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Investigating the Effectiveness of Using Bluetooth Low-Energy Technology to Trigger In-Vehicle Messages in Work Zones

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December 2016

Research Project
Final Report 2016-38

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16. Abstract (Limit: 250 words)

In order to reduce risky behavior around workzones, this project examines the effectiveness of using in-vehicle messages to heighten drivers' awareness of safety-critical and pertinent workzone information. This investigation centers around an inexpensive technology based on Bluetooth low-energy (BLE) tags that can be deployed in or ahead of the workzone. A smartphone app was developed to trigger non-distracting, auditory-visual messages in a smartphone mounted in a vehicle within range of the BLE workzone tags. Messages associated with BLE tags around the workzone can be updated remotely in real time and as such may provide significantly improved situational awareness about dynamic conditions at workzones such as: awareness of workers on site, changing traffic conditions, or hazards in the environment. Experiment results indicate that while travelling at 70 mph (113 km/h), the smartphone app is able to successfully detect a long-range BLE tag placed over 410 feet (125 meters) away on a traffic barrel on a roadway shoulder. Additional experiments are being conducted to validate the system performance under different roadway geometry, traffic, and weather conditions.

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Investigating the Effectiveness of Using Bluetooth Low-Energy Technology to Trigger In-Vehicle Messages in Work Zones

FINAL REPORT

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- Roadway Safety Institute (RSI), University of Minnesota
- Center for Transportation Studies (CTS), University of Minnesota

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LIST OF ACRONYMS AND ABBREVIATIONS

AL	Administration Liaison
API	Application Programming Interface
AVG	Average
BLE	Bluetooth Low Energy
CEGE	Civil Environmental and Geo- Engineering
COTS	Commercial Off-The-Shelf
CTS	Center for Transportation Studies
DOT	Department of Transportation
DSRC	Dedicated Short Range Communication
FHWA	Federal Highway Administration
GATT	Generic Attribute Profile
GPIO	General Purpose Input/Output
GPS	Global Positioning Systems
I2C	Inter-Integrated Circuit
ITS	Intelligent Transportation Systems
MAC	Media Access Control
MnDOT	Minnesota Department of Transportation
MPH	Miles Per Hour
NB	North Bound
NEMA	National Electrical Manufacturers Association
OS	Operation System

RSI	Roadway Safety Institute
RSSI	Received Signal Strength Indication
RX	Receive
SD	Standard Deviation
SIG	Special Interest Group
SoC	System-on-Chips
SPI	Serial Peripheral Interface
TAP	Technical Advisory Panel
TI	Texas Instruments
TL	Techanical Laiason
TTS	Text to Speech
TX	Transmit
UART	Universal Asynchronous Receiver/Transmitter
UMN	University of Minnesota

EXECUTIVE SUMMARY

Achieving smarter work zones is one of the initiatives promoted by the Federal Highway Administration (FHWA) in the U.S. that uses innovative strategies to improve workzone safety and mobility. Many intelligent transportation systems (ITS) tools and applications have been developed and implemented to effectively mitigate traffic impacts caused by construction.

In an attempt to reduce risky behavior around work zones, this project examines the effectiveness of using in-vehicle messages to raise drivers' awareness of safety-critical and pertinent workzone information. The objective of this project is to investigate Bluetooth low-energy (BLE) tags that can be deployed in or ahead of work zones to provide in-vehicle warning messages. The BLE tags will trigger spoken and contextual messages in existing smartphones located in vehicles passing by the tag. The goal of this task is to develop a smartphone app to detect BLE tags in the environment and announce an audible message through the text-to-speech (TTS) interface on the phone.

Drivers often rely on signs along the roadway to be cautious and slow down as they approach the upcoming work zone. However, most workzone crashes are caused by drivers not paying attention. Our approach aims to design and test an in-vehicle workzone alert system that announces additional messages through the driver's smartphone. These messages would be triggered by passing near specific BLE tags in or ahead of the work zone and adjacent to the road. Our goal is to understand whether this type of additional warning message tailored to the individual driver's behavior can improve the situation awareness of drivers and their response to the work zone, particularly when there are workers on site and construction work is in progress.

