the deployments with more closely spaced nodes. When nodes are spaced farther apart, speed differences and small areas of congestion are less apparent in the data.

Phases one and two of Deployment 6 have two of the three smallest average distances between nodes. In both of these deployments, the research team is evaluating the effects of having nodes spaced closely together. The team is looking to see if any coverage areas of the nodes overlap. If any issues arise, it is expected to come from phase two of Deployment 6, where the minimum spacing between two nodes is 0.5 miles and the average spacing is the lowest.

Deployment 9 has the second smallest average spacing. In this deployment, the research team is analyzing travel speeds in a construction zone. The nodes are placed in close proximity for higher resolution of any activities that may occur in the construction zone. Also, it should be noted that as the project has progressed, the minimum mile marker generally is lower, meaning the research team has moved nodes closer to the more urban areas near Columbus to evaluate the difference in the quantity of hits from urban and rural areas and to determine if increased traffic volumes result in decreased speeds.

CHAPTER IV
RESULTS

This chapter contains the results from the ten deployments described previously in the methodology section and is divided into eight sections:

- Section One – General Findings,
- Section Two – Hit Counts of Node Placed in Median Compared to Shoulder,
- Section Three – Hit Counts at Night Compared to Hit Counts During the Day,
- Section Four – Impact of Interchanges,
- Section Five – Urban Deployment,
- Section Six – Incident Detection,
- Section Seven – Evaluation of Speeds in the Construction Zone, and
- Section Eight – Summary of Findings.

4.1 General Findings

The first section describes the overall data collected during the project including matching Bluetooth hits, general speed profiles, and data from the winter hardening and technology development deployments described in the methodology section. Bluetooth hits are the total number of devices recorded by a node, including a device recorded multiple times by the same node in close succession. Unique Bluetooth hits are the number of devices recorded by a node with the duplicate hits removed. Matching Bluetooth hits, or matches, represent the number of devices that are recorded by the two nodes in question.

Table 4.1 is a breakdown of the number of matching Bluetooth devices per node, which are initially placed in the field in August of 2011 and remain in until the end of the project.

Table 4.1: Number of Matches per Node for Each Month of Project.

Month	Number of Nodes	Average Number of Matches per Node
August	4	7104
September	4	5428
October	4	15146
November	11	15072
December	12	9414
January	12	1179
February	12	23979
March	14	23389
April	14	30367
May	14	22860
June	14	38954

Note: Nodes are added to the field in September, November, December, and March. The node for these months is the number of nodes at the end of the month. July is excluded from this table because nodes are only in the field for the beginning of the month. A fifteenth node, which is solar powered, is developed and placed in the field in another area.

As the project progresses, the number of nodes collecting data and the number of matching Bluetooth devices generally increases, which is due in part to the field hardening of the system.

At the beginning of the project, the focus of the research team is to develop the Bluetooth technology. Figure 4.1 shows the speeds on August 20, 2011, between mile markers 170 and 165.

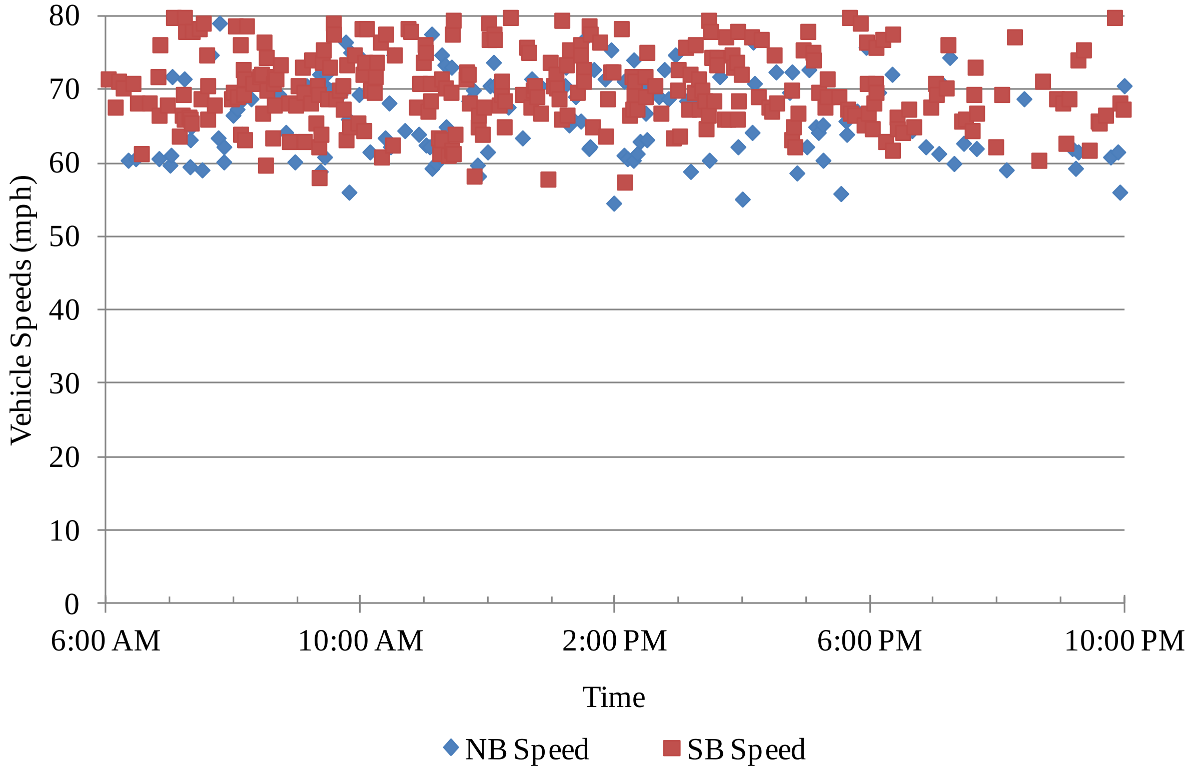


Figure 4.1: Travel Speeds on August 20, 2011, Corresponding to Deployment 1.

Traffic on this day is operating under normal conditions, which is shown by the scattering of speeds, with the majority between 65 and 75 mph.

Figure 4.2 depicts the travel speed on September 25, 2011 between mile markers 165 and 185.

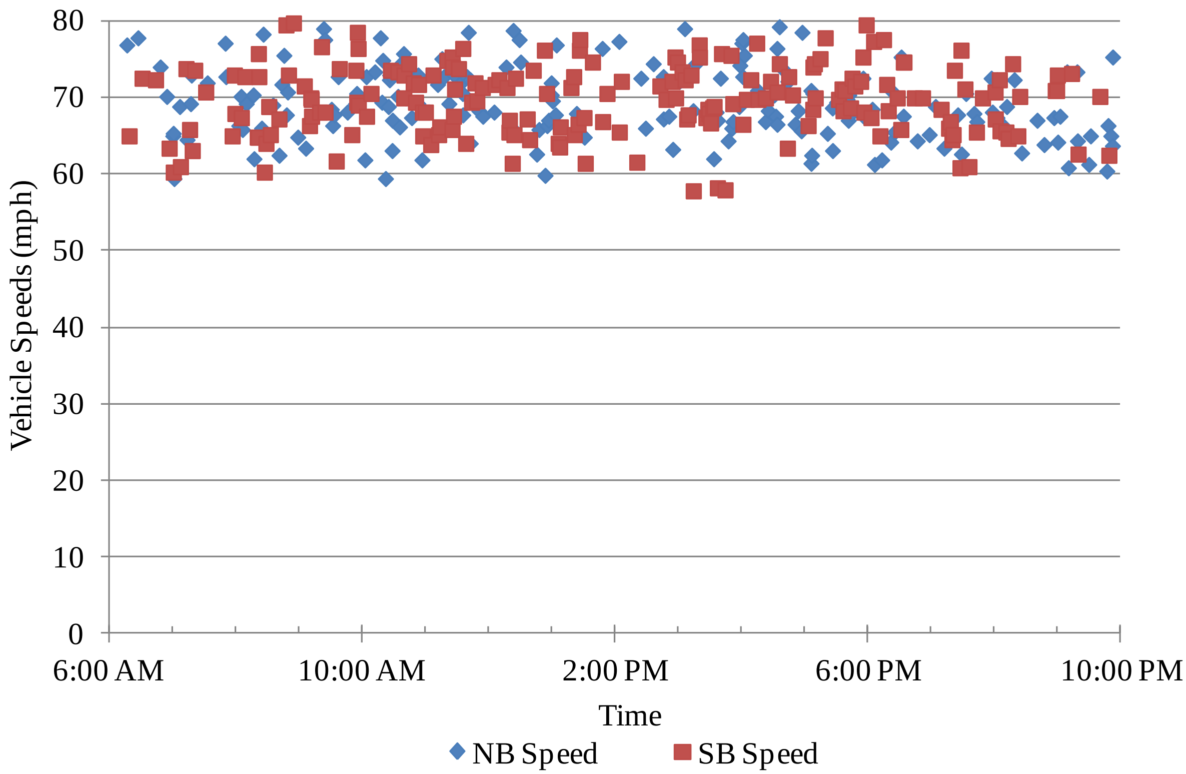


Figure 4.2: Travel Speeds on September 25, 2011, Corresponding to Deployment 2.

This figure illustrates that on this day, traffic is operating under normal conditions. This is shown by the varying speeds that vehicles are traveling.

Figure 4.3 illustrates the travel speeds on November 12, 2011, between mile markers 176 and 170.

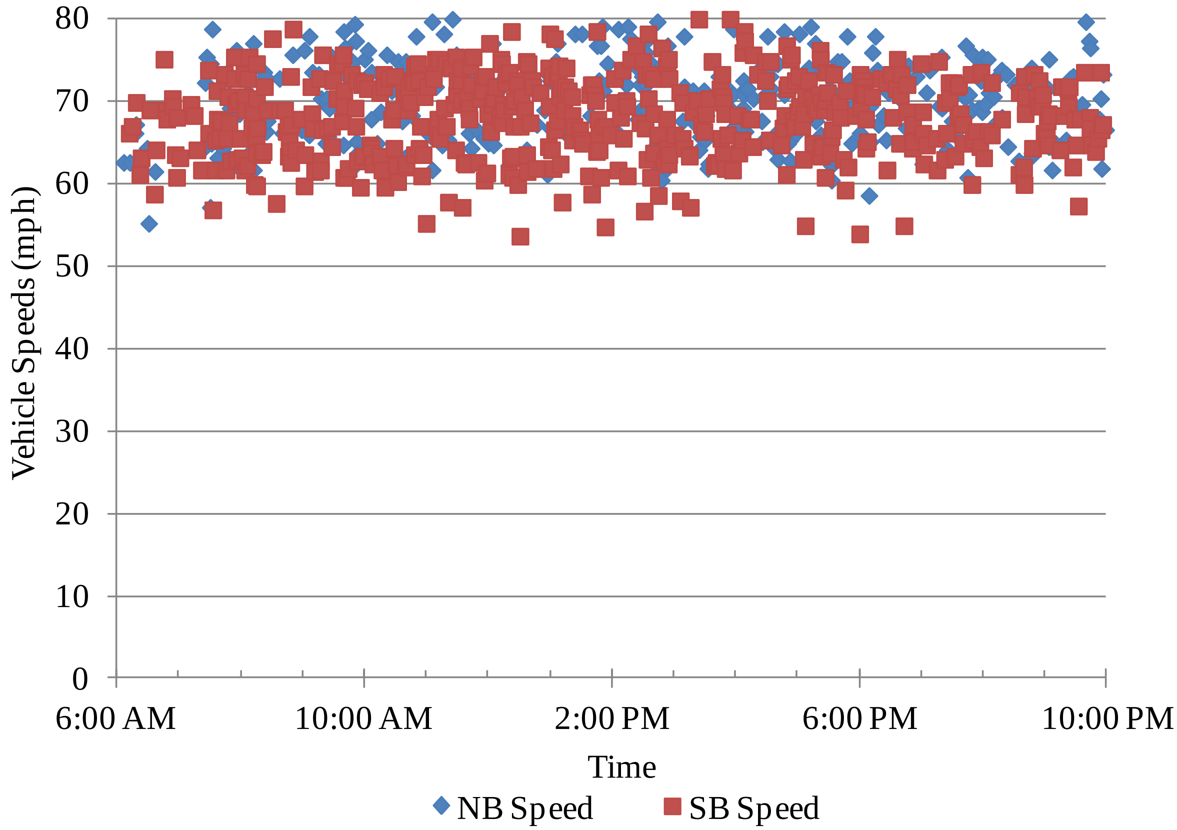


Figure 4.3: Travel Speeds on November 12, 2011, Corresponding to Deployment 3.

Traffic on this day is also operating under normal conditions. Traffic speeds vary, since there is no congestion forcing vehicles to travel at lower speeds.

Figure 4.4 illustrates the travel speeds on December 1, 2011, between mile markers 132 and 128.

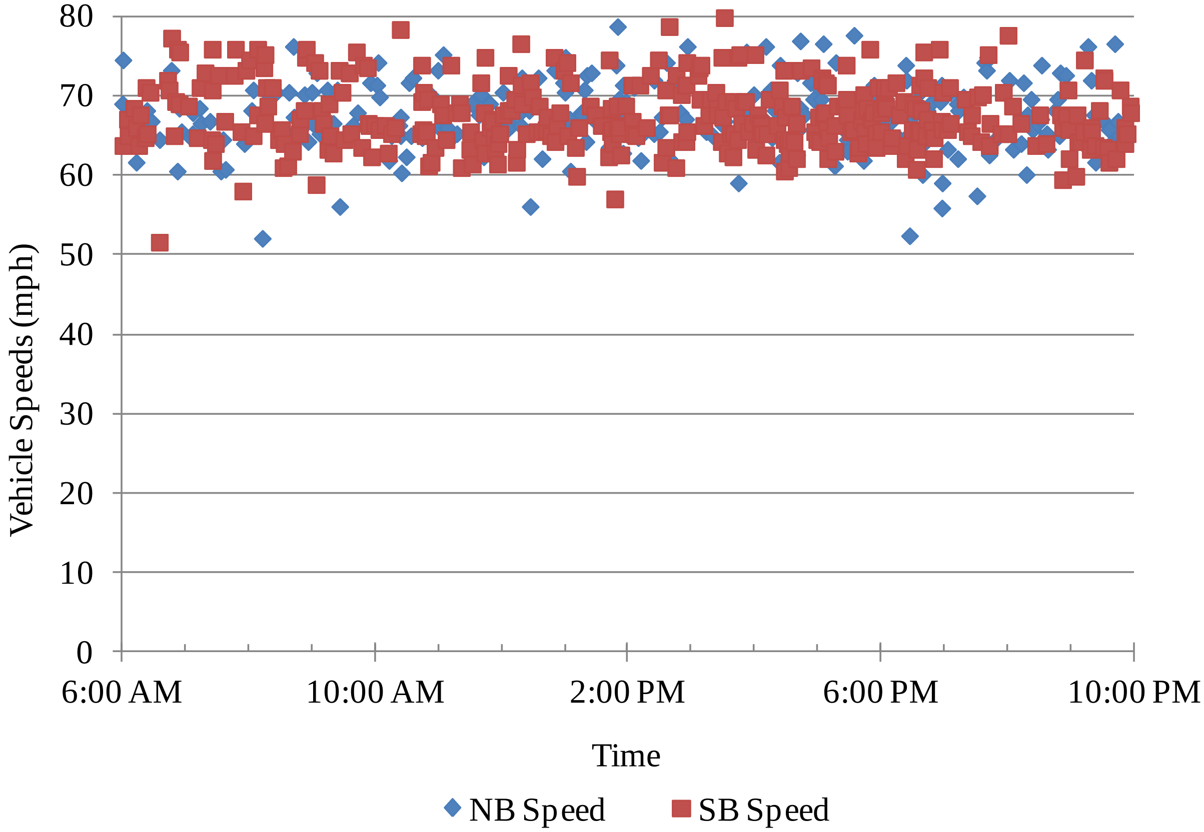


Figure 4.4: Travel Speeds on December 1, 2011, Corresponding to Deployment 4.

On this day, traffic is also operating under normal conditions and vehicles are able to travel at the speeds they desire.

Figure 4.5 illustrates the travel speeds on January 12, 2012, between mile markers 132 and 128.

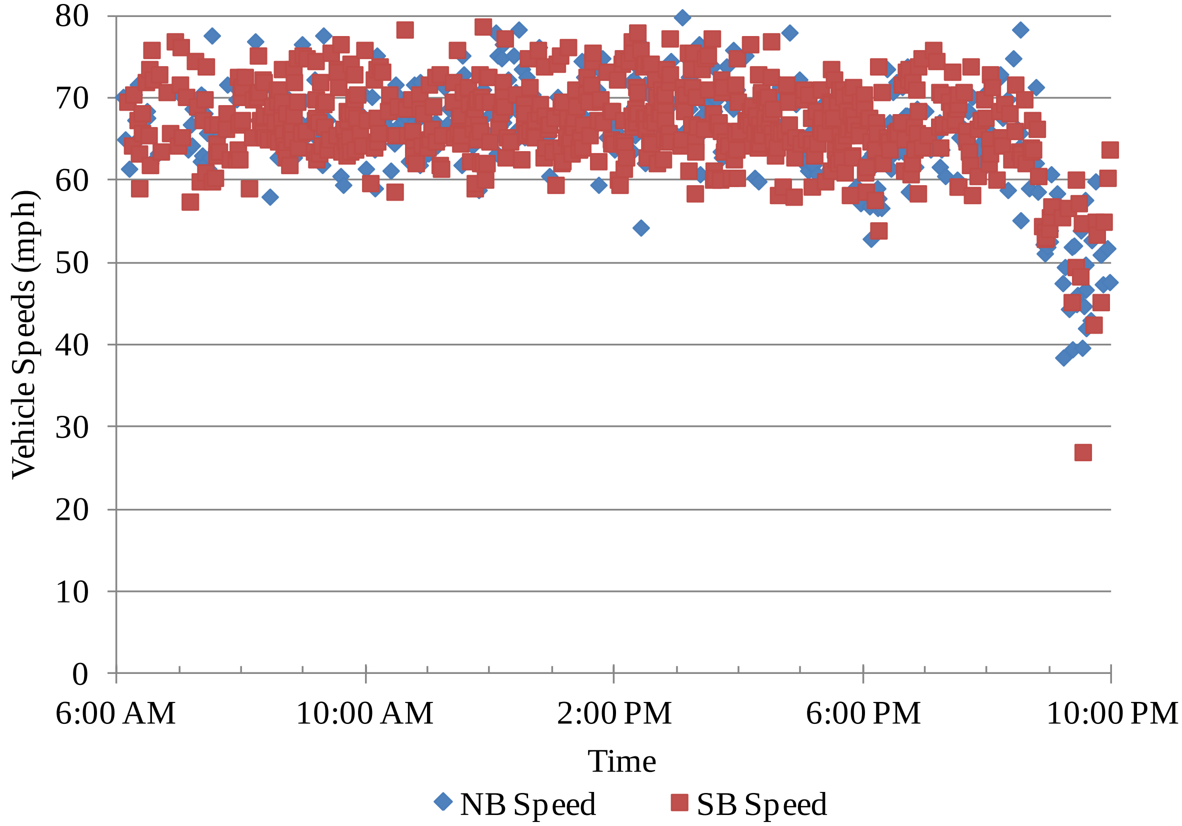


Figure 4.5: Travel Speeds on January 12, 2012, Corresponding to Deployment 5.

On this day, vehicles are operating under normal conditions until an incident occurs at 9:00 PM. The incident affects the travel speeds of both the northbound and southbound lanes, causing a decrease in travel speeds. Since both lanes are affected, the incident may have occurred on one side and drivers of vehicles traveling in the opposite direction slowed down to look i.e. rubbernecking, or it could have been the result of severe weather.

4.2 Hit Counts of Nodes Placed in the Median Compared to the Shoulder

Since it may not always be possible for a node to be deployed in the median due to attachment issues or obstructions, it is important to understand the outcomes of the data if other locations are utilized. This section discusses outcomes for other locations and is divided into three subsections:

- Section One – Comparison of Hit Counts from Node in the Median to Shoulder,
- Section Two – Matching Hits Across all Nodes, and

- Section Three – Quantity of Matches to Nodes North and South of Location.

4.2.1 Comparison of Hit Counts from Node in the Median to the Shoulder

The first location where a node on the shoulder is compared to a node in the median is located at mile marker 162, which is in the more rural northern end of Interstate 71 and is utilized from April 13, 2012, until April 19, 2012. Figure 4.6 is an image showing the node locations. The quantity of hits from these two locations is shown below in Table 4.2.

Note: This image was retrieved from Google Maps on 5/23/12 and edited to show the node locations.
Figure 4.6: Node Setup at Mile Marker 162 with Node in Median and Node on Each Shoulder.

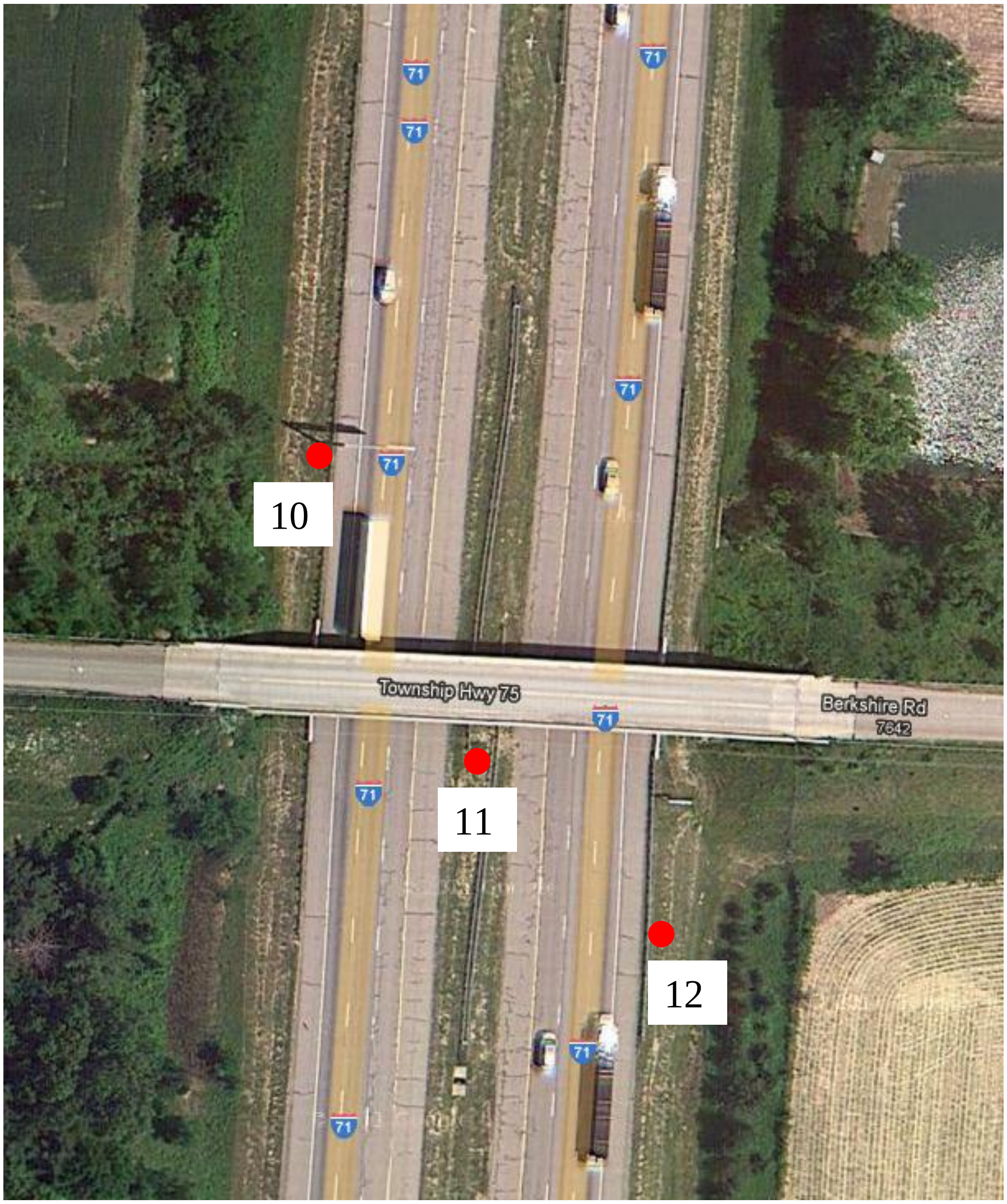
Table 4.2: Quantity of Bluetooth Hits on Nodes at Mile Marker 162.