This investigation centers around an inexpensive technology based on BLE tags that can be deployed in or ahead of the work zone. A smartphone app was developed to trigger non-distracting, auditory-visual messages in a smartphone mounted in a vehicle within range of the BLE workzone tags. Messages associated with BLE tags around the work zone can be updated remotely in real time and as such may provide significantly improved situational awareness about dynamic conditions at work zones such as: awareness of workers on site, changing traffic conditions, or hazards in the environment.

Experiment results indicate that while travelling at 70 mph (113 km/h), our smartphone app (called *Workzone Alert*) is able to successfully detect a long-range BLE tag placed over 410 feet (125 meters) away on a traffic barrel on a roadway shoulder. Several experiments were conducted to validate the system performance under different roadway geometry, traffic, and weather conditions.

The current system demonstrated that it is capable of providing in-vehicle messages for motorists approaching a work zone using a geo-fencing technique and the Bluetooth low-energy technology. Our experimental results indicated that communication between a smartphone and BLE tags at highway speed is feasible. In a subsequent phase of the study, we plan to: (1) incorporate the recommendations of in-vehicle message structure and content from a human factors study conducted by the HumanFirst Lab, and (2) conduct a pilot implementation with multiple participants to evaluate the effectiveness of using our system by providing in-vehicle workzone messages to drivers.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

According to work zone injury and fatality data published by the U.S. Federal Highway Administration (FHWA) in 2013, there were more than 67,500 crashes in work zones, resulting in 579 deaths and 47,758 injuries. More than 20,000 workers are injured in work zones each year, with 12% of those due to traffic incidents [1, 2]. Despite a trend towards fewer work zone crashes from 2011 to 2013, the number of estimated work zone injuries actually increased in 2013 [2].

Promoting amarter work zones is one of the initiatives promoted by the Federal Highway Administration (FHWA) in the US that uses innovative strategies to improve work zone safety and mobility. Strategies such as incident management, traffic control, work zone speed management, and use of Intelligent Transportation Systems (ITS) have been implemented by state Departments of Transportation (DOTs to improve mobility and safety by actively managing traffic through work zones [3]. Many ITS tools and applications have been developed and implemented to effectively mitigate traffic impacts caused by construction.

In recent years, challenges to work zone safety and mobility are exacerbated by the growing issue of distracted driving. The objective of this research is to investigate the effectiveness of using in-vehicle spoken messages to calibrate the drivers' understanding of the work zone in order to reduce risky behavior, associated with distraction.

1.2 OBJECTIVES

The objective of this project is to investigate Bluetooth Low Energy (BLE) tags that can be deployed in or ahead of work zones to provide in-vehicle warning messages. The BLE tags will trigger spoken and contextual messages in existing smartphones located in vehicles passing by the tag. The goal of this part of the project is to develop a smartphone app to detect BLE tags in the environment and to automatically announce audible message through the text-to-speech (TTS) interface on the phone.

1.3 LITERATURE REVIEW

Speed enforcement, speed advisory systems, or variable speed limit systems are often used for work zone speed management. For example, Mattox et al. [4] developed a speed-activated sign that informs vehicle drivers through a roadside visual cue if they were exceeding the speed limit in a work zone. They concluded that the speed-activated sign had a significant impact on lowering the speed of vehicles in work zones. Kwon et al. [5] implemented a two-stage speed reduction scheme at one of the

I-494 work zone bottlenecks in the Twin Cities metropolitan area in Minnesota. Despite the advisory speed limit, data collected from the field operation test indicated a 25–35% reduction of the average maximum speed difference. They also observed that drivers are less likely to comply with the variable speed limit if the posted speed is significantly different from the speed they would otherwise choose.

Automated traffic information systems have been proposed to improve safety by informing motorists with timely updates on travel time, delay, and queue length [6-11]. Ibrahim et al. [6] developed a hybrid work zone information system to notify motorists of travel delays and the starting location of congestion using dedicated short range communication (DSRC) technology and a portable changeable message sign. The simulation results suggested a DSRC market penetration rate ranging from 20 to 35% is needed for the system to work.