Count	Node ID	Location
12809	8	Median
9331	9	NB Right Shoulder

Note: Count refers to the count of unique MAC addresses by each node. Node ID 8 refers to node 1303 and Node ID 9 refers to node 1F23, which is also true for Figure 4.6.

Node 8, which is located in the median, records the most Bluetooth devices, while Node 9, located on the northbound right shoulder, records 27% less data than the node in the median. This decrease in quantity of data is a result of the node location. The node in the median is able to record Bluetooth devices from vehicles in both the northbound and southbound directions of travel. The node on the northbound shoulder is able to easily record the northbound traffic but with a larger distance to the southbound lanes and the guardrail blocking some of the signal strength, less data is recorded.

The second location compares nodes on the shoulder to a node in the median and is located at mile marker 132, which is in the more urban southern end of the deployment area, and is utilized from April 19, 2012 until April 27, 2012. The node placement at this location is shown in Figure 4.7. Additionally, the quantity of hits from these the three nodes at this location are presented in Table 4.3.



Note: This image was retrieved from Google Maps on 5/23/12 and edited to show the node locations.
Figure 4.7: Node Setup at Mile Marker 132 with Node in Median and Node on Each Shoulder.

Table 4.3: Quantity of Bluetooth Hits on Nodes at Mile Marker 132.

Count	Node ID	Location
14593	10	SB Right Shoulder
12953	11	Median
5480	12	NB Right Shoulder

Note: Count refers to the count of unique MAC addresses by each node. Node ID 10 refers to node 12E3, Node ID 11 refers to node 122E, and Node ID 12 refers to node 01D3, which is also true for Figure 4.7.

Node 10, located on the southbound right shoulder, collects the highest number of Bluetooth hits, while Node 11, located in the median, records 11% less data. Node 12, located on the northbound right shoulder, records 58% less data than the node in the median and 62% less data than the node on the southbound shoulder.

When comparing the two node placements, there are 3,443 hits per day at mile marker 132 and 3,690 hits per day at mile marker 162. These hit counts are within 7% of each other, indicating that similar hit counts are found in the urban and rural areas. The slight decrease in hit counts at the node at mile marker 132 may be a result of higher traffic volumes limiting the number of devices the node is able to record: if several vehicles with active Bluetooth devices pass the node near one another, the node may only record one of the devices. In contrast, at mile marker 162 in the more rural area, the probability of having several vehicles with active devices passing at the same time is lower and the time between vehicles in increased, allowing the node to record the devices in more vehicles.

4.2.2 Matching Hits Across all Nodes

An additional aspect the research team evaluates with this node setup is the number of Bluetooth devices recorded from the node on the shoulder that are also recorded by the node in the median. Table 4.4 shows the number of Bluetooth hits received in the median and on the shoulder, as well as the number of matching hits between them.

Table 4.4: Quantity of Devices Recorded by Nodes on Shoulders and Median.

Date	Hits from Median	Hits from Shoulder	Hits Recorded on Shoulder and Median
4/13 - 4/19	8385	6389	3971
4/19 - 4/27	11446	11923	4288

Note: This table shows the amount of Bluetooth hits on the nodes on the shoulder and the nodes in the median for Deployment 8 and the amount of Bluetooth devices recorded on both the node on the shoulder and the node in the median.

This table compares the number of Bluetooth devices that are recorded on both the shoulders and the median. From the rural setup utilized from April 13, 2012, until April 19, 2012, a total of 47% of the Bluetooth hits recorded from the median matched the hits on the northbound shoulder. From the urban setup utilized from April 19, 2012, until April 27, 2012, a total of 37% of the hits from the median matched the hits on both shoulders.

4.2.3 Quantity of Matches to Nodes North and South of Location

The final aspect of this deployment the research team analyzes is the number of hits from a node on the shoulder that match with vehicles in the opposite direction of travel - i.e. how many matching devices the node on the southbound shoulder has with the node north of it and vice versa. Table 4.5 presents the breakdown of matches for the nodes located at mile marker 162, and Table 4.6 presents the breakdown of matches for the nodes located at mile marker 132.

Table 4.5: Matches North and South of Nodes at Mile Marker 162.

Node (Location)	Matches SB	Matches NB
8 (Median)	3597	3535
9 (NB Shoulder)	1052	4278

Note: This table compares the number of matching Bluetooth hits from the nodes on the shoulder and the median to the nodes north and south of the location.

This table compares the matching Bluetooth hits of the node in the median and the shoulder with the nodes north and south of this location. The node in the median has a similar number of matches to the node north and south of it, while the node on the northbound shoulder has a higher number of matches with the node to the north than the south. Because of the greater distance from a node on one shoulder to the lane travelling in the opposite direction, it is harder for a node on one shoulder to record Bluetooth devices traveling the opposite direction.

Node 9, which is located on the northbound shoulder at mile marker 162, as shown in Figure 4.6, has 75% fewer matching hits to the south than the north. Since the node is located on the northbound shoulder, it is reasonable that there are more matches to the node to the north than the node to the south. Node 8, which is in the median, has nearly identical matching hits to the nodes to the north and south of it. Since this node is located in the median, it is expected to have similar matches of vehicles traveling both north and south.

Table 4.6: Matches North and South of Nodes at Mile Marker 132.

Node (Location)	Matches SB	Matches NB
10 (SB Shoulder)	1581	2956
11 (Median)	1850	1357
12 (NB Shoulder)	83	2417

Note: This table compares the number of matching Bluetooth hits from the nodes on the shoulder and the median to the nodes north and south of the location.

For Node 11, which is located in the median, the number of matches one node north and one node south are similar. This result is to be expected, since the node in the median is an equal distance from both the northbound and southbound lanes. Node 12, located off the northbound shoulder, records substantially more hits in the northbound direction than the southbound direction. With the node being positioned in close proximity to the northbound lane, it is reasonable for it to record more matching hits in that direction. Node 10, located off the southbound shoulder, records 47% fewer matches in the southbound direction than in the northbound direction, which is not an expected result.

4.3 Hit Counts at Night Compared to Hit Counts during the Day

This section compares the amount of Bluetooth hits at nighttime to the amount of Bluetooth hits during daytime. Unique Bluetooth hits and matching hits will be examined to quantify how many fewer hits occur at night. For this purpose, daytime is defined as 6 AM to 10 PM and nighttime is defined as 10 PM to 6 AM. Since the time periods are not of equal duration, the results will be evaluated on a per-hour basis. Table 4.7 shows the hits and matches per node per hour during the day and night for the duration of the project.

Table 4.7: Hit Counts per Node and Matches per Node During Day and Night.

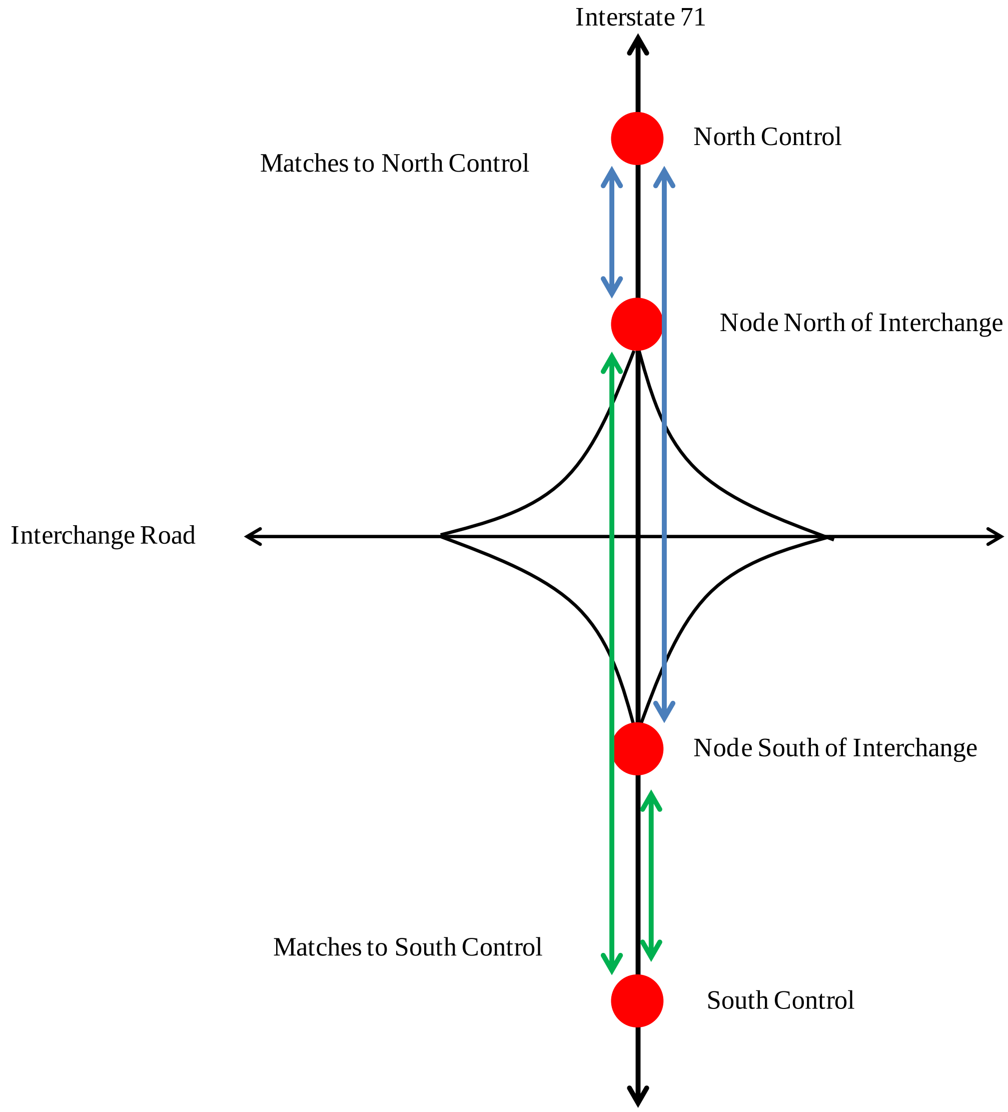
	Daytime		Nighttime			
Month	Hits per Node per Hour	Matches per Node per Hour	Hits per Node per Hour	Matches per Node per Hour	Percent Less Hits at Night	Percent Less Matches at Night
November	87	49	37	24	58%	50%
December	73	30	29	16	60%	46%
January	82	11	38	8	54%	26%
February	93	51	32	19	65%	62%
March	99	58	24	15	76%	74%
April	101	62	30	20	71%	68%
May	106	52	30	17	72%	68%
Totals	640	313	219	119	66%	62%

Note: “Hits” refers to the unique Bluetooth MAC addresses recorded on a node and “Matches” refers to the amount of unique hits that match with another node. Both are evaluated on a per node and per hour basis since the amount of nodes varies from month to month and the times considered for day and night are not equal. To get the total number of hits and matches, the values must be multiplied by the number of nodes and the length of times.

To compare all the months on the same basis, the number of hits and matches are compared on a per node basis and, since the length of daytime and nighttime are not the same, the amount of hits and matches are also compared on a per-hour basis. When comparing Bluetooth hits per node and matches per node during the daytime and the nighttime, it is apparent that a considerable number of hits and matches are lost at night. There are 66% fewer Bluetooth hits at night and 62% fewer Bluetooth matches at night. This shows that between 6:00 AM and 10:00 PM, there are substantially more hits per node per hour and matches per node per hour than between 10:00 PM and 6:00 AM As expected, lower traffic volumes result in fewer hits and matches. From an operational standpoint, this is an excellent time to conserve energy within the nodes.

4.4 Impacts of Interchanges

This section will discuss what impacts interchanges have on the data collection system. Nodes are placed on either side of the interchanges within the project area of Interstate 71 to determine the amount of matching Bluetooth hits. In addition, this node placement allows the amount of hits gained and lost at interchanges to be determined. Figure 4.8 shows the location of the nodes with respect to the interchanges and the control nodes used to compare the number of matching Bluetooth hits.



Note: This figure shows the location of the nodes with respect to the interchanges and control nodes used to determine the number of matches. The blue arrows represent the matches of Bluetooth devices to the north control and the green arrows represent the matches of Bluetooth devices to the south control.
Figure 4.8: Node Setup Used to Determine Number of Hits Lost at Interchanges.

The research team uses two node placements in this evaluation to collect data from interchanges within the project area. The first deployment is utilized from April 13, 2012, until April 27, 2012. Table 4.8 shows the breakdown of matches of nodes on each side of the interchanges with the control node north of the interchange. Table 4.9 presents the matching

Bluetooth hits of the nodes on each side of the interchanges with the control node south of the interchange.

Table 4.8: Matching Bluetooth Hits of Node on Each Side of Interchange with Control Node to the North.

Exit Number	Route	Matches of Node North of Interchange to North Control	Matches of Node South of Interchange to North Control	Hits Lost/Gained Traveling North	Percent Change
176	U.S. 30	-	-	-	-
173	S.R. 39	-	-	-	-
169	S.R. 13/S.R. 97	2432	2928	Lose 496	17%
165	S.R. 97	3311	3230	Gain 81	2%
151	S.R. 95	2786	3821	Lose 1035	27%
131	U.S. 36/S.R. 37	2956	2758	Gain 198	7%

Note: The matching Bluetooth hits north and south of the interchanges are compared to the control node to the north of the interchange to find the quantity of hits lost or gained traveling north. The nodes are placed on either side of the interchange ramps shown by the exit number and route. U.S. 30 and S.R. 39 do not have a node to the north to use as a control node.

Table 4.9: Matching Bluetooth Hits of Node on Each Side of Interchange with Control Node to the South.

Exit Number	Route	Matches of Node North of Interchange to South Control	Matches of Node South of Interchange to South Control	Hits Lost/Gained Traveling South	Percent Change
176	U.S. 30	2838	3853	Gain 1015	26%
173	S.R. 39	4512	3548	Lose 964	21%
169	S.R. 13/S.R. 97	4551	3311	Lose 1240	27%
165	S.R. 97	1885	1479	Lose 406	22%
151	S.R. 95	1660	1447	Lose 213	13%
131	U.S. 36/S.R. 37	1367	1011	Lose 356	26%

Note: The matching Bluetooth hits north and south of the interchanges are compared to the control node to the south of the interchange to find the quantity of hits lost or gained traveling south. The nodes are placed on either side of the interchange ramps shown by the exit number and route.

These tables show the amount of matching Bluetooth hits of nodes on each side of the interchanges with the control nodes north and south of the interchanges. By using only matching hits, the hits from vehicles on the minor roads are excluded. The matching Bluetooth hits fluctuate from a 2% to 27% change when traveling north and fluctuate from 13% to 27% when traveling south.

Table 4.10 shows the average daily traffic (ADT) of the roads evaluated in the previous two tables.

Table 4.10: ADT of Roads with Interchanges to Interstate 71.

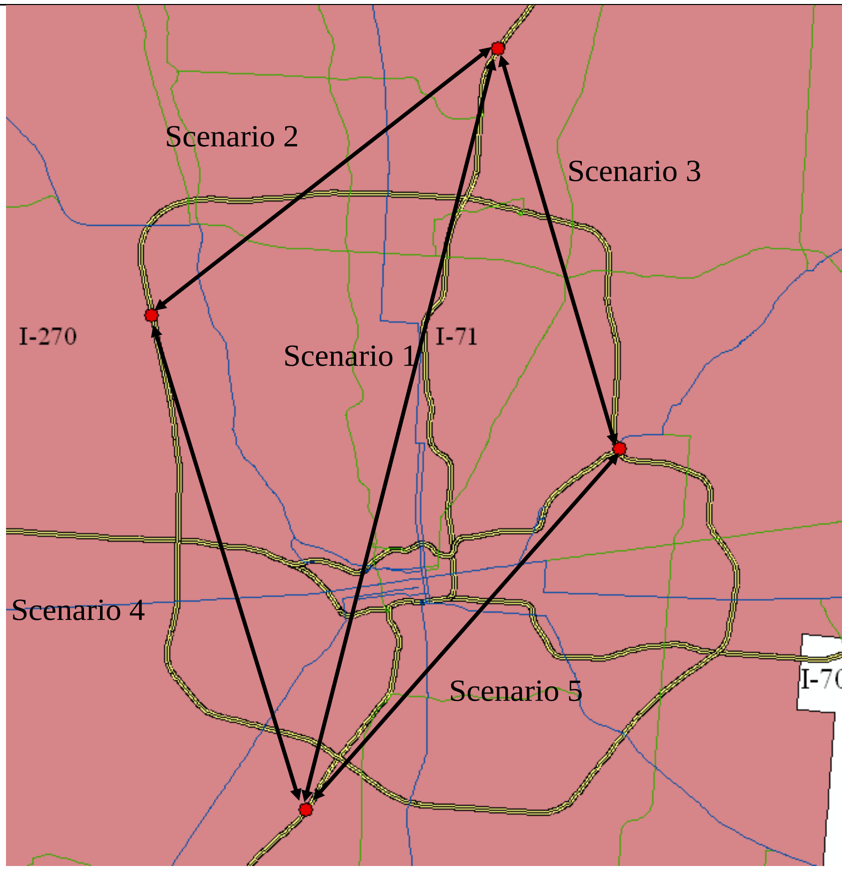
Exit Number	Route	ADT East of I-71	ADT West of I-71	Percent Change
176	U.S. 30	13796	20288	32%
173	S.R. 39	3848	6615	42%
169	S.R. 13/S.R. 97	7784	13277	41%
165	S.R. 97	10336	7822	24%
151	S.R. 95	6052	5222	14%
131	U.S. 36/S.R. 37	24740	19724	20%

Note: The ADT values in this table are from 2011 and are found in the Ohio Department of Transportation Short Term ADT Count Data.

The ADT east and west of the interchange with Interstate 71 is presented in the table above. When comparing the percent change in ADT from one side of the interchange to the other, the routes with the higher change correspond to the higher changes in matching Bluetooth hits from Tables 4.8 and 4.9. Also, the routes with the lowest changes in ADT have lower changes in matching Bluetooth hits from Tables 4.8 and 4.9. This is an expected result, since Interstate 71 is a major route and a majority of the vehicles causing the change in ADT are entering the highway. Consequently, the interchanges with the largest change in ADT have the most vehicles lost or gained at the interchange and vice versa.

4.5 Urban Deployment

This section looks at the feasibility of using large distances between the nodes in an urban center. Four nodes are placed on and just outside of the Interstate 270 loop around Columbus. These nodes are placed on the north, south, east, and west sides of Columbus. With having large spacing between the nodes, the amount of matching Bluetooth hits and the resulting travel times and speeds are analyzed. Figure 4.9 shows the location of the nodes around Columbus and presents five scenarios in which speeds are evaluated.



Scenario	Node Location
1	North and South
2	North and West
3	North and East
4	South and West
5	South and East

Note: All GIS maps are developed by the research team.
Figure 4.9: Node Locations and Speed Evaluation Scenarios around Columbus.

The nodes are placed in a manner that allows the research team to gather speeds on Interstate 71 traveling through Columbus and from Interstate 71 to Interstate 270 east and west of Columbus.

4.5.1 Scenario 1

Figure 4.10 shows the travel speeds of the northbound and southbound vehicles from mile marker 124 to mile marker 100 on Interstate 71.

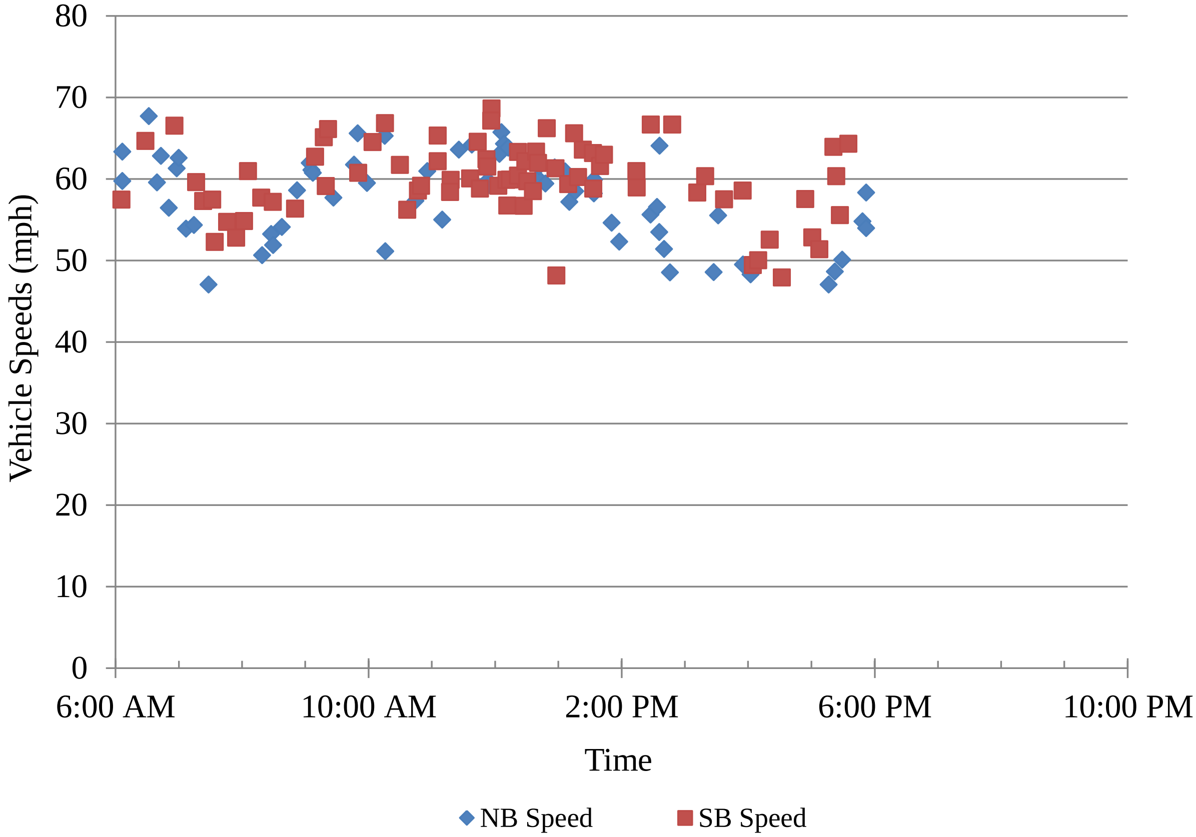


Figure 4.10: Vehicle Speeds on Interstate 71 Through Columbus on a Weekday.

With the larger distances between the nodes, fewer matching hits are found when compared with closer spaced nodes during the same time frame, due to the amount of interchanges between the nodes and the length of time that a Bluetooth device must remain active in order to be recorded on both nodes. However, the nodes are still able to record the decreased travel speeds during the morning and evening peak volume hours.

4.5.2 Scenario 2

Figure 4.11 illustrates the northbound and southbound travel speeds from the north side of Columbus on Interstate 71 to the node on Interstate 270 west of Columbus.

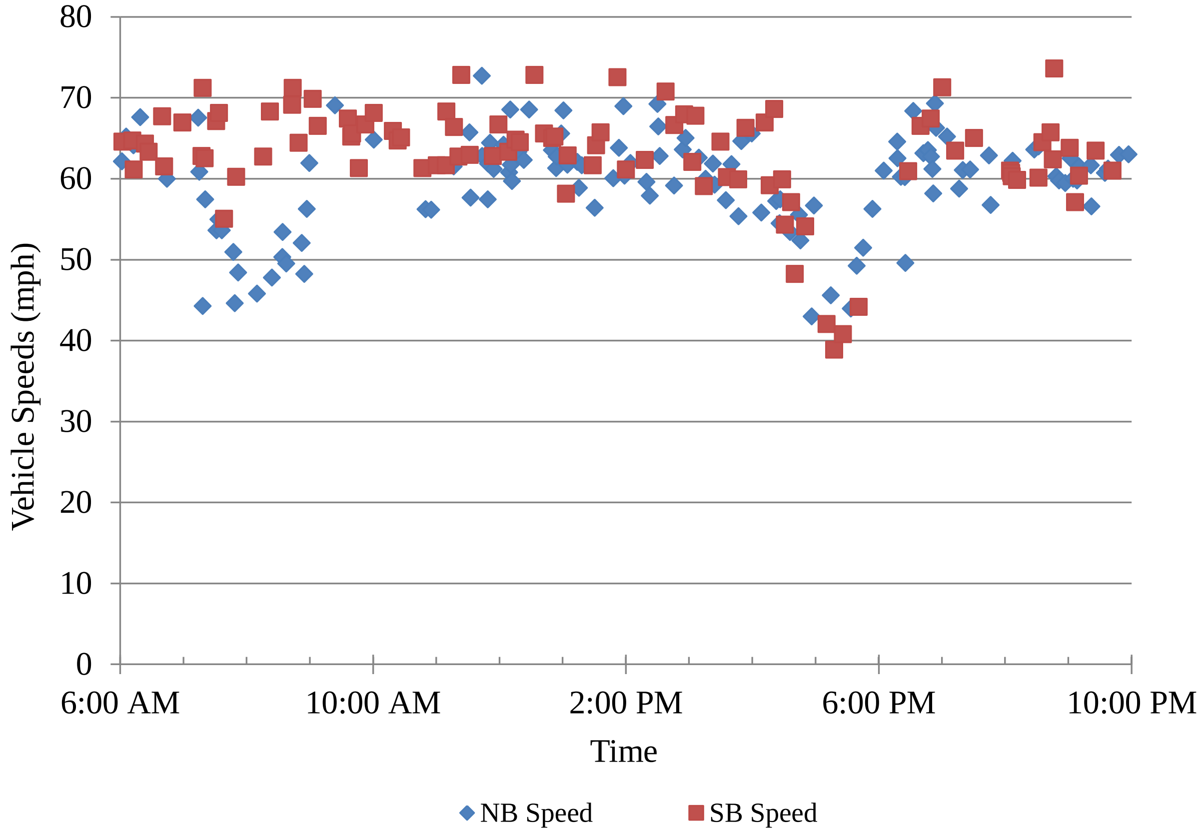


Figure 4.11: Vehicle Speeds On Northwest Side of Columbus.

Even with having fewer matching hits, which result from a large distance between nodes, congestion is still visible during the peak morning and evening hours. This finding suggests that the nodes are still effective at determining travel speeds at large distances.

4.5.3 Scenario 3

Figure 4.12 illustrates the northbound and southbound travel speeds from Interstate 71 north of Columbus to the node east of Columbus.

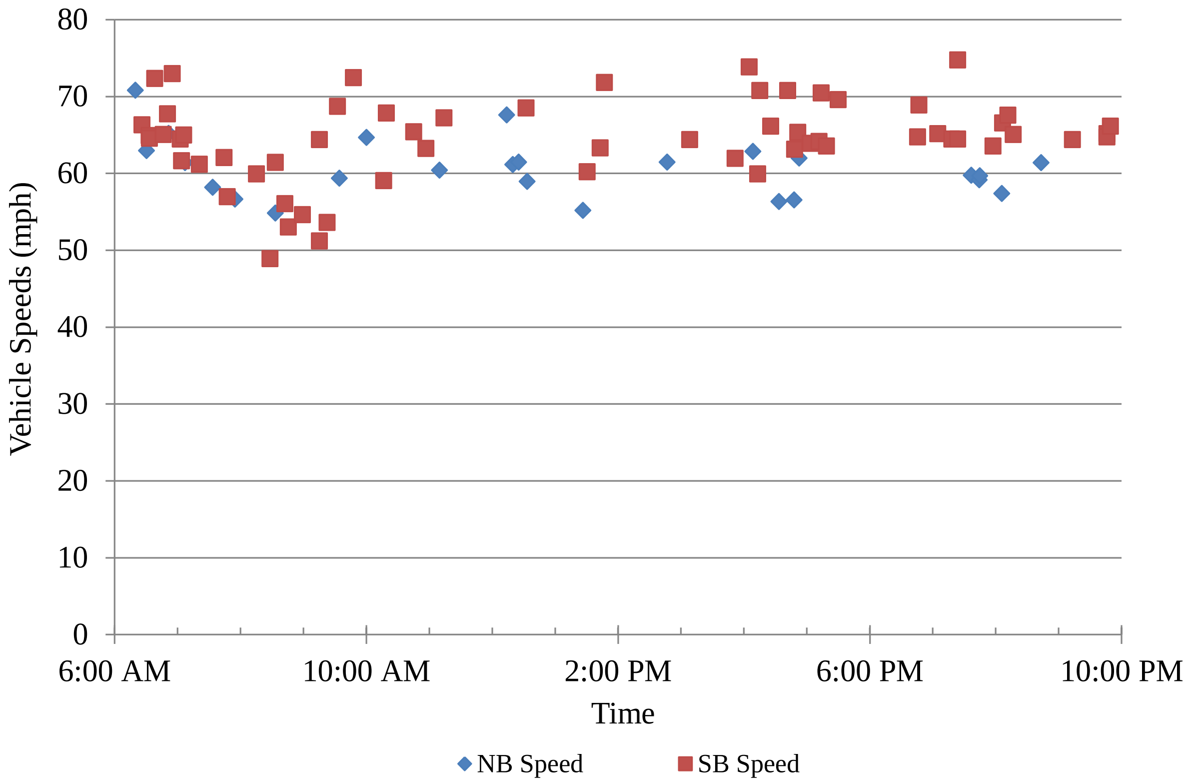


Figure 4.12: Vehicle Speeds On Northeast Side of Columbus.

Fewer hits are visible in Scenario 3, which evaluates the speeds between the nodes North and East of Columbus. However, a slight decrease in travel speeds is visible during the morning peak hours. The lack of hits makes it difficult to evaluate speeds throughout the day.

4.5.4 Scenario 4

Figure 4.13 illustrates the northbound and southbound travel speeds from the south side of Columbus on Interstate 71 to the node on Interstate 270 west of Columbus.

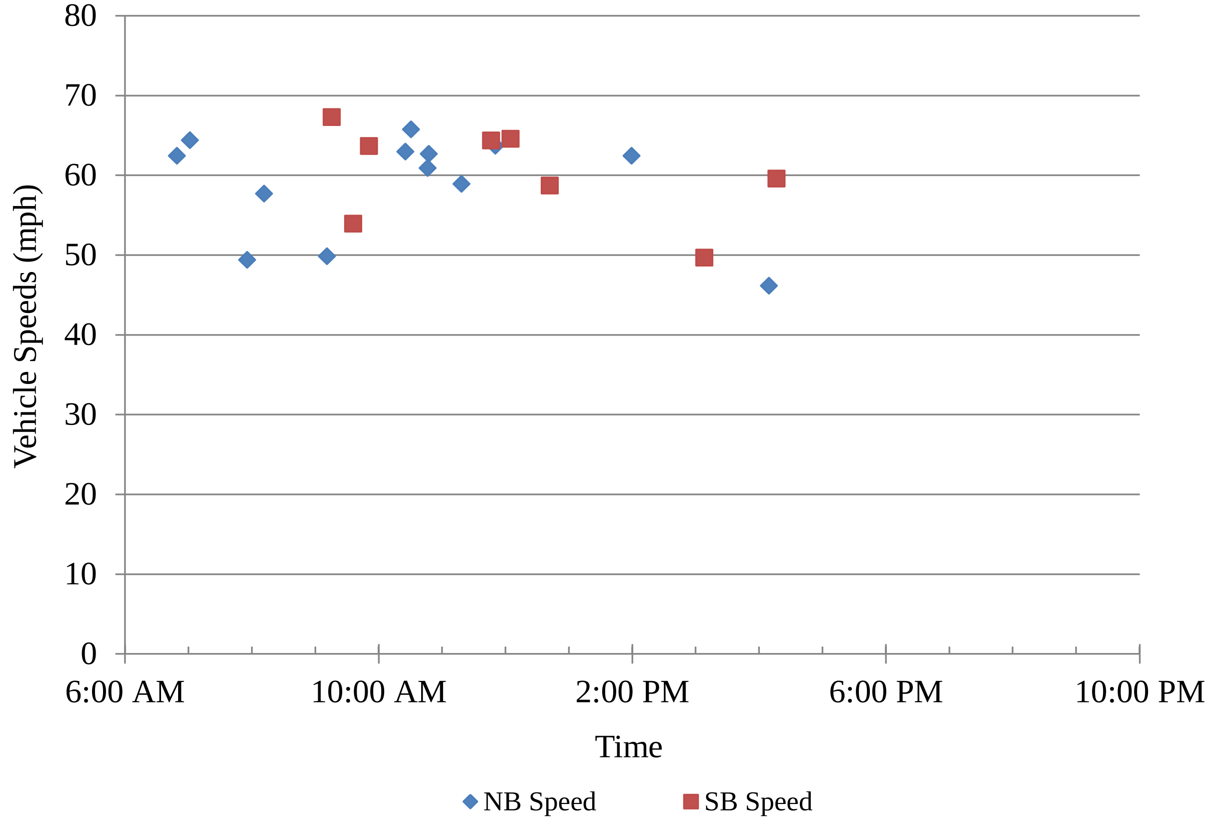


Figure 4.13: Vehicle Speeds On Southwest Side of Columbus.

The lack of nodes in an urban area is apparent in Figure 4.13. With a large distance, 16 miles, and many interchanges between the nodes, very few matching hits are recorded between the nodes south and west of Columbus.

4.5.5 Scenario 5

Figure 4.14 illustrates the northbound and southbound travel speeds from Interstate 71 south of Columbus to the node east of Columbus on Interstate 270.

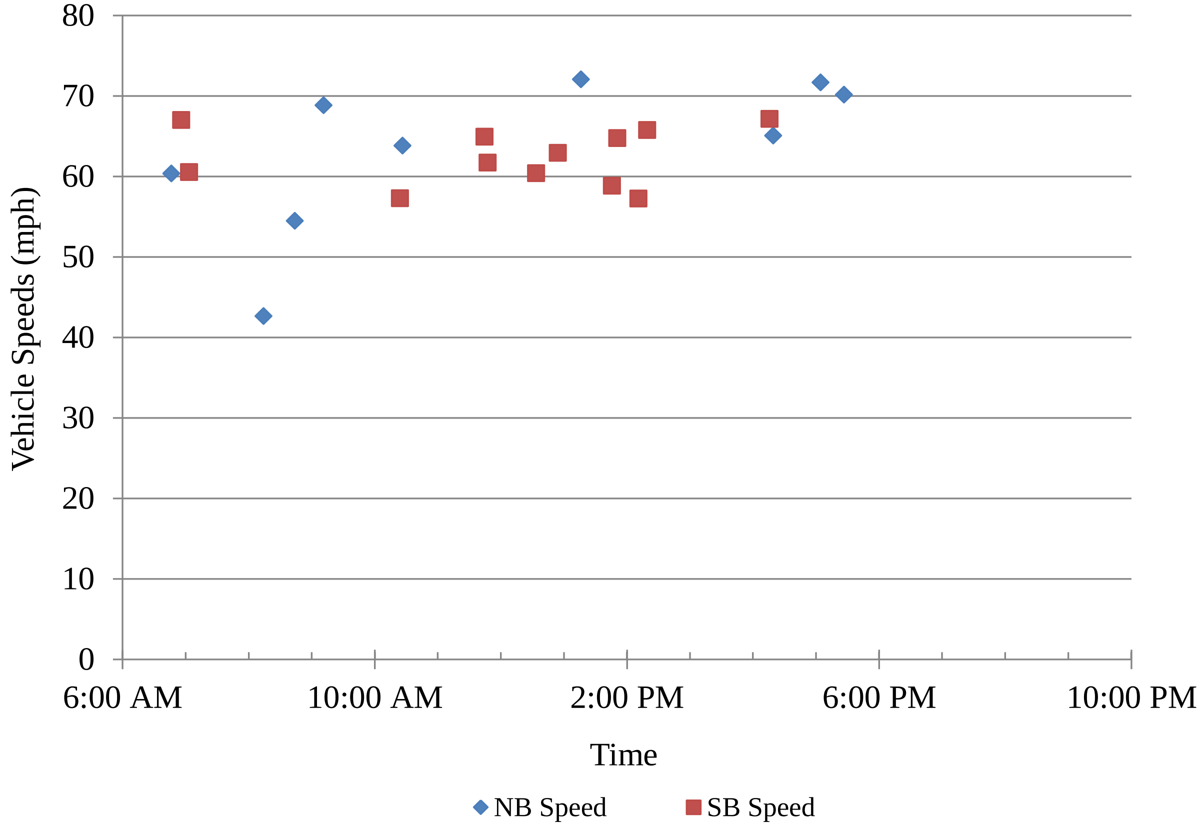


Figure 4.14: Vehicle Speeds On Southeast Side of Columbus.

As with the nodes south and west of Columbus, very few matching hits are recorded between the nodes south and east of Columbus.

As expected, the small number of nodes in an urban area will not provide enough coverage to adequately monitor travel speeds or travel times at a useful level. The large distances and the number of interchanges between the nodes create a lack of matching data points to monitor speeds and travel times. In addition, the resolution of the data decreases with larger distances, making it harder to identify congestion and incidents.

4.6 Incident Detection

This section analyzes the effects of node spacing during a traffic incident and is divided into three sections:

- Section One – Incident Detection,
- Section Two – Hit Counts During Incident, and
- Section Three – Congestion Created by Incident.

4.6.1 Incident Detection

Figure 4.15 presents a schematic showing the spacing of different nodes used in gathering speed data. Figures 4.16 to 4.18 are developed to show the data of closely spaced nodes during an incident and nodes spaced farther apart.

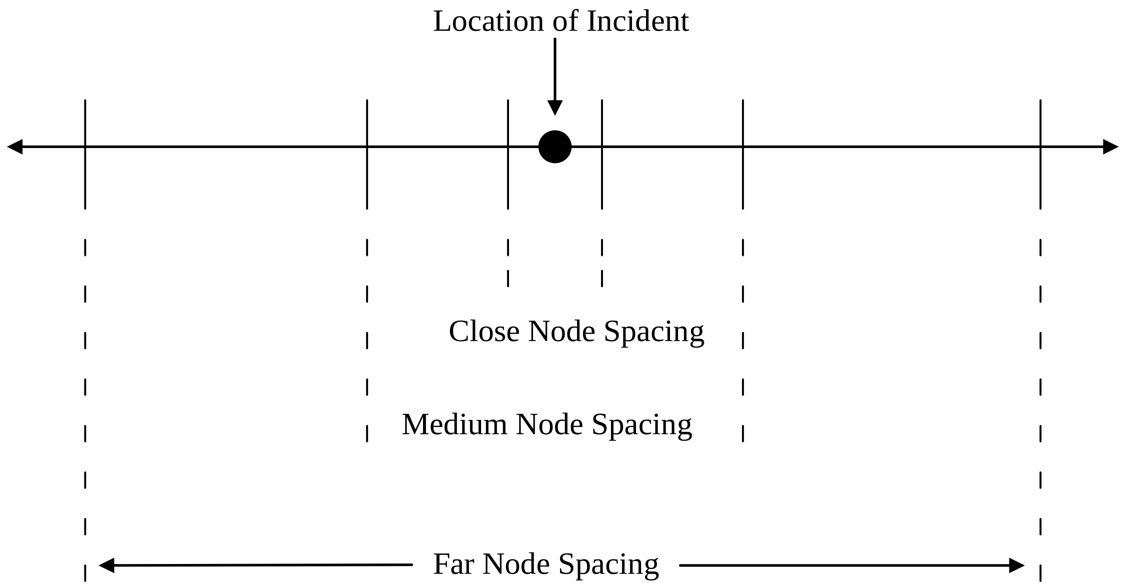


Figure 4.15: Spacing of Nodes with Respect to Incident.

The first incident the research team will evaluate occurs on May 4, 2012, near mile marker 151 in the southbound direction. The location of the incident is determined by finding the point at which vehicle speeds at a node return to their normal levels. Figure 4.16 illustrates the speeds between the two nodes nearest to the location of the incident.

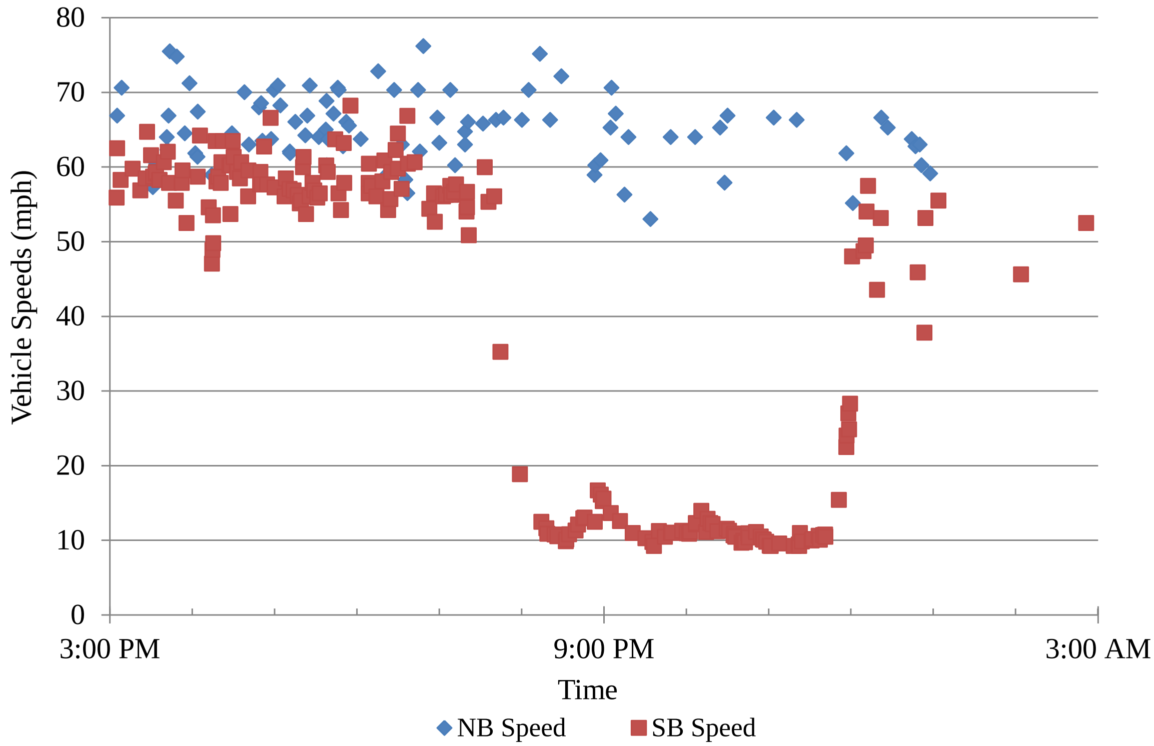


Figure 4.16: Speeds Between Nodes Close to Incident.

The two nodes in question are 4.5 miles apart. With the nodes spaced so closely, the drop in speeds when the incident occurs is clearly visible. In addition, vehicle speed fluctuations are visible between 7:00 PM and 11:00 PM in locations where the nodes are spaced closely. An interesting finding to notice with this incident is when speeds are reduced and congestion is increased, the variation in speeds is much less than before the incident occurs. This is shown by the thin band of speeds after the incident, from 7:00 PM to 11:00 PM, as compared to the larger variation of speeds prior to the incident, from 3:00 PM to 6:00 PM.

Figure 4.17 illustrates the same incident that occurred on May 4, 2012, using data from nodes that are spaced further apart.

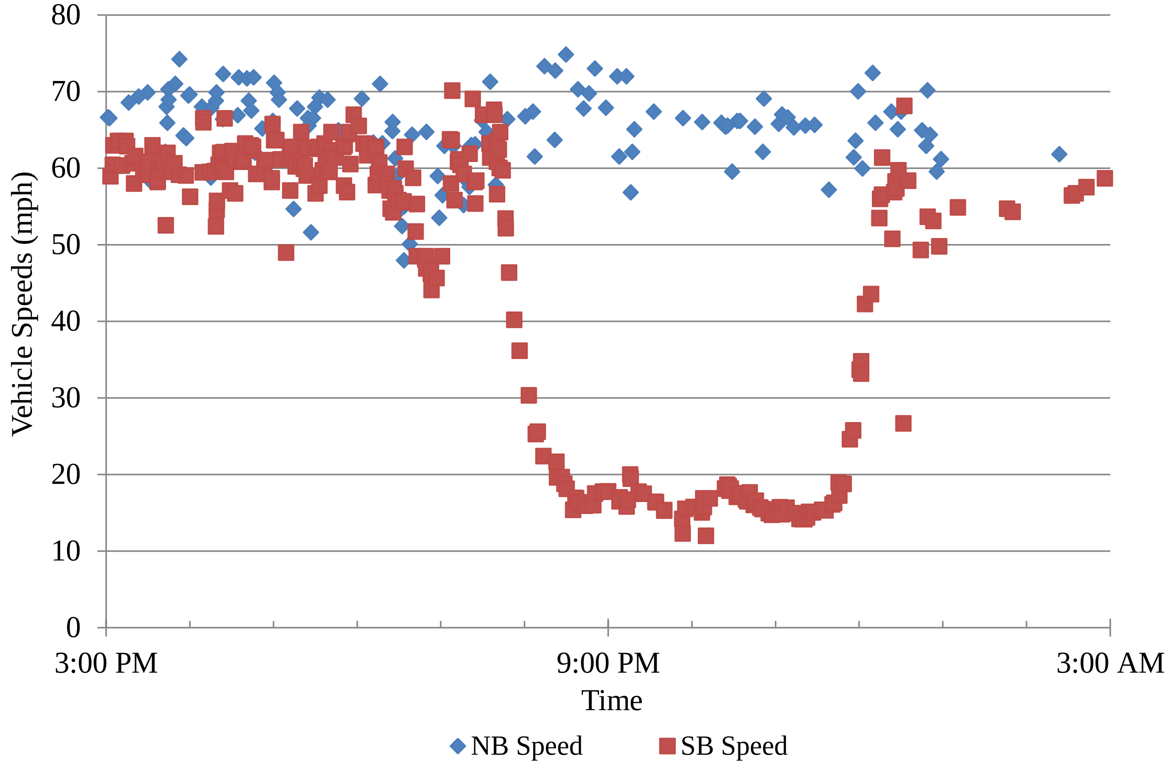


Figure 4.17: Speeds Between Nodes Medium Spaced from Incident.

The two nodes in this figure are spaced 10 miles apart. With the nodes being spaced farther apart than the previous nodes, a more gradual drop and rise in speeds is seen. In addition, the average speed during the incident is increased. The instability in the traffic as seen by the small rises and drops in vehicle speeds are still visible between 7:00 PM and 11:00 PM; however, they are less distinct when compared with the data for closely spaced nodes. Another difference is that the minimum speed during the incident is greater than for the nodes spaced close together. Since the speeds are determined by the time it takes to travel the distance between the nodes, the vehicles are traveling at full speed for a longer time, resulting in a higher average speed.

Figure 4.18 illustrates the same incident occurred on May 4, 2012, with an even greater distance between the nodes.

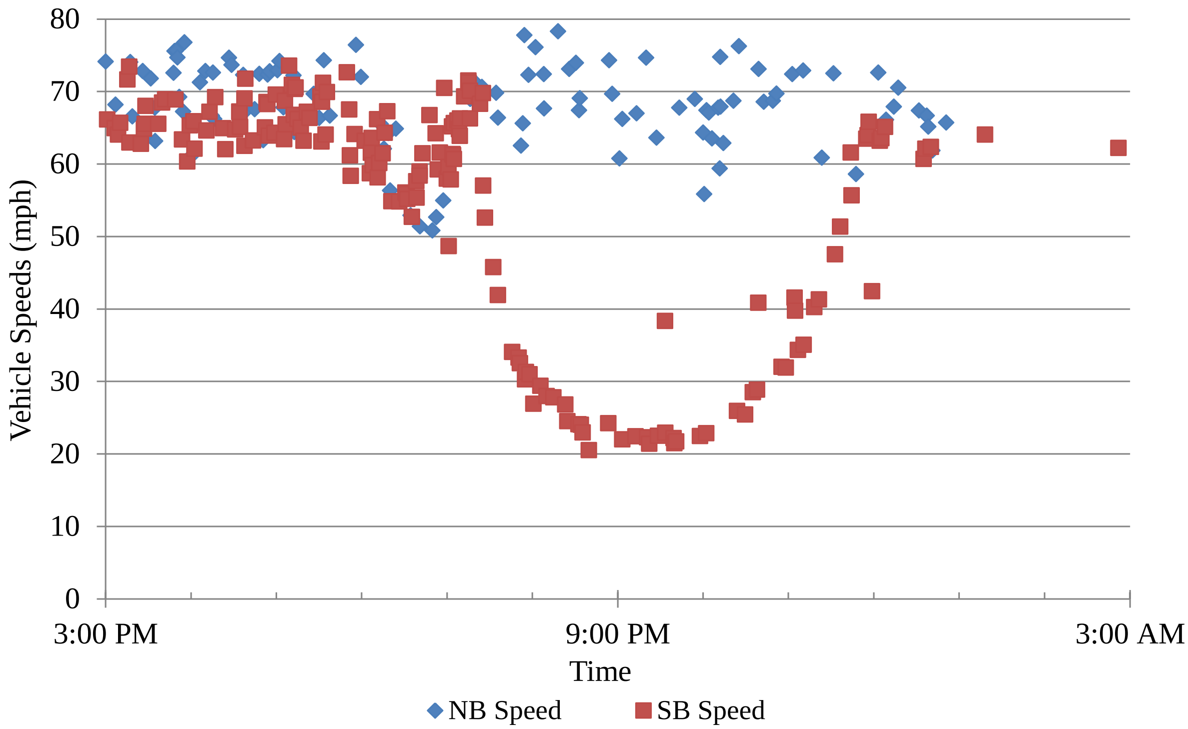


Figure 4.18: Speeds Between Nodes Placed Far Away from Incident.

The two nodes used to gather these speeds are 27 miles apart. With the nodes being so far apart, the speeds decrease much more gradually than the sharp drop-off seen with the more closely spaced nodes. In addition, the duration of time where speeds are at their minimum is much less. As with the medium spaced nodes, the speed from the far spaced nodes are increased from the previous figures. The incident is still visible at this distance due to the severity and the duration of the event.

Table 4.11 summarizes the data from Figures 4.16 to 4.18, showing the average speed during the incident, the duration of time at which speeds are minimal, and the time at which the incident is detected.

Table 4.11: Summary of May 4, 2012 Incident with Different Node Spacing.

Distance Between Nodes	Average Speed Between 7:00 PM and 11:00 PM (mph)	Duration of Minimal Speeds (hours)	Time Incident is Detected
4.5	12.5	4	7:21 PM
10	17.9	3.5	7:35 PM
27	29.0	2	7:45 PM

Note: This table shows the average speed during the time frame of the incident, the duration of minimal speeds, and the time at which the incident is detected for the different node spacings.

This table shows that as the node spacing increases, the average speed of the vehicles also increases and the duration of time that speeds are at their minimum due to the incident are less. In addition, the time at which the incident is detected is later as the distance between the nodes increases. The time the incident is detected is the time at which the speeds reach their minimum. The table shows that rather large node spacing is capable of capturing large incidents, and the next step is to have the research team evaluate the capabilities of large node spacing in capturing smaller incidents.

The research team identified an incident with a shorter duration period in order to evaluate the effects of node spacing on smaller incidents. This incident occurs on May 11, 2012, near mile marker 155 in the southbound lanes. An even smaller incident occurring on the same day in the northbound lanes will also be evaluated. Figure 4.19 illustrates the speeds between the nodes nearest to the incident.

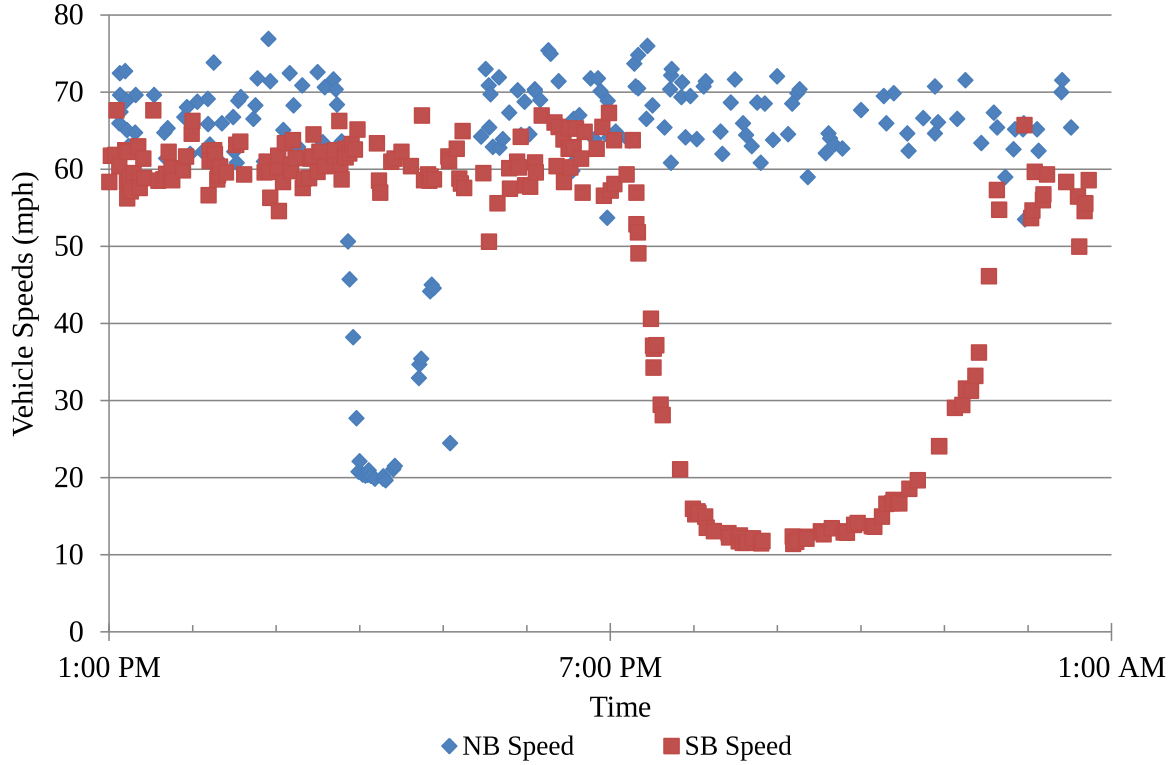


Figure 4.19: Incident Detection Between Closely Spaced Nodes.

The nodes used to collect this data are spaced 10 miles apart and the two incidents are easily identifiable. The incident in the northbound lanes occurs between 3:00 PM and 4:00 PM and the incident in the southbound lanes occurs between 6:00 PM and 11:00 PM. With the incident in the southbound direction lasting longer, the speeds are all within a very thin band, indicating that the road is congested to the point where it is not possible to travel any faster. With the northbound incident being so short in duration, the speeds are not as clearly defined but the decrease is still visible.

Figure 4.20 illustrates the same incident occurring on May 11, 2012, with nodes spaced farther apart.

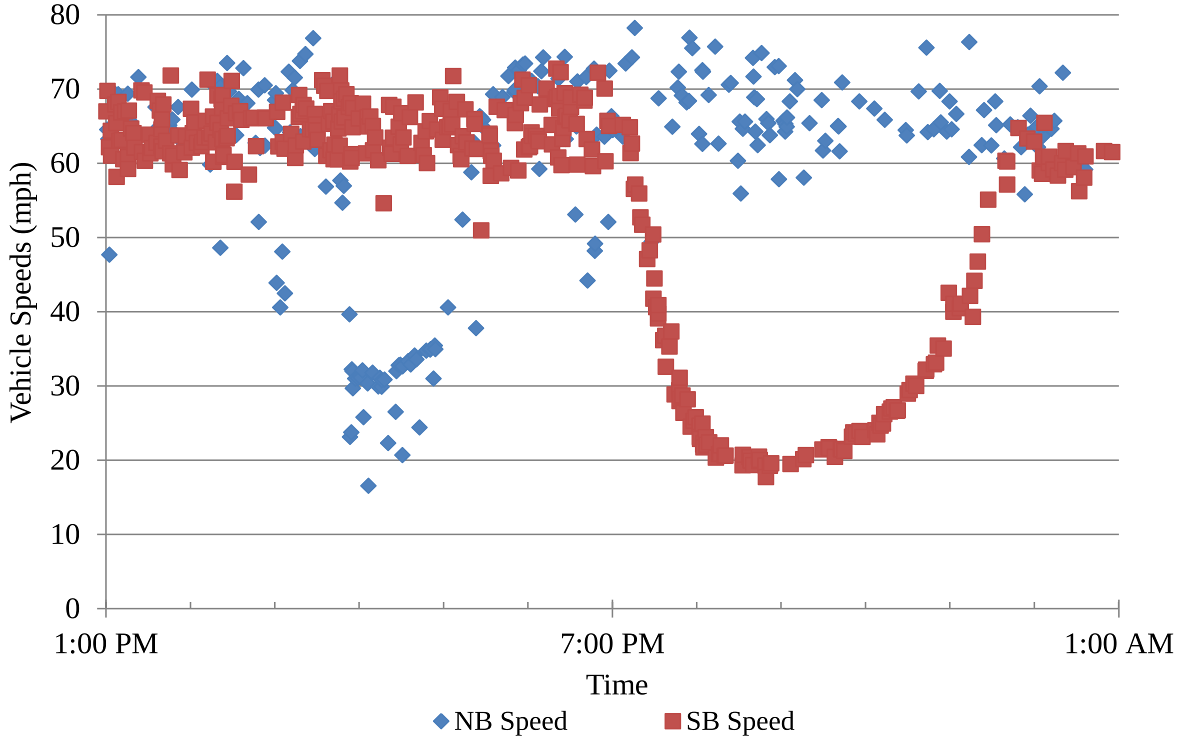


Figure 4.20: Incident Detection with Medium Spaced Nodes.

The nodes in this case are 22 miles apart. With this increased distance, the minimum speeds recorded during the two incidents are slightly increased from the closely spaced nodes. Since the northbound incident is short in duration, it is becoming harder to identify the congestion speeds as they are more spread out. The instability in the northbound direction, visible between 5:00 PM and 6:00 PM, shows a smaller drop in speeds after the incident occurs. With the southbound incident, the speed at which vehicles are forced to travel because of congestion is still apparent.

Figure 4.21 illustrates the same incident occurring on May 11, 2012, with nodes spaced medium-far apart.

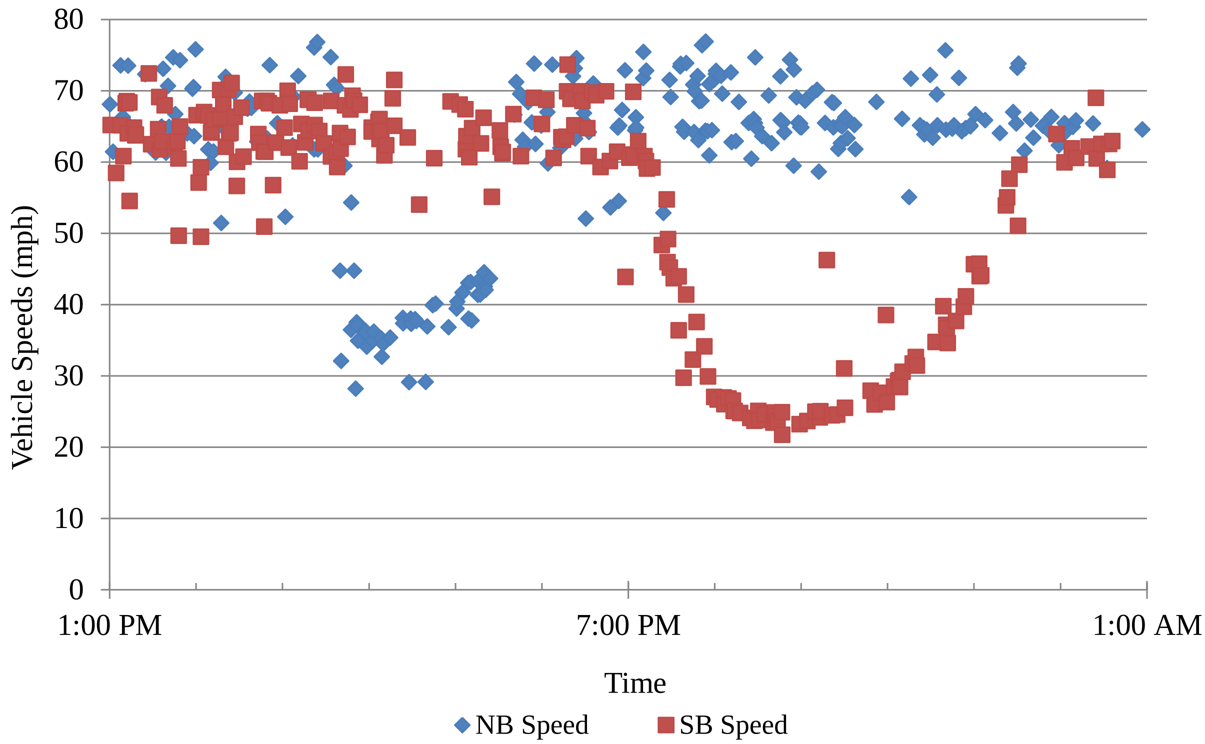


Figure 4.21: Incident Detection with Medium-Far Spaced Nodes.

The nodes used to record the speed data are 29 miles apart. With the greater distance between nodes, the speeds during the two incidents are increased from the more closely spaced nodes. The speeds during the northbound incident are more scattered than the speeds during the southbound incident. This is a result of the duration of the incident, causing the traffic in the southbound lanes to become more congested than the northbound lanes.

Figure 4.22 illustrates the same incident occurring on May 11, 2012, with nodes spaced far apart.

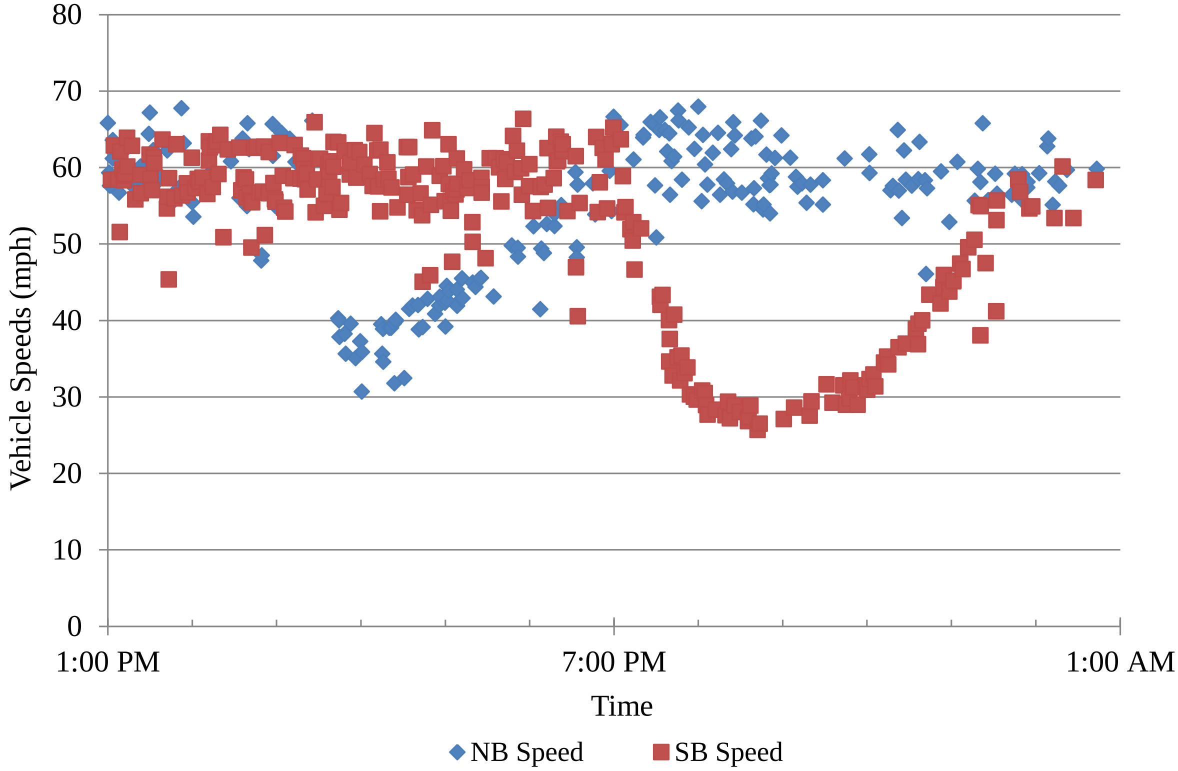


Figure 4.22: Incident Detection with Far Spaced Nodes.

The nodes used to record the speeds in this figure are 39 miles apart. With the increased distance, the speeds during the two incidents are increased from the closer spaced nodes, and the bands of speeds are larger and less defined. Again, the incident in the northbound lanes has speeds that are more scattered than the speeds from the incident in the southbound lanes.

Table 4.12 summarizes the data presented in Figures 4.19 to 4.22 by showing the speeds during the northbound and southbound incidents and the time the southbound incident is detected for the different node distances.

Table 4.12: Summary of May 11, 2012 Incident with Varying Distances Between Nodes

Distance Between Nodes	Speed During NB Incident 2:00 - 4:00 PM (mph)	Speed During SB Incident 6:00 - 11:00 PM (mph)	Time SB Incident is Detected
10	43.0	25.4	7:02
22	41.4	32.6	7:15
29	44.7	36.4	7:26
39	44.0	38.7	7:32

Note: This table shows the average speed during the time frame of the incident and the duration of minimal speeds for the different node spacings.

Table 4.12 shows that as the distance between the nodes increases, so too do the speeds recorded during the incident as well as the time to detect the incident. This is due to the fact that vehicles are traveling at full speed for a longer amount of time, resulting in higher average speeds. In addition, as the distance between the nodes increases, the duration of the incident appears shorter. This is clearly seen in Figures 4.19 through 4.22, where the apex of the curve is smaller than the one in the subsequent figure.

For the incident in the southbound lanes, the average speed increases as the distance between the nodes increases. The time the southbound incident is detected is later as the spacing between the nodes increases. This is a result of the decrease in resolution that arises when the spacing between nodes is increased.

For the incident in the northbound lanes, the average speed is similar for all four node distances. This is due to the fact that the northbound incident has a shorter duration, and speeds did not decrease as much as during the southbound incident. However, even with the large node spacing, the incident is still visible in the data. This finding suggests that smaller incidents are still being picked up at the larger node spacing.

4.6.2 Congestion Created by Incidents

Another aspect of incidents the research team is evaluating is congestion. When an incident occurs, traffic often stops quickly, causing a wave traveling backwards where speeds decrease quickly. The research team is creating graphs of the nodes one segment farther away from the incident in order to determine when congestion begins to occur and how that relates to the location where the incident began. Figure 4.23 illustrates the concept of stepping back one segment at a time.

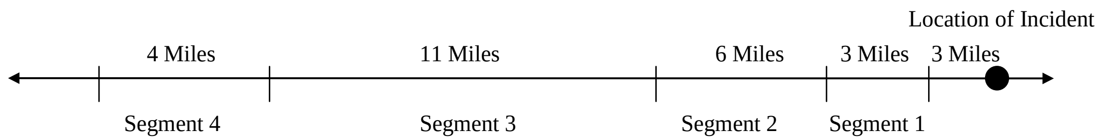


Figure 4.23: Explanation of One Segment Farther From Incident.

To show how congestion and travel speeds change farther away from an incident, the research team identified an incident occurring on Sunday April 8, 2012. Figure 4.24 illustrates the speeds between the nodes three miles from where the incident occurs.

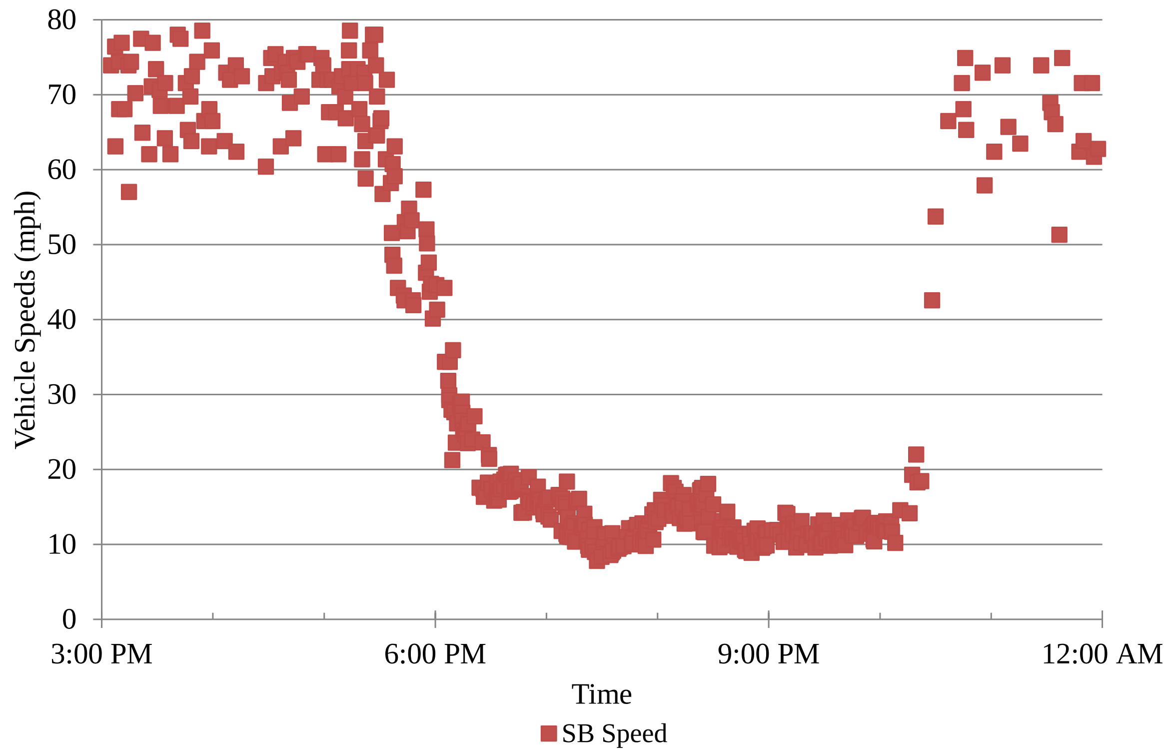


Figure 4.24: Travel Speeds in Segment 1, Closest to Incident on April 8, 2012.

This graph is created using the nodes between which the incident occurs. The congestion created from the incident starts at 5:40 PM and dissipates at 10:30 PM. This incident lasts for four hours and the speeds through this segment are between 10 and 20 mph for the majority of the time, suggesting it is a more severe incident.

Figure 4.25 illustrates the vehicle speeds through segment 2, which is six miles long, for the same incident occurring on April 8, 2012.

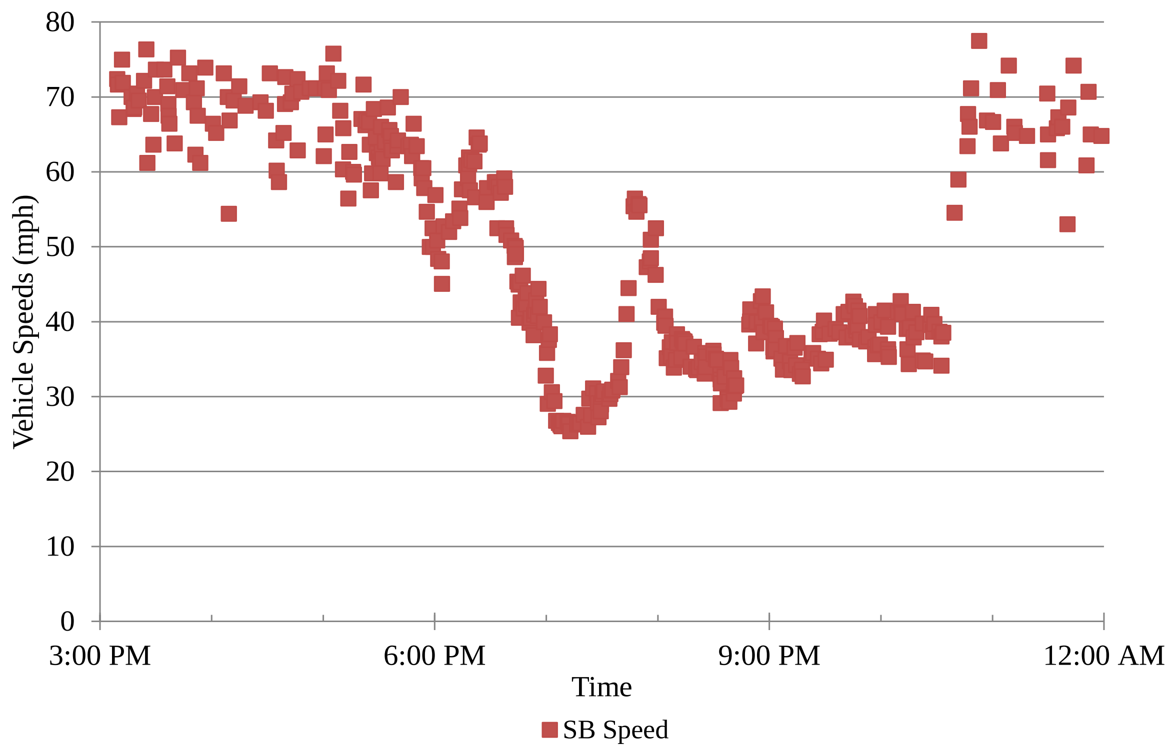


Figure 4.25: Travel Speeds in Segment 2 on April 8, 2012.

In Segment 2, the congestion begins at 5:50 PM and dissipates at 10:30 PM. When compared to the segment where the incident occurs, the time that speeds begin to decrease occurs later. This signifies that travel speeds were still at a normal level for a longer period of time in this segment, and it took a longer time for congestion to slow the traffic in this segment. Also, the travel speeds at the beginning of the incident are unstable – indicating that vehicles are forced to slow down, followed by a time when some congestion disperses but subsequently forms again, causing a decrease in speed. The majority of speeds in this segment are between 30 and 40 mph, which are an increase from the previous segment.

Figure 4.26 illustrates the vehicle speeds in Segment 3, which is 11 miles long.

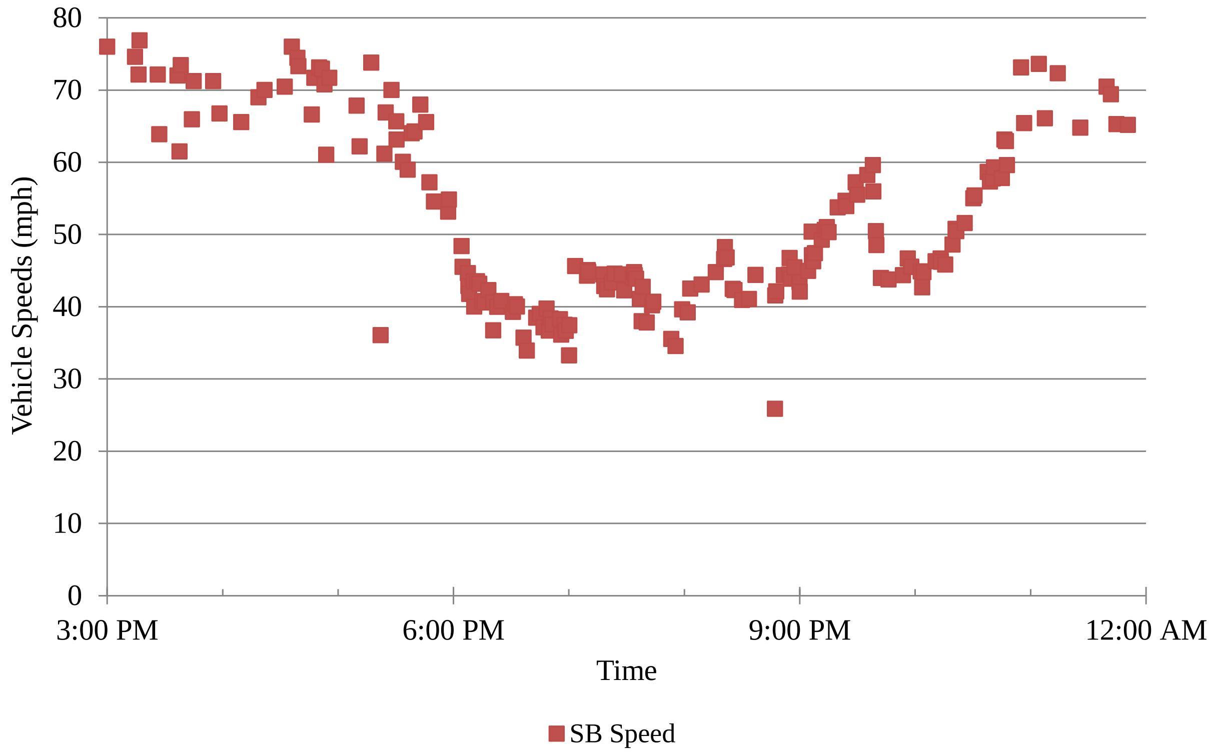


Figure 4.26: Travel Speeds in Segment 3 on April 8, 2012.

In Segment 3, congestion begins at 5:50 PM and dissipates at 10:30 PM. The congestion begins at the same time as the previous segment, indicating the wave created by stopping vehicles has traveled quickly. During the incident, the speeds are between 35 and 45 mph in this segment, which is an increase from the previous segment.

Figure 4.27 illustrates the travel speeds through Segment 4, which is 4 miles long, during the same incident.

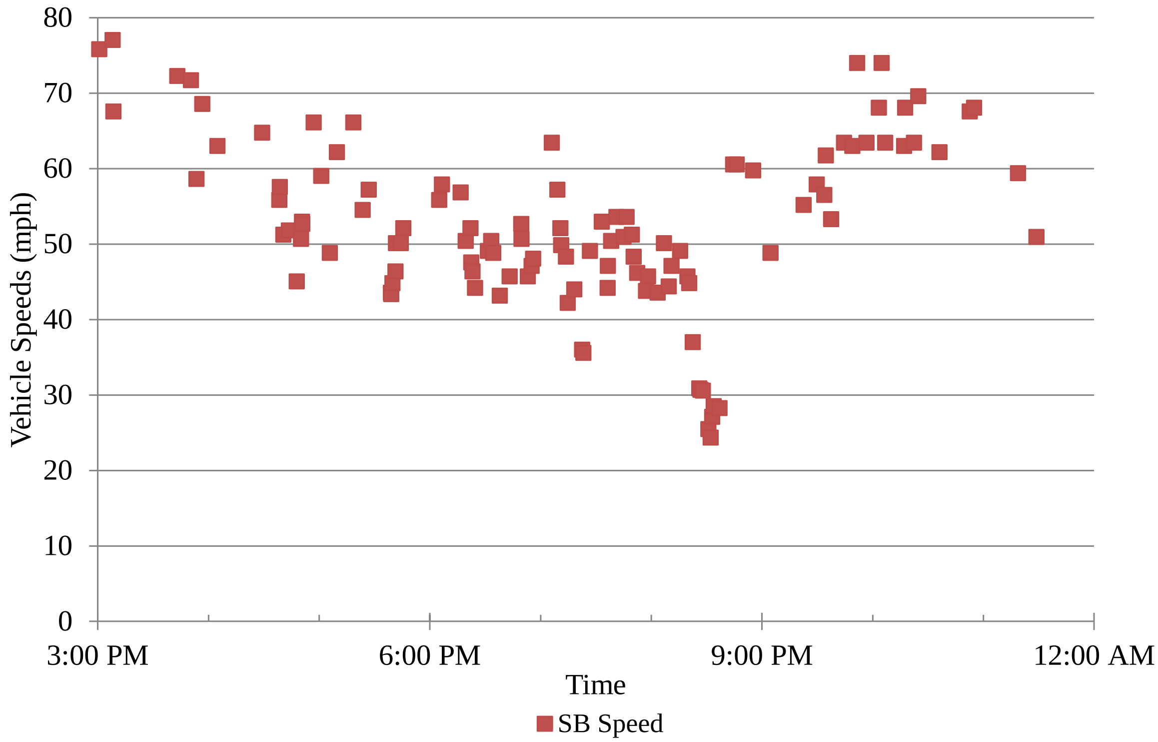


Figure 4.27: Travel Speeds in Segment 4 on April 8, 2012.

The congestion begins at 6:00 PM and ends at 10:30 PM. The congestion begins later than in the previous segments, indicating that it took a longer time for vehicles to be forced to slow down in this segment. The speeds in this segment are also the highest, between 40 and 50 mph during the time of the incident.

4.6.3 Hit Counts during Incidents

The research team evaluates the amount of Bluetooth device hits during incidents to determine if there is an increase compared to normal traffic. During an incident, traffic becomes congested and a vehicle may be stopped within the range of a Bluetooth node for a long enough time to be recorded multiple times. The research team has evaluated the possibility of improving the time of incident detection based solely on hits counts. Table 4.13 shows the amount of unique and total Bluetooth hits during the May 4, 2012, incident when compared to unique and total hits on May 3, 2012, during the same time frame.

Table 4.13: Bluetooth Hits During May 4, 2012 Incident Compared to Previous Day.

Unique MAC Hits 5/4/12 (8-12 PM)	Total MAC Hits (5/4/12) (8-12 PM)	Percent Less Unique Hits	Unique MAC Hits (5/3/12) (8-12 PM)	Total MAC Hits (5/3/12) (8-12 PM)	Percent Less Unique Hits
326	1322	75%	254	364	30%

Note: This table compares the number of unique Bluetooth hits to the total number of Bluetooth hits on the node closest to the incident on the day of the incident and that is compared to the hits on the same node the day before the incident.

Bluetooth hits are counted on the node just north of the location where the incident occurs. The unique MAC hits count as only one hit if a MAC address is recorded multiple times, and total MAC hits include each MAC address regardless of amount of duplicate hits. For the incident occurring on May 4, there are 75% fewer unique hits compared to total hits from 7:00 PM to 11:00 PM. During the same time of day on the day prior to the incident, there are 30% fewer unique hits than total hits, which demonstrate a large increase in duplicate MAC hits during this incident.

The research team identified several incidents with smaller duration times and less of a decrease in speed in order to evaluate hit counts during these incidents. Table 4.14 presents the hit counts at the node nearest to the location where the incident occurs on April 22, 2012.

Table 4.14: Bluetooth Hits During April 22, 2012 Incident Compared to Previous Day.

Unique MAC Hits 4/22/12 (8:30-10:30 PM	Total MAC Hits 4/22/12 (8:30-10:30 PM	Percent Less Unique Hits	Unique MAC Hits 4/21/12 (8:30-10:30 PM	Total MAC Hits 4/21/12 (8:30-10:30 PM	Percent Less Unique Hits
118	307	62%	85	93	9%

Note: This table compares the number of unique Bluetooth hits to the total number of Bluetooth hits on the node closest to the incident on the day of the incident and that is compared to the hits on the same node the day before the incident.

There are 62% fewer unique hits during the incident compared to 9% fewer on the day prior to the incident. This large increase signals that congestion is occurring near this node during the incident.

Table 4.15 presents the hit counts at the node nearest the incident that occurs on April 6, 2012.

Table 4.15: Bluetooth Hits During April 6, 2012 Incident Compared to Previous Day.

Unique MAC Hits 4/6/12 (3:30-7:30 PM	Total MAC Hits 4/6/12 (3:30-7:30 PM	Percent Less Unique Hits	Unique MAC Hits 4/5/12 (3:30-7:30 PM	Total MAC Hits 4/5/12 (3:30-7:30 PM	Percent Less Unique Hits
440	652	33%	373	428	13%

Note: This table compares the number of unique Bluetooth hits to the total number of Bluetooth hits on the node closest to the incident on the day of the incident and that is compared to the hits on the same node the day before the incident.

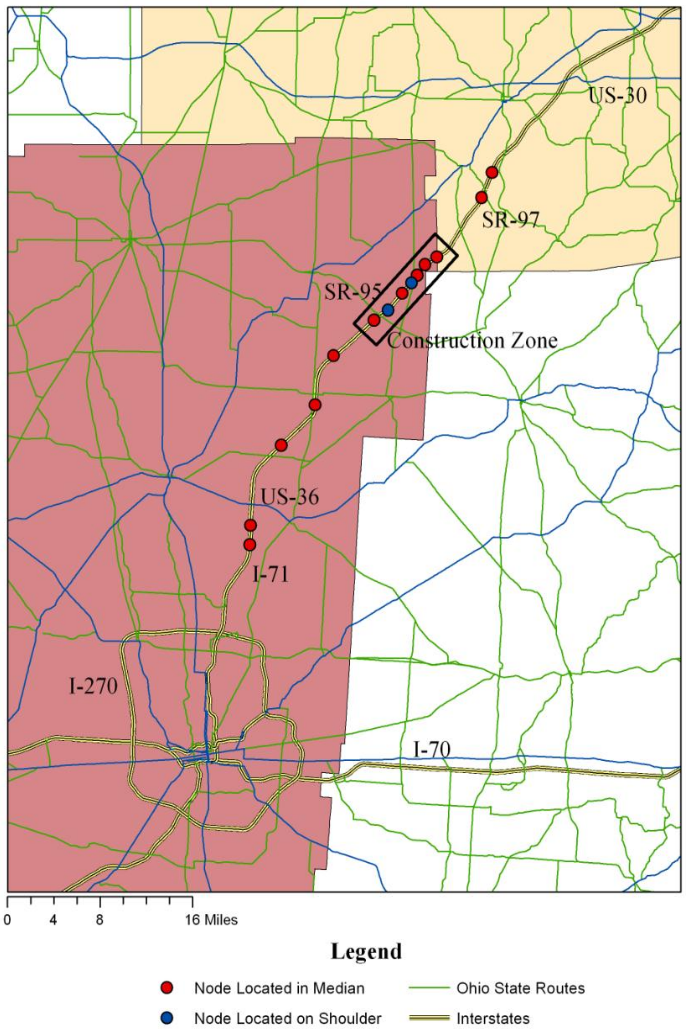
During this incident, there are 33% fewer unique Bluetooth hits compared to 13% fewer the day prior to the incident. This is less of a change, but it is still enough of an increase to signal that congestion is occurring. Tables 4.14 and 4.15 show that hit counts may signal traffic congestion during less severe incidents.

4.7 Evaluation of Speeds in the Construction Zone

The next section of this chapter focuses on the feasibility of using Bluetooth nodes in construction zones. The construction zone in this project is in existence from April 27, 2012, through the duration of the project. This section is divided into three subsections:

- Section One – Hit Counts,
- Section Two – Variation of Speeds Over Time, and
- Section Three – Speeds Before and After the Construction Zone is in Place.

The construction zone is shown in Figure 4.28 and is located between mile markers 159 and 150 of Interstate 71.



Node ID	Mile Marker	Node Location
1	167	Median
2	165	Median
3	158	Median
4	157	Median
5	156	Median
6	155	Shoulder
7	154	Median
8	152	Shoulder
9	151	Median
10	146	Median
11	142	Median
12	132	Median
13	129	Median
14	128	Median

Note: Mile markers decrease from North to South. All GIS maps are developed by the research team.
Figure 4.28: April 27, 2012 Bluetooth Node Deployment.

This map shows the nodes located in the construction zone when it is first established. The construction zone encompasses only the southbound lanes of Interstate 71; therefore, nodes are placed on the southbound shoulder and the median within the construction zone from April 27, 2012, until May 8, 2012.

4.7.1 Hit Counts within the Construction Zone

To further evaluate the feasibility of using Bluetooth nodes within construction zones, the research team quantifies hit counts and matches in the construction zone. This section compares the amount of Bluetooth hits from nodes in two ways:

- Hits on the shoulder versus the median and
- Number of hits prior to establishment of the construction zone versus hits during the construction.

These performance measures allow the research team to evaluate the feasibility of using Bluetooth nodes in construction areas, particularly in areas having limited space or non-ideal locations, or in areas where permanent installations are not viable.

<u>Hits on the Shoulder versus the Median</u>

Table 4.16 presents a count of matching Bluetooth devices recorded by each node located within the construction zone and the location of that node.

Table 4.16: Quantity of Matching Bluetooth Devices Recorded by Nodes in the Construction Zone.

Count	Node ID	Mile Marker	Location
4157	3	158	Median
1049	4	157	Median
4132	5	156	Median
12251	6	155	SB Shoulder
7273	7	154	Median
28789	8	152	SB Shoulder
4049	9	151	Median

Note: This table shows the count of unique MAC addresses recorded from April 27, 2012, until May 8, 2012, which corresponds with Phase 1 of Deployment 9.

The nodes on the shoulder record more matching Bluetooth devices than the nodes in the median; this is likely due to the fact that the barrier wall prevents the nodes from reading the signal from a passing vehicle with a Bluetooth device enabled. Additional information in regard to the effective range of Bluetooth devices may be found in Bakula, 2012. The lower amount of matching devices highlights the effects the environment of the area may have on the Bluetooth nodes. The location of a node and barrier wall in the construction zone is shown in Figure 4.29.

Figure 4.29: Location of Node with Nearby Barrier Wall in Construction Zone.

With the limited locations for deploying nodes within work zones, it is important to understand the capabilities of the nodes at the locations selected. It is reasonable for one node to record more hits than another and, based on the configuration of the work zone, the node may be placed with a barrier wall limiting signal strength in one direction of travel. Consequently, Table 4.16 illustrates some of the impacts of lower signal strength locations.

Hits before the Construction Zone is in Place and during Construction

In order to compare hits within the construction zone to hits on the same section of roadway before the construction zone is in place, the research team recreates phase one of Deployment six by placing nodes in the exact same locations. This allows for a side-by-side comparison of hit counts from before and during the construction to determine the feasibility of using Bluetooth nodes within a construction zone. The deployment before the construction zone is in place is from March 9, 2012, until March 16, 2012, and the deployment during the construction zone is in place is from May 24, 2012, through the end of the research project. Table 4.17 shows the hit counts from Saturday through Thursday from both before and after the construction zone is in place.

Table 4.17: Hit Counts Before and After the Construction Zone is in Place.

Date	Day of Week	Before or During Construction Zone	Hits per Node on Nodes in Construction Zone Area	Hits per Node on Nodes Outside Construction Zone Area
3/10/2012	Saturday	Before	1527	1340
5/26/2012	Saturday	During	1891	1517
3/11/2012	Sunday	Before	1529	1565
5/27/2012	Sunday	During	1503	1529
3/12/2012	Monday	Before	1804	1837
5/28/2012	Monday	During	1896	1811
3/13/2012	Tuesday	Before	1974	1946
5/29/2012	Tuesday	During	2248	2187
3/14/2012	Wednesday	Before	2121	2100
5/30/2012	Wednesday	During	2470	2351
3/15/2012	Thursday	Before	1776	2196
5/31/2012	Thursday	During	1804	1838

Note: This table compares the unique hit counts per node inside and outside of the construction zone from Phase 1 of Deployment 6, which occurs before the construction zone is in place, to Phase 2 of Deployment 9, when the construction zone is in place. The nodes are placed in the same locations for the two deployments. The nodes from Phase 1 of Deployment 6 are considered inside the construction zone if they are placed in the area that the construction zone later encompasses.

Since the number of nodes inside and outside of the zone are not equal, the nodes are evaluated on a per node basis to compare the nodes inside the construction zone to the nodes outside of it. Except for the two Sundays, a higher amount of hits may be seen on the nodes during the construction zone in May when compared to the hits per node before the construction zone is in place in March. On the weekends, there are 10% fewer hits before the construction zone is in place and on the weekdays there are 9% fewer hits. This increase may be caused by the increased efficiency of the Bluetooth nodes.

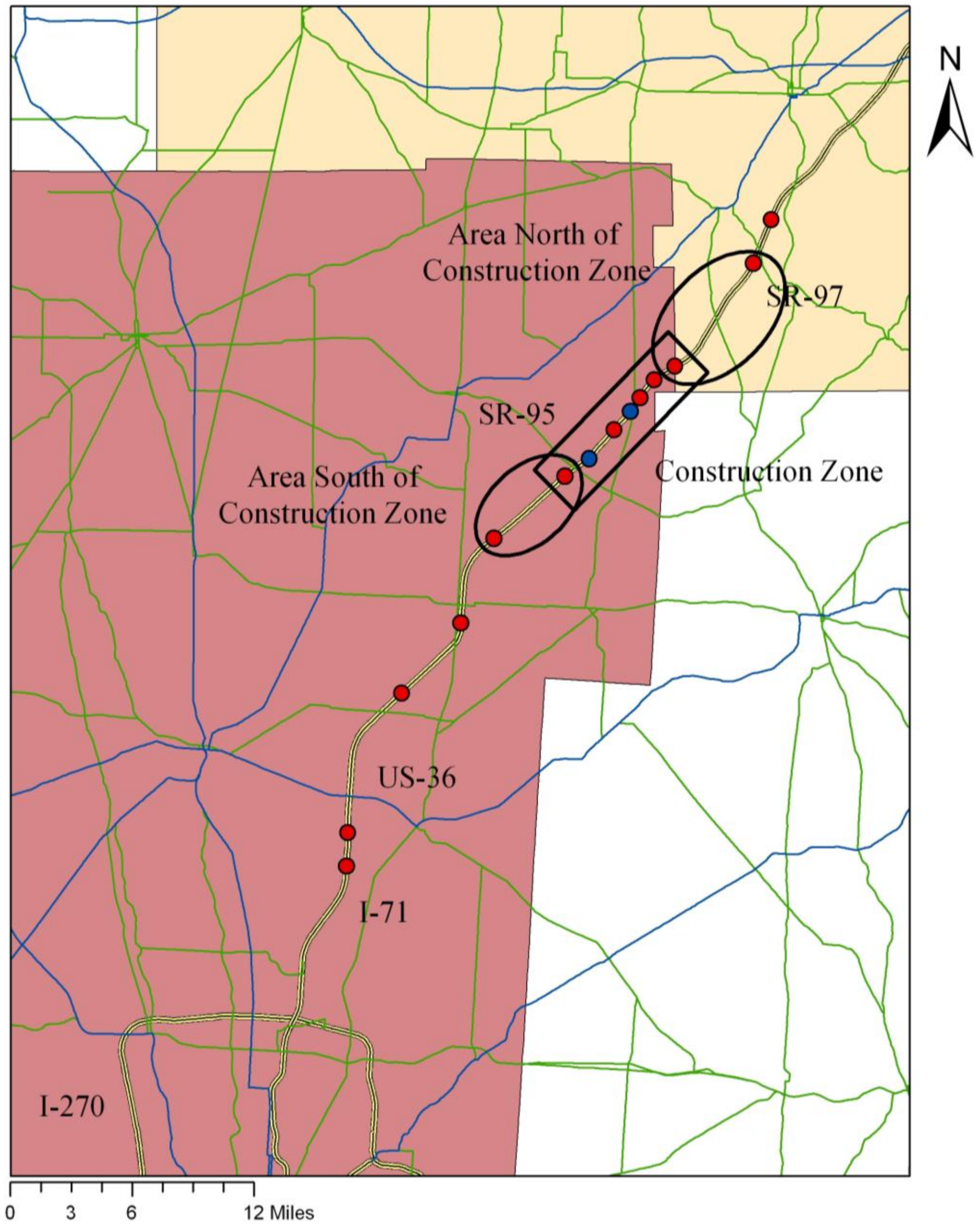
Table 4.17 shows that before the construction zone is in place, the nodes within the area where the construction zone will be located receive 2% fewer hits than the nodes outside of the zone. For the week evaluated while the construction zone is in place, the nodes outside the construction zone receive 5% fewer hits than the nodes inside the construction zone. This shows that using Bluetooth nodes in the construction zone is a viable form of measuring travel times and speeds.

4.7.2 Variation of Speeds over Time

The second subsection within the work zone deployment allows the comparison of the speeds within the construction zone over the duration of the construction project. More specifically, it shows if motorists become more comfortable with the zone over time and if so, do the motorists increase their speed. Within the section, the speeds are analyzed in the area approaching the work zone, in the work zone itself, and the area after the construction zone to determine speed profiles of the sections. The speed profiles may then be used to determine if there are negative impacts on the travel times and vehicle speeds as a result of decreased capacity throughout the construction zone. Two factors are evaluated in this section to determine travel speeds over time:

- Speeds Before, In, and After the Construction Zone and
- Speeds of Same Section Measured Bi-Weekly.

Figure 4.30 shows the locations of the nodes used to evaluate the travel speeds before, in, and after the construction zone.



Note: The box in the figure is the location of the construction zone, the two ovals north and south of the box encompass the two nodes used in gathering the travel speeds north and south of the construction zone. All GIS maps are developed by the research team.
Figure 4.30: Location of Nodes Used to Determine Speeds Before, In, and After Construction Zone.

Speeds are compared in these three zones to determine if any congestion occurs before the construction zone, if speeds increase after the zone, or if speeds are still limited by congestion.

Speeds Before, In, and After the Construction Zone

Figures 4.31, 4.32, and 4.33 show northbound and southbound speeds averaged over 15 minute intervals before, in, and after the construction zone from the first day the construction zone is in place.

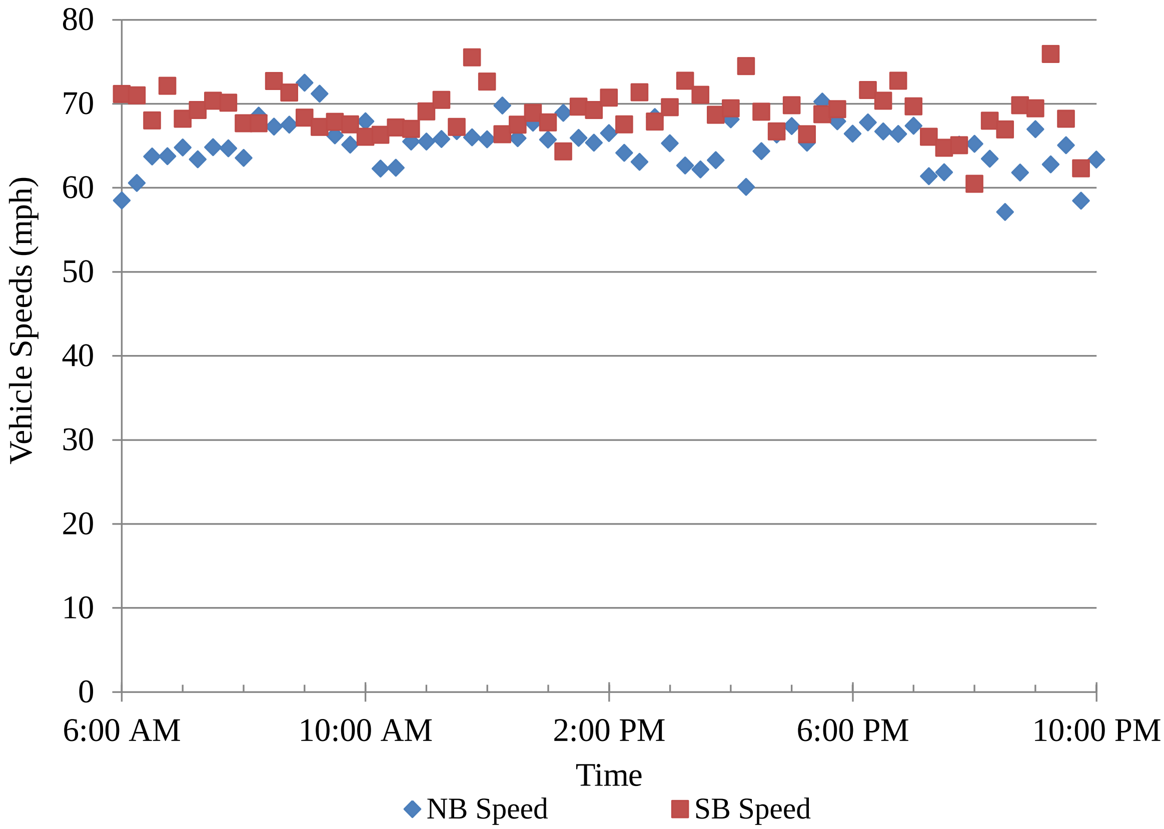


Figure 4.31: Speeds North of Construction Zone.

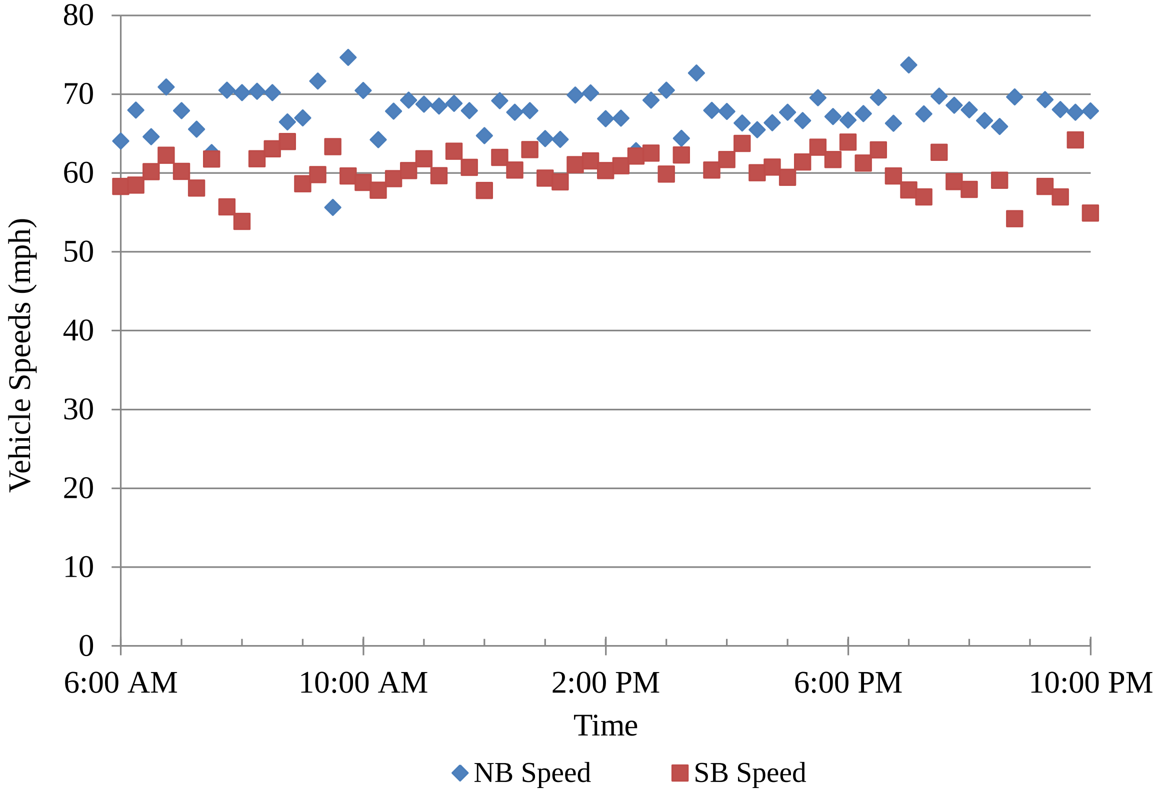


Figure 4.32: Speeds in Construction Zone.

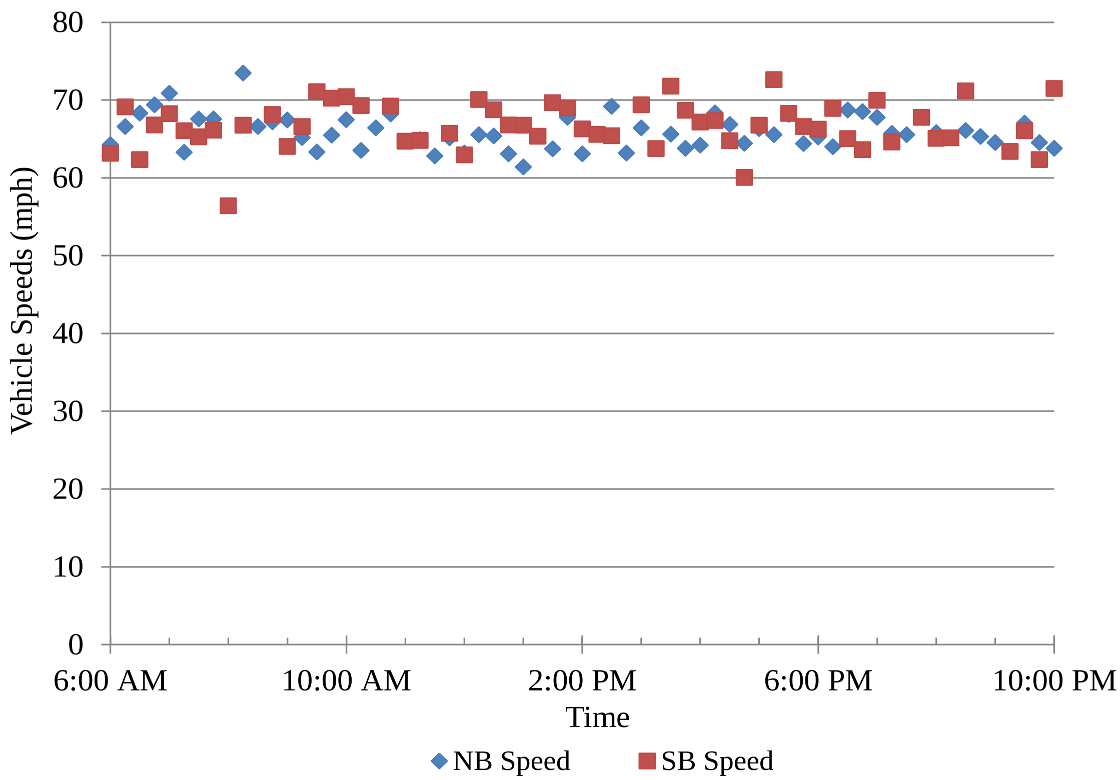


Figure 4.33: Speeds South of Construction Zone.

The construction zone encompasses only the southbound lanes, so the travel speeds of the northbound vehicles are around the speed limit of 65 mph, as shown in Figures 4.31 to 4.33. In Figure 4.32, the southbound speeds show a clear 10 mph drop from north of the construction zone and increase back to near the speed limit south of the construction zone in Figure 4.33. This reduction in speed is expected, since the speed limit is reduced to 55 mph in the construction zone.

Another important factor shown in these figures is that the construction zone does not negatively impact the upstream traffic. The speeds north of the construction zone are near the speed limit showing that capacity within the construction zone remains optimum. If the capacity in the construction zone is lower, congestion will cause decreased travel speeds just north of the construction zone. This holds true for the duration of the construction zone under normal conditions.

Speeds of Same Section Measured Bi-Weekly

The research team is evaluating vehicle speeds within the construction zone over time to see if speeds increase as motorists become more familiar with the construction zone. In order to accomplish this, travel speeds for Wednesday of every other week are compared to see if the southbound speeds are increasing. Figures 4.34 through 4.37 are the plots of travel speeds for May 2, 2012; May 16, 2012; May 30, 2012; and June 13, 2012, respectively.

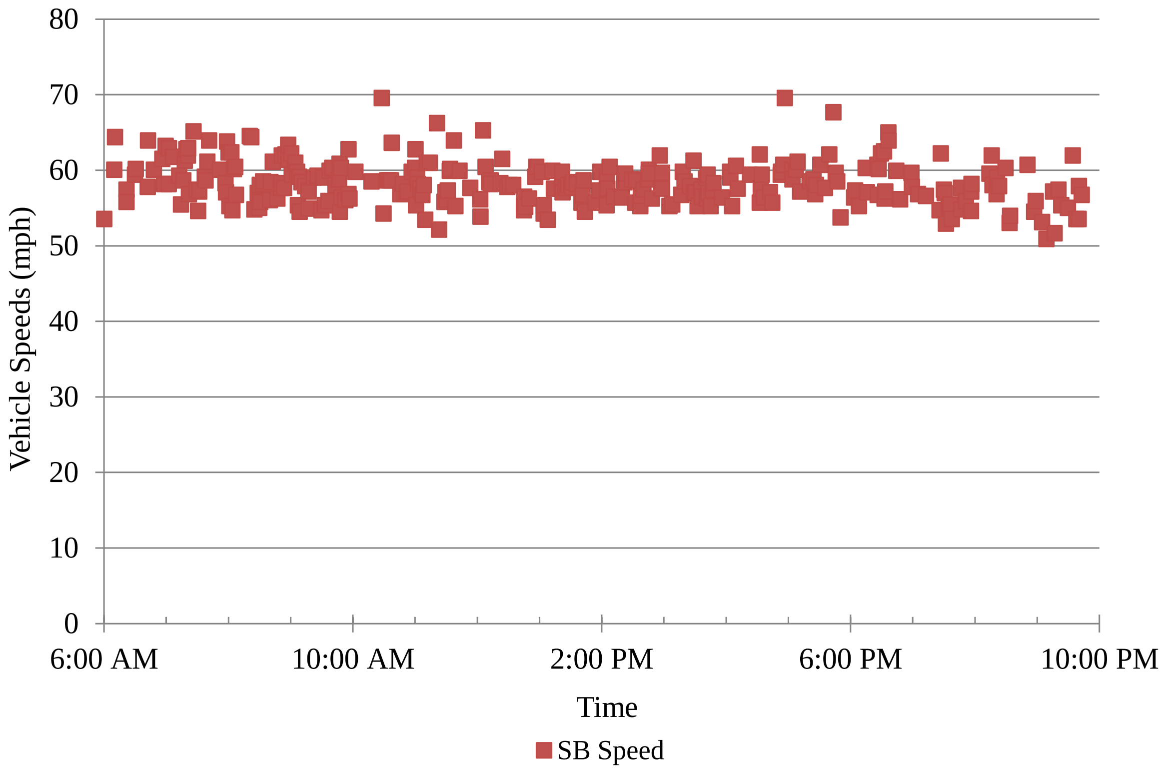


Figure 4.34: Travel Speeds in Construction Zone on May 2, 2012.

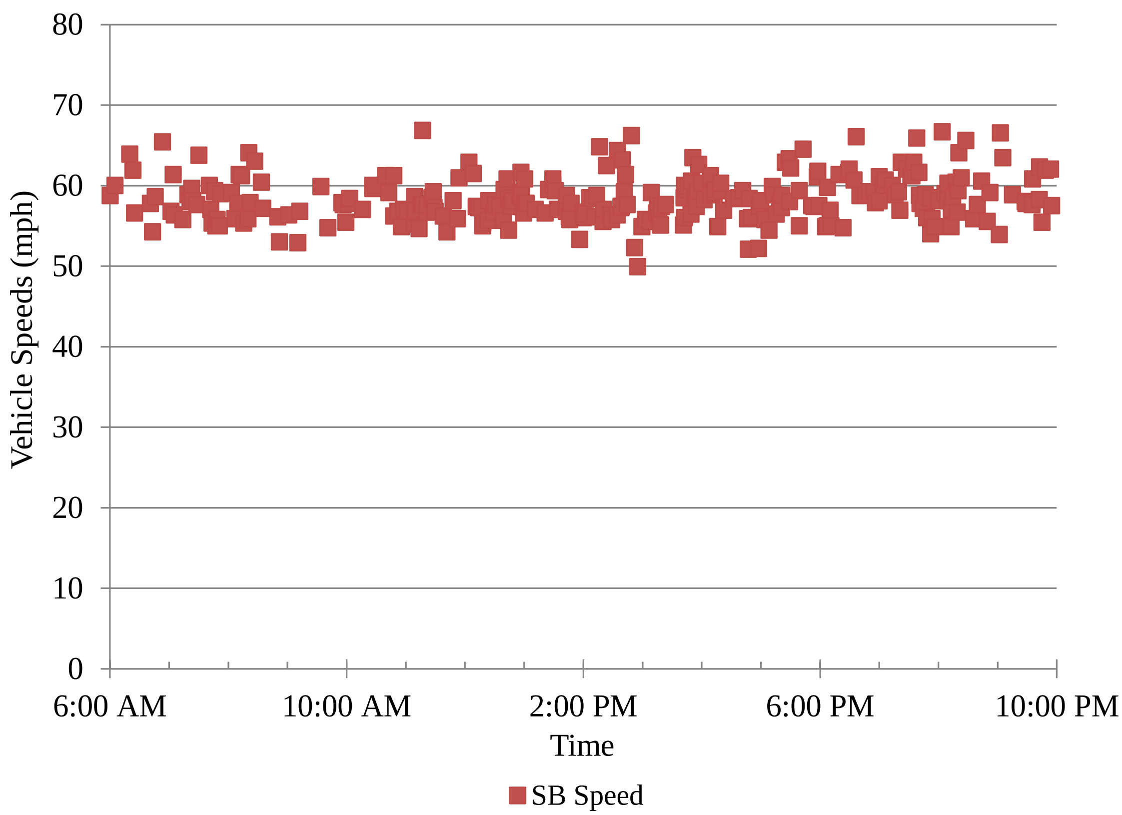


Figure 4.35: Travel Speeds in Construction Zone on May 16, 2012.

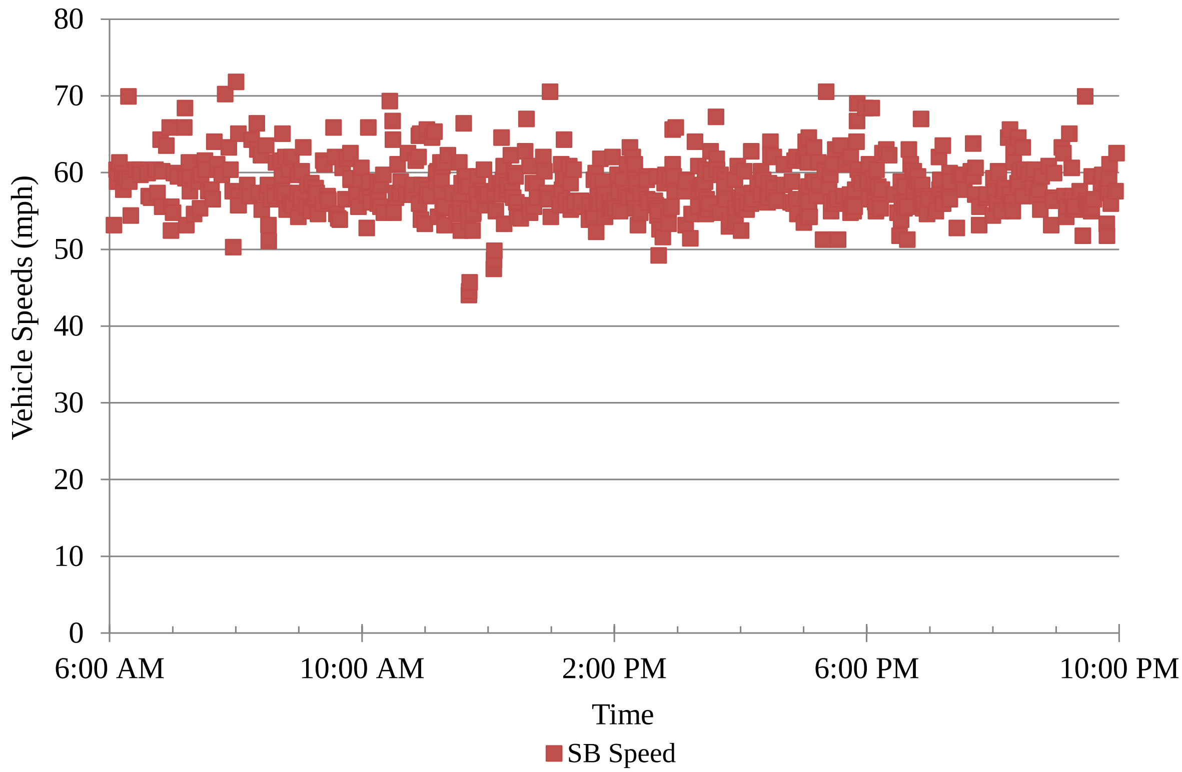


Figure 4.36: Travel Speeds in Construction Zone on May 30, 2012.

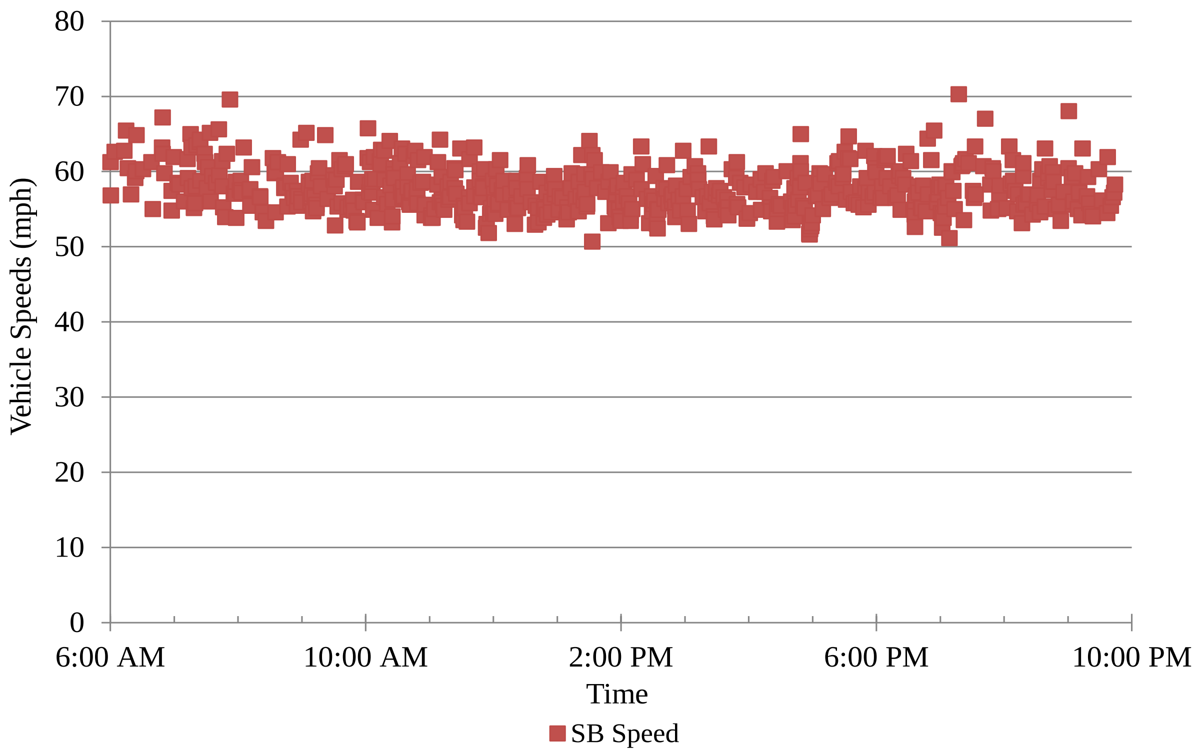


Figure 4.37: Travel Speeds in Construction Zone on June 13, 2012.

To summarize Figures 4.34 to 4.37, Table 4.18 is created.

Table 4.18: Summary of Bi-Weekly Travel Speeds in Construction Zone.

Date	Average Southbound Speed in Construction Zone
May 2, 2012	57
May 16, 2012	58
May 30, 2012	58
June 13, 2012	58

Note: This table summarizes the bi-weekly travel speed data presented in Figures 4.34 through 4.37.

In Figures 4.34 through 4.37, only the southbound speeds in the construction zone are of interest, so the northbound speeds are not included. For all the figures, the majority of the travel speeds are between 55 and 65 miles per hour. The average speed on May 2, 2012, is 57 miles per hour; on May 16, 2012, the average speed is 58 miles per hour; on May 30, 2012, the average speed is 58 miles per hour; and on June 13, 2012, the average speed is 58 miles per hour. This shows that as motorists become more familiar with the construction zone, the speeds are not increasing, and motorists are mostly compliant with the work zone. Also there is little variation in the travel speeds with respect to time of day, indicating that congestion within the work zone is not an issue during peak volume hours.

4.7.3 Speeds before and while the Construction Zone is in Place

The third section will compare speeds from a time period before the construction zone is in place to speeds within the construction zone in both the northbound and southbound directions. In order to compare these accurately, the nodes are placed in the same location before and after the construction zone is in place.

Figure 4.38 shows the southbound travel speeds on March 14, 2012, before the construction zone is created in the area where the zone is later located, as well as the southbound travel speeds on June 6, 2012, when the construction zone is in place. Both dates are Wednesdays and, in each figure, the nodes are placed in the same locations to accurately compare the speeds for the two days.

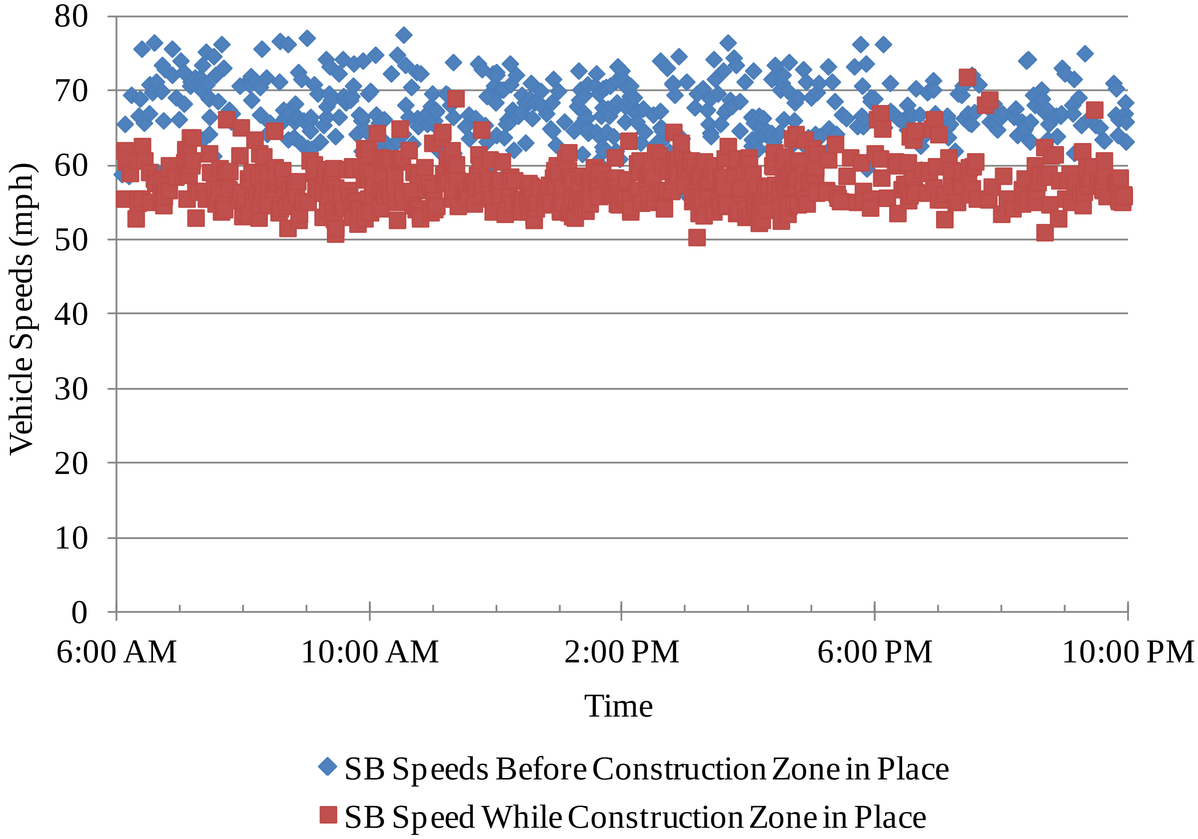


Figure 4.38: Southbound Speeds Before and After Construction Zone is in Place on Wednesday.

Before the construction zone is in place, the average northbound and southbound speed on a weekday is 67 mph. On the same day of the week after the construction zone is in place, the average northbound speed is 65 miles per hour and the average southbound speed is 58 miles per hour.

Figure 4.39 shows the travel times of vehicles traveling southbound through the construction zone before and during construction on Wednesday March 14, 2012, and Wednesday June 6, 2012.

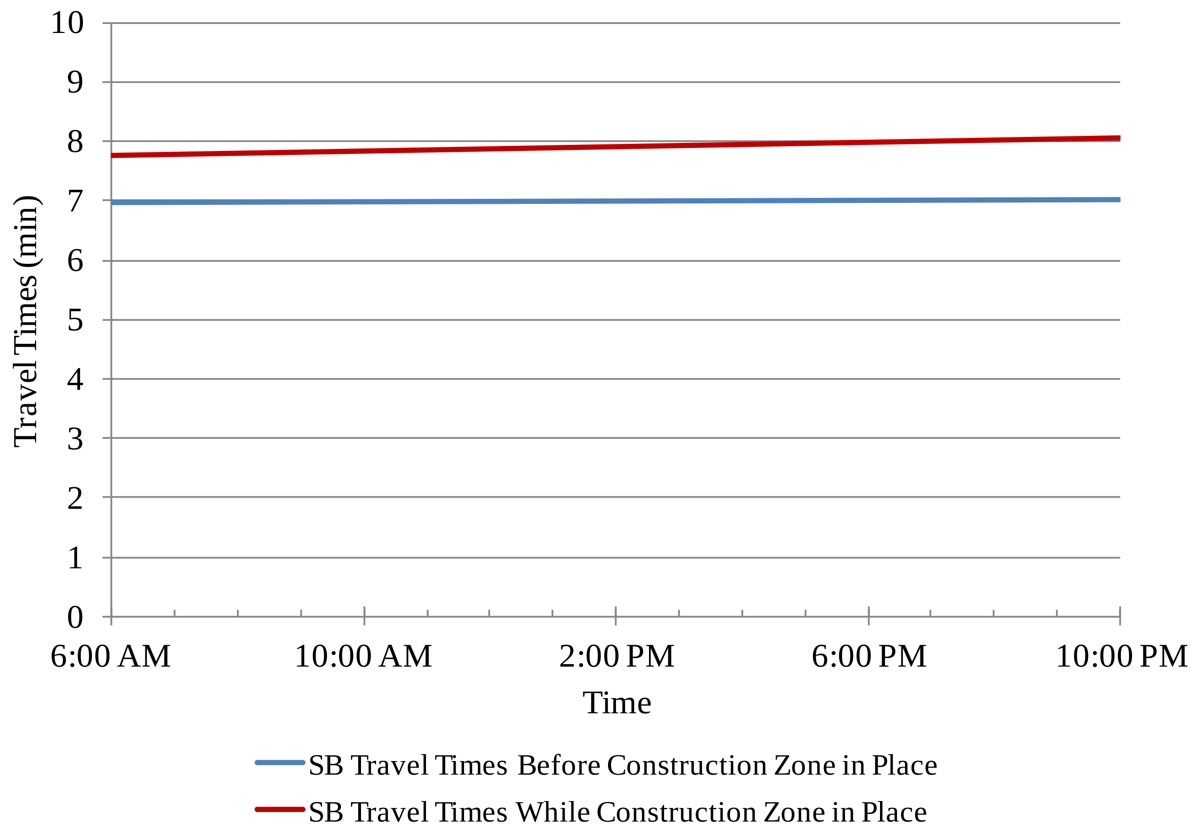


Figure 4.39: Southbound Travel Times Before and While Construction Zone in Place on Wednesday.

Before the construction zone is in place, the average travel time through the zone is 7 minutes; after the construction zone is in place, the average travel time is around 8 minutes. This shows that vehicles are spending a longer time in the construction zone, but with the decrease in speed, the vehicles do not have any delay due to decreased capacity.

The research team also compares travel speeds on the weekend from before and after the construction zone is in place. Figure 4.40 illustrates the southbound travel speeds on Saturday March 10, 2012, which is before the construction zone is in place, and the southbound travel speeds on Saturday June 2, 2012, after the construction zone is in place.

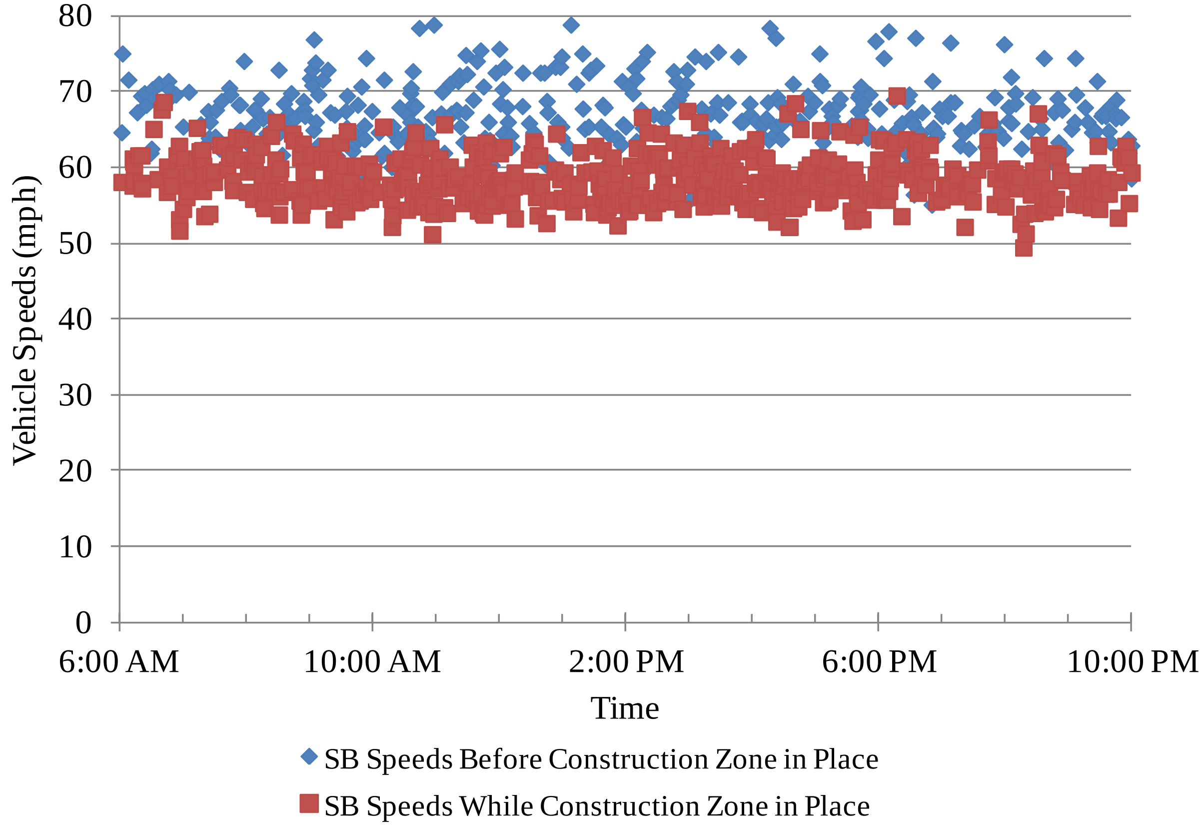


Figure 4.40: Southbound Speeds Before and After Construction Zone is in Place on Saturday.

On a Saturday before the construction zone is in place, the average speed of vehicles traveling from mile markers 158 to 151 is 68 mph in the northbound direction and 69 mph in the southbound direction. On a Saturday after the construction zone is in place, the average speed in the northbound direction is 67 mph and the average speed in the southbound direction is 60 mph.

On both the weekday and weekend, the vehicles in the northbound lane are traveling 2 miles per hour less after the construction zone is in place than before the construction zone is in place. This is not a large drop, but it indicates that even though the construction zone only encompasses the southbound lanes, the northbound travel speeds are decreased due to the activity. In addition, travel speeds in the southbound direction increase by 2 miles per hour more on Saturday than on Monday. This increase in speed may be a result of lower traffic volume on weekends, allowing traffic to be less congested especially during the morning and afternoon peak hours. This is also due to a change in motorist behavior on the weekends, as compared to weekdays.

Figure 4.41 shows the travel times of vehicles traveling southbound through the construction zone before and during construction on Saturday March 10, 2012, and Saturday June 2, 2012.

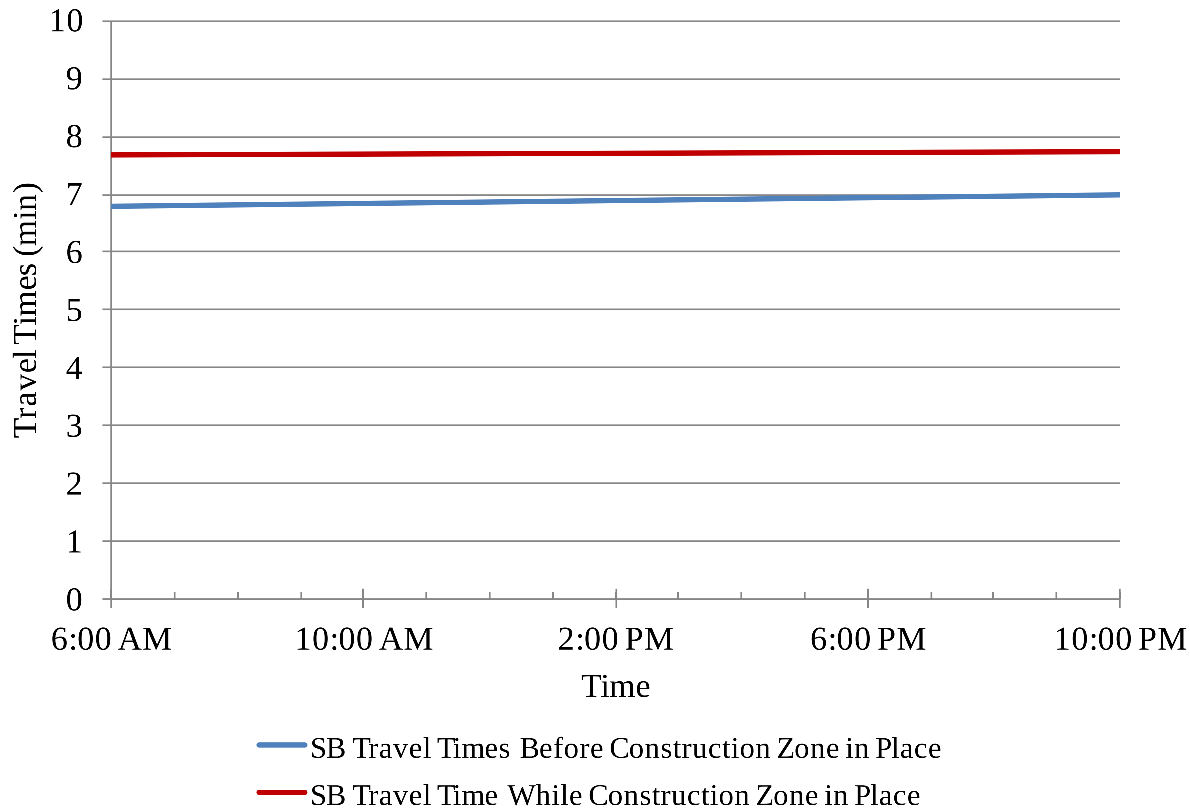


Figure 4.41: Southbound Travel Times Before and While Construction Zone in Place on Saturday.

The average travel time before the construction zone is in place is just less than 7 minutes; while the construction zone is in place, the average travel time is just less than 8 minutes. The travel times are slightly less than those found on Monday, further indicating a change in driver behavior on the weekends.

4.8 Summary of Findings

This section summarizes the results gathered throughout this section of the report. The first nodes are placed in the field in August 2011 and more nodes are added as the project progresses, including a solar powered node.

The hit counts of Bluetooth devices are used throughout the project. This includes matching Bluetooth devices, unique Bluetooth hits, and total Bluetooth hits. The research team found when comparing nodes on the shoulder and median in the same location, the node in the median has similar matches to the node north and south of the location, and the nodes on the shoulder have more matching hits in the direction of travel. In other words, the node on the southbound shoulder has more matching hits with the node to the south than the node to the north.

When comparing Bluetooth hits from daytime to nighttime, the research team found there are 66% fewer hits at night and 62% fewer matching Bluetooth hits at night. This indicates that nighttime is a good time to conserve power within the Bluetooth nodes. Another aspect of Bluetooth hits the research team evaluated is the quantity of matches within the construction zone. There are more matching devices from the nodes on the southbound shoulder than the nodes in the median. This is the result of the barrier walls limiting the range of the Bluetooth antennae, causing a decrease in devices recorded.

To determine the impact of interchanges, the research team utilized several node locations on either side of interchanges. The research team evaluated the number of matching hits from the node north and south of the interchange with the control node to the north and the control node to the south. The change in matches is compared to the ADT of the interchange road east and west of Interstate 71. The roads with a greater change in ADT also had the higher change in matching Bluetooth hits, indicating a greater number of vehicles exited or entered the highway at these locations.

The feasibility of using nodes with large spacing in an urban center is evaluated on Interstate 270 and Interstate 71 around Columbus. With the large distances and many interchanges between nodes, the amount of matching Bluetooth hits is decreased. In some cases, the resolution of the data is low enough that speed profiles are not discernible.

The research team focused on many incidents to determine hit counts, speeds, and detection times. Closely spaced nodes pick up the incidents, and the instability of traffic is clearly visible. As node spacing increases, the minimum speeds reached increases and the instability becomes less well defined. Even with nodes spaced over 30 miles apart, smaller incidents are still picked up between the nodes. The research team looked at detection times of incidents based on the distance of the node from the incident. The farther away the nodes are from the incident, the later the incident is detected. This is due to the fact that congestion takes a longer time to reach the nodes causing decreased speeds. To improve the time for incidents to be detected, the research team evaluated hit counts during incidents. When incidents occur, the number of total Bluetooth hits is much greater than the unique number of Bluetooth hits.

A work zone within the project area has been established during the study. The research team has placed several nodes within the zone to determine travel speeds and any congestion issues with the work zone. The travel speeds did not increase the longer the construction zone is in place. In addition, congestion is not an issue as traffic does not back up outside of the zone; this is true regardless of the time of day.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

The fifth chapter within this research report contains the conclusions and recommendations gathered from the project and is divided into four sections:

- Section One – Node Placement,
- Section Two – Node Spacing,
- Section Three – Bluetooth Technology Applications, and
- Section Four – Future use of Bluetooth Technology.

These sections provide suggestions for placing Bluetooth nodes in order to gather travel speeds and travel times, also discussed are several applications of Bluetooth technology and the future of Bluetooth data collections systems.

5.1 Node Placement

The research team developed two types of Bluetooth nodes for this project, battery powered nodes and solar powered nodes. For the battery powered node, the ideal placement is to mount the antennae to a pole at a level that is not obstructed by any objects such as guardrails or median dividers. However, when using a portable Bluetooth node contained in a case, such as the ones in this project, the node should be locked to a guardrail at an elevation above or at least level with the roadway. There should be as few obstructions as possible between the node and the roadway. An example of such a location is shown in Figure 5.1

Figure 5.1: Bluetooth Device Location.

In areas where a barrier wall is placed in the median to divide the sides of the highway or in construction zones where a barrier wall protects the work zone from traffic, nodes may need to be placed just off the shoulders. Figure 5.2 shows a work zone with a barrier wall limiting the range of a Bluetooth antenna.

Figure 5.2: Barrier Wall in Construction Zone Limiting Range of Bluetooth Antenna.

When placed near the shoulder, the node will collect more hits in that direction of travel. Depending on the resolution required, nodes may need to be placed in an area near the northbound and southbound shoulders. If it is not possible to place nodes near the median in these situations, the number of matching Bluetooth hits is reduced when the node is not placed in the median.

Under normal conditions with no barrier walls limiting signal strength of the antennae, the median is the best location for nodes. When placed in the median, the nodes record a more even number of matches from vehicles travelling northbound and southbound than a node placed on the shoulder. The nodes on the shoulder record more matches with the node in the direction of travel, that is the node near the southbound shoulder records more matches with the node to the south than the north and vice versa. If speed profiles in both directions of travel are desired, nodes placed in the median will provide more data points for each direction.

For this research project, portable Bluetooth nodes are used since the research team is more concerned with the speed of moving the nodes than the optimization of the individual nodes. A more permanent option including pole mount, external antenna, and solar powered battery is also developed and is shown in Figure 3.3 on page 16. A recommendation for employing both types of nodes is to use the portable nodes in various set-ups to find areas of reoccurring congestion and high incident areas and then deploy permanent nodes in these locations.

5.2 Node Spacing

During the project, the research team utilized a distance between nodes as small as 0.5 miles and as large as 26 miles. The average node spacing used during the project is 5.4 miles. This section is divided into four subsections evaluating different distances between nodes:

- Section One – Nodes Spaced Under Two Miles,
- Section Two – Nodes Spaced Two to Ten Miles,
- Section Three – Nodes Spaced Greater than Ten Miles, and
- Section Four – Recommended Spacing for Interstate 71.

5.2.1 Nodes Spaced Under Two Miles

The research team used many nodes spaced less than two miles apart. Nodes are placed close together in order to increase the resolution of the data collected. The closer the nodes are spaced, the variation in speeds become more visible. The Bluetooth nodes calculate space mean speeds, which is equal to the distance between the nodes divided by the time it takes a vehicle to travel between the nodes. With smaller distances between the nodes, the variations in speeds become more apparent. Figure 5.3 shows the speeds found between nodes spaced 0.7 miles apart.

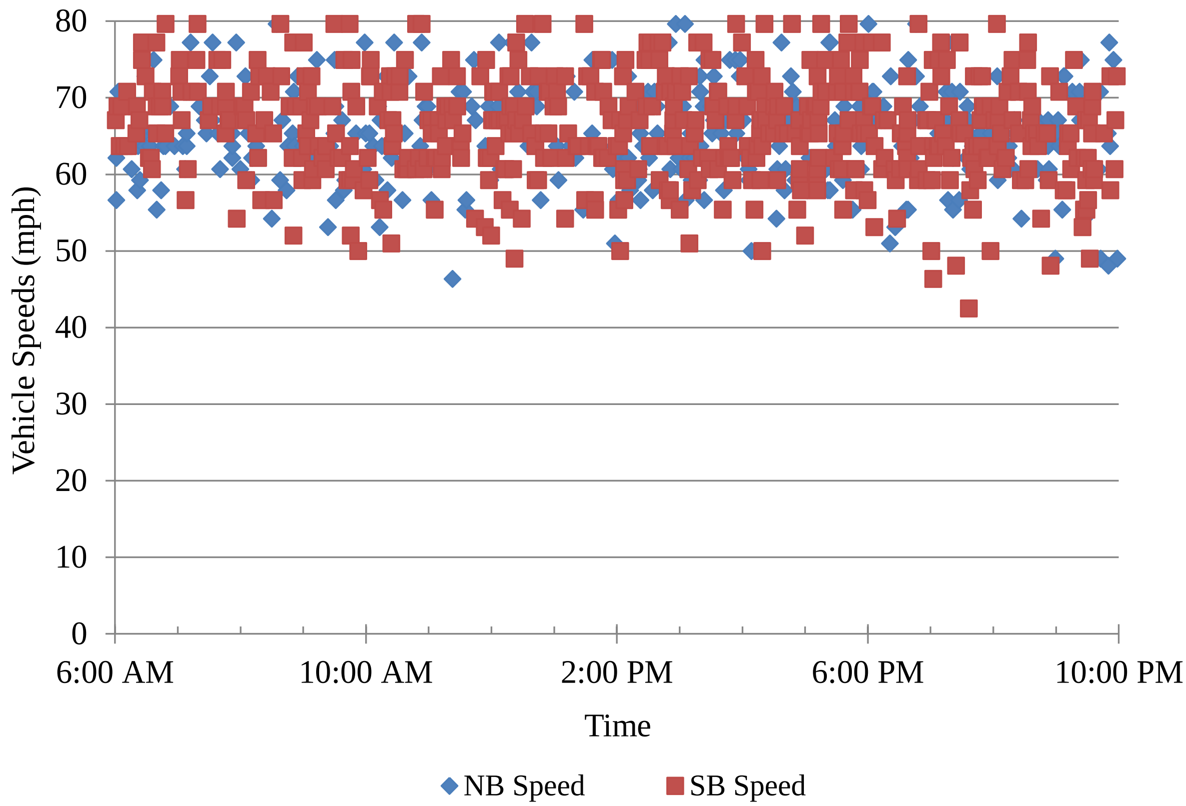


Figure 5.3: Travel Speeds between Nodes Spaced 0.7 Miles Apart.

With a small distance between nodes, the vehicle speeds are more spread out with the majority ranging from 55 to 75 mph. The resolution of data is greater with smaller distances, which is shown by the more scattered data points. With shorter distances smaller variations in speeds are captured on the Bluetooth nodes.

To show the difference in node spacing, Figure 5.4 shows the speeds between nodes spaced 1.9 miles apart.

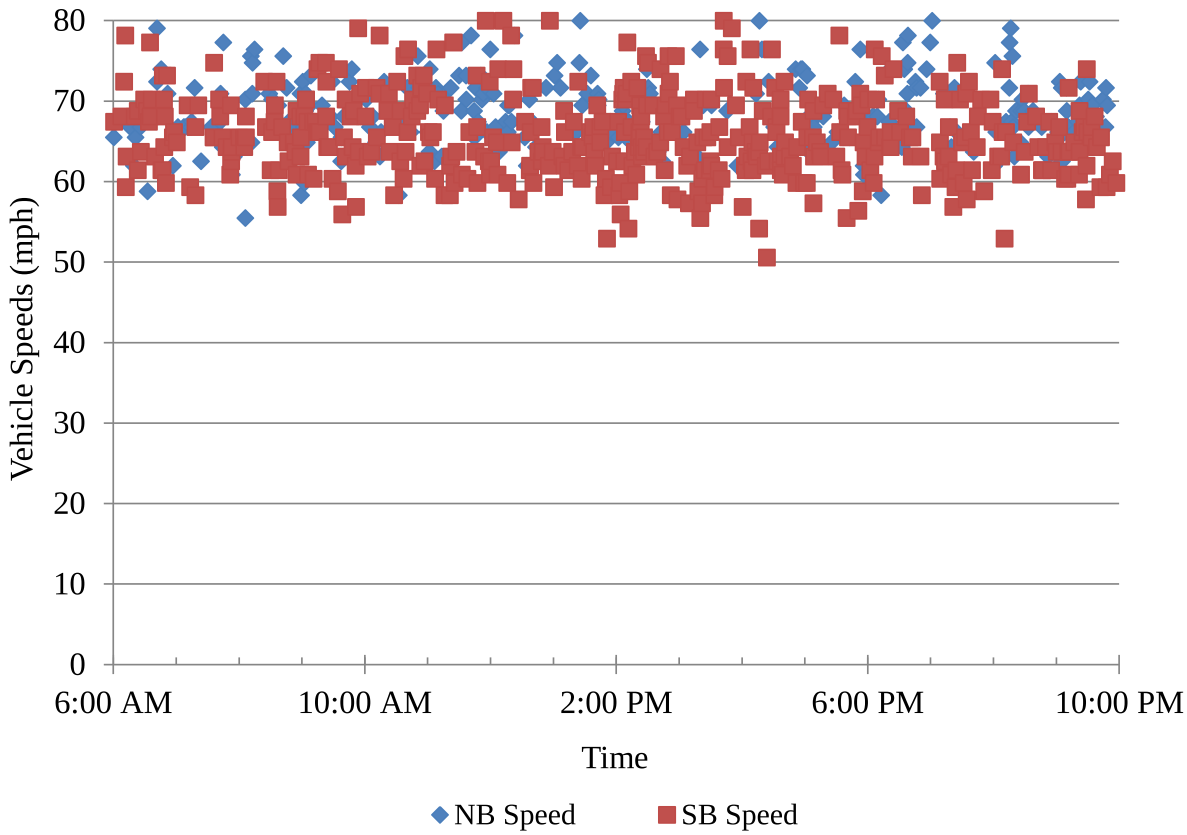


Figure 5.4: Travel Speeds between Nodes Spaced 1.9 Miles Apart.

In Figure 5.4, the band of travel speeds is smaller, but vehicles are still free to travel at speeds they chose. The majority of speeds range from 60 to 70 mph.

5.2.2 Nodes Spaced Two to Ten Miles

To determine the optimal distance between nodes, the research team places many nodes two to ten miles apart throughout the project. This spacing balances out the resolution of data with the cost of developing, deploying, and maintaining the Bluetooth nodes. Figure 5.5 shows the travel speeds between nodes spaced 9.3 miles apart.

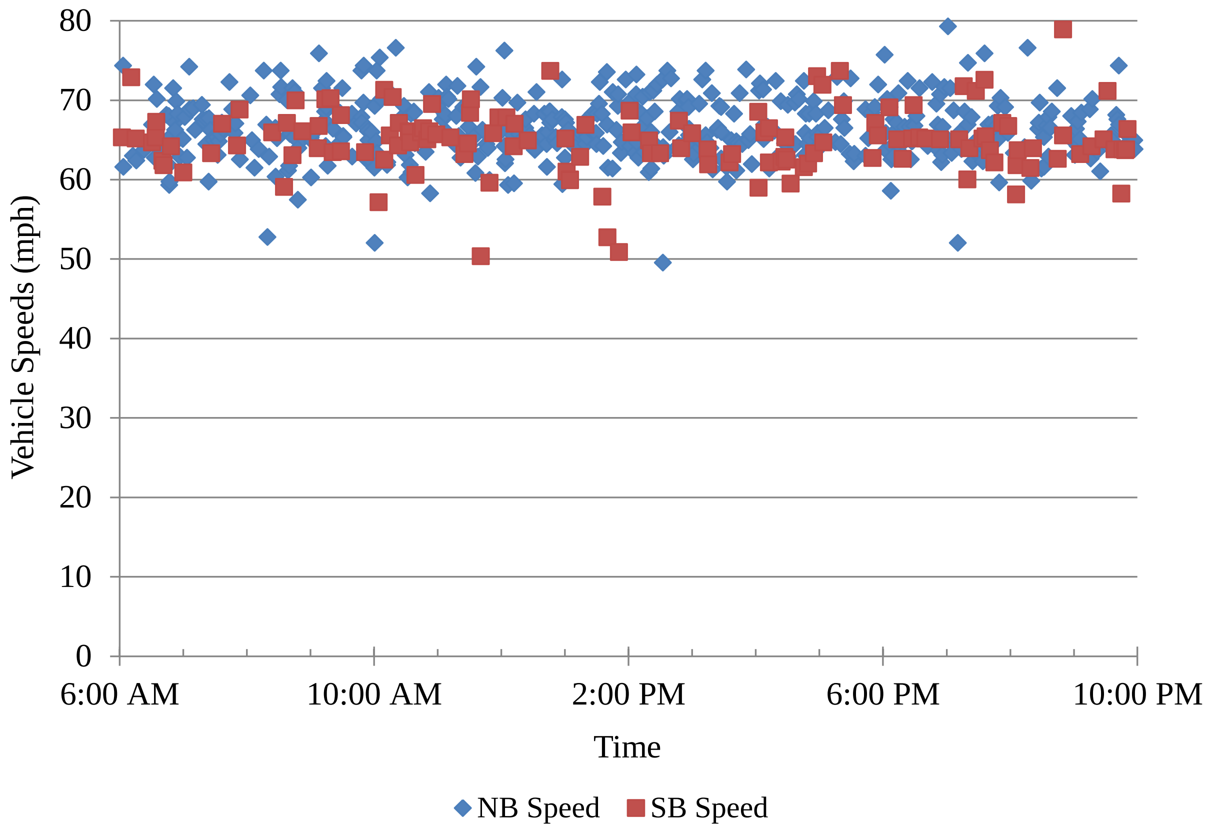


Figure 5.5: Travel Speeds between Nodes Spaced 9.3 Miles Apart.

The 9.3-mile spacing has a smaller band of travel speeds, indicating slightly less resolution of data. However, there is still a significant amount of data with nodes spaced two to ten miles apart.

5.2.3 Nodes Spaced Greater Than Ten Miles

The research team utilized nodes spaced greater than ten miles apart in the urban deployment around Columbus. In this deployment, there is a significant decrease in data points between nodes as shown in Figures 4.10 to 4.14. This is in part due to the amount of interchanges between the nodes. Few nodes are spaced greater than ten miles apart on Interstate 71. However, graphs are still created with distances further than ten miles apart by using nodes that are not next to each other, such as Figures 4.18, 4.20, 4.21, 4.22, and 4.26. In these situations, travel speeds are discernible and incidents are detected if they occur. As spacing increases, the resolution of data decreases, as seen in Section 4.6. The distance between the nodes is increased, and so is the time it takes a vehicle to travel between the nodes. This causes the differences in speeds to be less apparent, resulting in fewer variations in speed.

5.2.4 Recommended Node Spacing for Interstate 71

Based on the findings of this project, the research team develops the following recommendations on the node spacing for the entirety of Interstate 71. With several urban and rural areas along Interstate 71, the node spacing varies based on the environmental setting. In general, closer node spacing should be used in areas with reoccurring congestion, high incident areas, and urban areas.

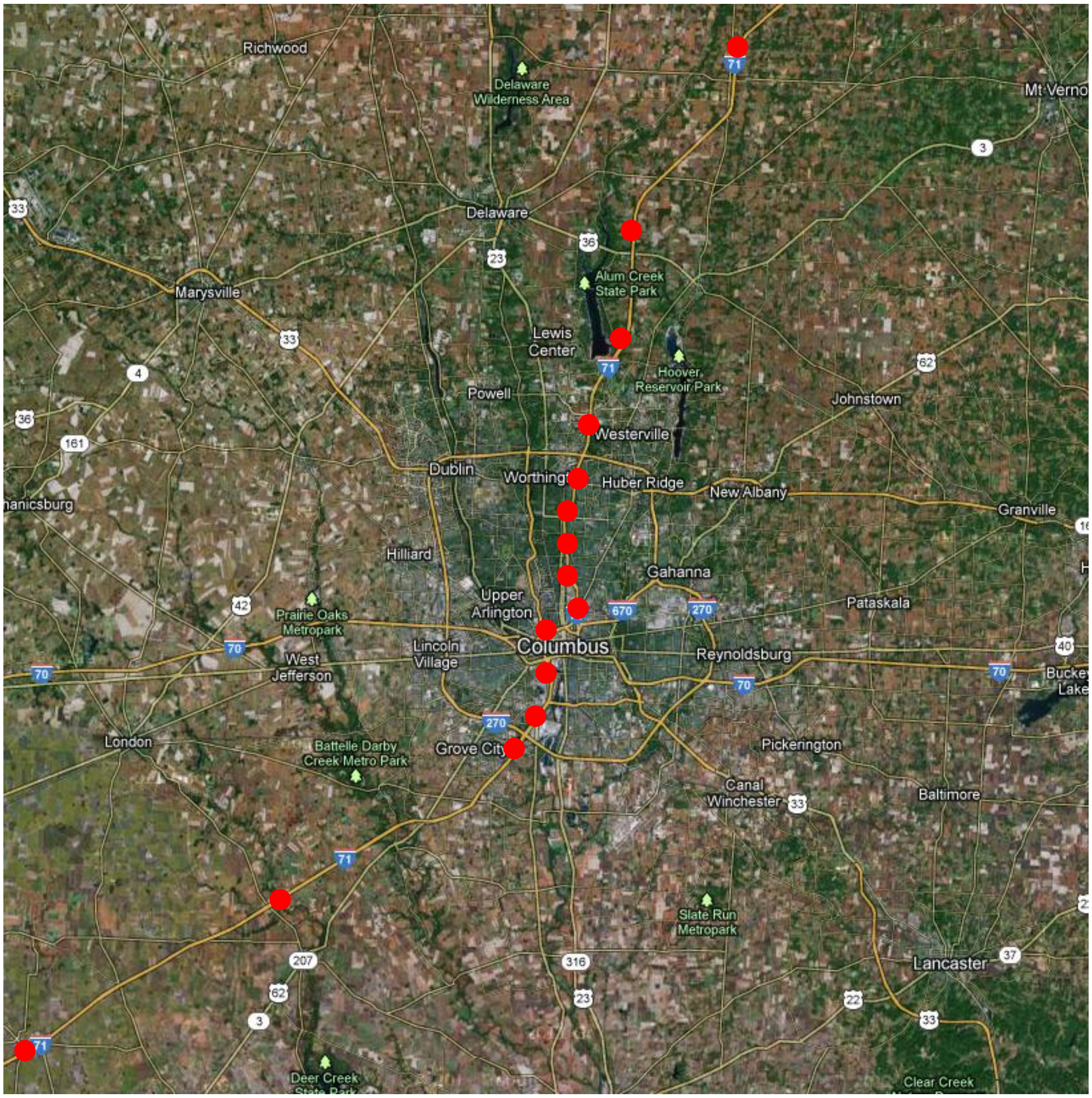
If a spacing of one mile per node is used for the entire length of Interstate 71, approximately 248 nodes will be required. While this will provide the highest level of resolution of data, it is unrealistic to place nodes that closely especially in rural areas. At the other extreme, nodes may be placed every 10 miles requiring approximately 25 nodes. This node spacing requires far fewer nodes, but the resolution of data will be far less. Also, the number of matching hits in urban areas will decrease, possibly to the point that speed profiles will not be determined. For a more realistic deployment strategy, the research team recommends shorter distances between nodes in urban areas and larger spacing in rural areas.

Starting at the northern portion of Interstate 71, which is in Cleveland, the nodes should be spaced at two miles apart from mile marker 247 to mile marker 226. Node spacing in this area is close because the high interchange density will cause a loss of matching hits at higher distances. Nodes should be spaced five miles apart from mile marker 226 to 218. This area is between the State Route 303 interchange and the State Route 18 interchange. There are fewer interchanges in this area but more than in rural areas. From mile marker 218 to mile marker 165, nodes spaced eight miles apart should be used. This is a more rural area with decreased interchange density. From mile marker 165 to mile marker 133, nodes should be placed ten miles apart due to the large distance between interchanges in this area.

The next urban area is in and near Columbus. From mile marker 132 to mile marker 119, nodes should be spaced five miles apart. This area is just north of the Interstate 270 loop around Columbus and has a higher amount of interchanges than the more rural areas. From mile marker 119 to mile marker 100, nodes should be placed every two miles, due to the frequency of interchanges. From mile marker 100 to mile marker 36, nodes should be placed every 10 miles since this is a rural area with very few interchanges.

From mile marker 36 to 19, near Cincinnati, nodes should be placed every five miles. From mile marker 19 to mile marker 1, nodes should be spaced two miles apart due to the higher interchange density in the urban area.

These distances are recommendations, and they do not take into account the need for necessary locations to attach nodes. In certain counties, bridges do not have guardrails in the median, eliminating these as potential locations to lock the nodes. However, distances near those recommended by the research team will provide the highest resolution of data in the urban areas while also providing adequate coverage in the rural areas and limiting the number of nodes required. A sample of possible node spacing in the Columbus area is shown in Figure 5.6.



Note: This image was retrieved from Goggle Maps on 7/18/2012 and modified to show the potential node locations around Columbus.

Figure 5.6: Sample Node Positioning in Columbus Area.

The red circles in this figure represent potential node placements on Interstate 71 in the Columbus area. Figure 5.6 gives a representation of the different distances between nodes in the rural areas outside the city and the urban area closer to the Interstate 270 loop.

5.3 Bluetooth Technology Applications

The research team identified three key applications for Bluetooth nodes, which are described in the following subsections:

- Section One – Vehicle Speeds and Travel Times,
- Section Two – Work Zone Analysis, and
- Section Three – Incident Detection.

5.3.1 Vehicle Speeds and Travel Times

The primary function of the Bluetooth nodes in this project is the determination of vehicles speeds and travel times. There have been nodes in the field collecting data used to determine travel speeds and travel times for nearly a year. The other applications grew from this initial objective.

5.3.2 Work Zone Analysis

The research team evaluated the feasibility of using Bluetooth nodes in construction zones and determined that the physical environment may be a limiting factor for more intrusive speed devices. Nodes need to be positioned in such a manner that the effective range of the Bluetooth antennae is not limited by barrier walls or other objects.

The nodes are used to determine travel times and travel speeds in the construction zone in the same manner as the rest of the project area. They are also used to determine if the capacity, using vehicle speeds and motorists' travel times as surrogate measures for capacity, of the work zone is sufficient. The research team found normal traffic patterns on the nodes before and when first entering into the construction zone, indicating that capacity is not an issue. This is evaluated during all parts of the day to determine if there are any differences during the morning and evening peak volume hours. If capacity is an issue, reoccurring congestion will occur daily at the nodes near the beginning of the construction zone.

5.3.3 Incident Detection

The research team identified many incidents, both small and large, that occur throughout the duration of the project. The minimum speeds and times when the incidents are detected all vary with node spacing. Also, congestion is evaluated on different segments farther from where the incident occurs to show the wave of congestion traveling backwards in traffic. Since it takes a longer time to detect incidents with the Bluetooth nodes than an instantaneous spot speed, the research team evaluated hit counts to determine if an increase occurs during incidents. There is an increase in total Bluetooth hits during times of congestion when compared to the unique Bluetooth hits. This indicates vehicles have a higher probability of recording multiple times on one node, since the vehicle is in the range of the antennae for a longer period of time. This improves the time of incident detection, since it may take several minutes for a vehicle to be recorded on two nodes and a travel speed to be determined.

5.4 Future use of Bluetooth Technology

Several factors affect the future use of Bluetooth data collection technology including laws prohibiting cell phone use and decreased discoverable times for cell phones. Table 5.1 shows the average number of matching Bluetooth devices per node for the duration of the project.

Table 5.1: Number of Matches per Node for Each Month of Project.

Month	Average Number of Matches per Node
August	7104
September	5428
October	15146
November	15072
December	9414
January	1179
February	23979
March	23389
April	30367
May	22860
June	38954

Note: July is excluded from this table because nodes are only in the field for the beginning of the month.

This table shows an increase in average number of matching Bluetooth devices per node, which is due in part to the field hardening of the system. It also indicates that a sufficient amount of data are collected in order to determine vehicles speeds and travel times, even with shorter discoverable times for Bluetooth devices.

Recent legislation in Ohio, Ohio Revised Code sections 4511.204 and 4511.205, prohibits texting while driving for adults and all cell phone use for minors. With this in mind, some hits will be lost by not allowing teen drivers to use cell phones. However, vehicles using

Bluetooth to pair cell phones with the audio system are becoming more common. This may also increase the use of Bluetooth headsets, which when turned on have a discoverable MAC address.

This research report proves that Bluetooth nodes are a viable technology to collect travel times and travel speeds under multiple configurations for extended periods of time. The resulting data may be used in several applications of interest to ODOT, including work zones and high incident areas.

CHAPTER VI

IMPLEMENTATION PLAN

The implementation plan developed from this research study is divided into eight sections, including:

- Section One – Recommendations for Implementation,
- Section Two – Steps Needed to Implement Findings,
- Section Three – Suggested Time Frame for Implementation,
- Section Four – Expected Benefits from Implementation,
- Section Five – Potential Risks and Obstacles to Implementation,
- Section Six – Strategies to Overcome Potential Risks and Obstacles,
- Section Seven – Potential Users and Other Organizations that May be Affected, and
- Section Eight – Estimated Costs of Implementation.

These sections will provide the best plan for implementation and the outcomes of utilizing the Bluetooth system developed from this research study.

6.1 Recommendations for Implementation

The research team recommends using the portable nodes developed in this study to determine areas with reoccurring congestion and high incident areas. Once these areas are located, a permanent node may be placed in the location. The permanent node consists of a pole mount for elevating the Bluetooth antenna and solar panel.

In section 5.2.4, a plan for deploying nodes throughout the length of Interstate 71 is developed. The basis of this plan is to place nodes closer together in urban areas, two miles apart, and further apart in rural areas, five to ten miles apart. This placement may be utilized on freeways throughout the state.

6.2 Steps Needed to Implement Findings

The main step required to implement these findings is to develop a user guide for the Bluetooth nodes and system. This guide will include steps to deploy nodes in the field, including ideal node placements and spacing. Also included will be maintenance recommendations for the Bluetooth nodes, including guidance on how frequently the batteries will need to be changed.

6.3 Suggested Time Frame for Implementation

The time frame for implementation of these results is relatively short. The Bluetooth nodes used in this study will be turned over with the conclusion of the project and may be implemented immediately based on placement suggestions made by the research team. If additional nodes are desired, additional time to order parts and build the nodes will be required. Also time for creating the user guide will be needed if this is also desired.

6.4 Expected Benefits from Implementation

The immediate results of this research project are the data presented within this research report. These data are also used to craft the suggestions for deploying the nodes in the future. These nodes may be used in determining if the capacity of work zones is adequate based on the traffic volume at various times of day. Incidents may be detected based on hit counts as presented in section 4.6. Also, the impact incidents have on the traffic may be analyzed post incident. These impacts include speeds after the incident and how far away the traffic is affected by congestion.

The long term benefit is that ODOT has a portable system capable of measuring travel speeds and travel times on segments of roadways of their choice over an extended period of time. With this portable system, ODOT may increase or decrease the resolution of data by adjusting the distances between nodes. This system may be used to evaluate all future construction zones to determine what changes if any need to be made to construction zones in the state.

6.5 Potential Risks and Obstacles to Implementation

Potential obstacles to the future use of Bluetooth nodes include the decreased discoverable time of newer cell phones. However, laws restricting cell phone use while driving, such as Ohio Revised Code sections 4511.204 and 4511.205, may decrease the quantity of Bluetooth hits recorded.

6.6 Strategies to Overcome Potential Risks and Obstacles

There is no way to estimate how long Bluetooth will be a relevant technology. While Bluetooth segment speeds are more accurate than spot speeds, the research team does not know how long Bluetooth technology will be utilized. Whereas side fire speeds radars may always record vehicles speeds.

6.7 Potential Users and Other Organizations that May be Affected

The potential users of this information will include the ODOT Office of Traffic Engineering. The motoring public may be affected in a positive manner by the outcomes of ODOT utilizing these systems. Affects to motorists may include increased incident detection times and improvements to work zones creating congestion.

6.8 Estimated Costs of Implementation

The final cost for implementation is based on the quantity of nodes required as well as if a user guide is required for further education on utilizing Bluetooth technologies.

CHAPTER VII

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