Haseman et al. [12] use Bluetooth probe data from multiple field collection sites to communicate travel delay times to the motoring public, assess drivers' diversion rates, and develop performance metrics for a state transportation agency to evaluate work zone mobility performance. They suggested that work zone travel time information provides a mechanism for assessing the relationship between crashes and work zone delay.

In addition, Bluetooth technology has been used in recent years as an inexpensive and reliable way to collect travel time information on roadways [13-15]. Anonymous travel time monitoring is performed by matching the Media Access Control (MAC) addresses of Bluetooth devices embedded on cell phones or GPS navigation devices. Bluetooth technology does not require line of sight, however its signal attenuation may be influenced by physical obstacles. Bluetooth travel time monitoring systems typically produce a matching rate in the 1% to 6% range [16, 17]. Dunlap et al. [18] use Wi-Fi and Bluetooth signals from transit riders' mobile devices to estimate origin and destination information, number of boarding and alighting, and passengers' waiting time at stops. Their results suggest that the Bluetooth and Wi-Fi signal based methodology is reliable at providing a robust and detailed source of data for transit planning and operations analysis.

Liao [19] previously developed a system using smartphone and Bluetooth technologies to help people with vision impairment navigate in or around a work zone. A smartphone app based on the Android operation system was developed for providing audible messages to people with vision impairment at a work zone. Global positioning system (GPS), Bluetooth technology, a text-to-speech (TTS) interface, and a digital compass already present on a smartphone were integrated with a digital map in the smartphone app. The smartphone app communicates with Bluetooth beacons installed near a work zone to help determine a user's location and provides corresponding navigational guidance instructions.

The latest Bluetooth technology, Bluetooth Low Energy (BLE) or Bluetooth Smart, has considerably reduced power consumption as compared to earlier versions. Low-cost BLE devices have enabled many applications using BLE tags and smartphones to locate or identify personal items or alert owners when personal belongings are left behind. All newer generations of smartphones are now equipped with BLE technology. For example, iBeacon from Apple uses BLE technology to identify locations that trigger an action on the iPhone. Many articles, including Ashford [20] quoted the Bluetooth Special Interest Group (SIG) that predicts that more than 90% of Bluetooth-enabled smartphones will support the low energy standard by 2018 [21].

BLE technology typically has a wireless communication range up to 50 meters based on line of sight, according to its specifications. Commercially available BLE tags are usually configured as non-paired and discoverable Bluetooth devices. A BLE equipped smartphone app can continuously scan for BLE devices in the environment. The BLE tag can "broadcast" its service name or other information. When the smartphone app receives the wireless signal from a BLE tag, it will also receive a Received Signal Strength Indicator (RSSI) value with that broadcasted message. The RSSI can be used to evaluate distance from the tag. Whether BLE tags can be used to alert drivers of high-speed vehicles about work zones ahead is one of the key questions being addressed here.

1.4 REPORT ORGANIZATION

This report is organized as follows. System architecture design and smartphone app development are presented in Chapter 2. Results from field testing and experiments are discussed in Chapter 3. Finally, summary and conclusion of our study are presented in Chapter 4.

Database schema design for the smartphone app and additional experiment results are included in Appendix A and B, respectively.

CHAPTER 2: SYSTEM DESIGN AND DEVELOPMENT

Drivers often rely on signs along the roadway to be cautious and slow down as they approach the upcoming work zone. However, most work zone crashes are caused by drivers not paying attention. Our approach aims to design and test an in-vehicle work zone alert system that announces additional messages through the driver's smartphone. These messages would be triggered by passing near specific BLE tags in or ahead of the work zone and adjacent to the road. Our goal is to understand whether this type of additional warning message tailored to the individual driver's behavior can improve the situation awareness of the driver and their response to the work zone, particularly when there are workers on site and construction work is in progress.

2.1 OUR APPROACH

The system architecture of the proposed in-vehicle work zone alert system is illustrated in Figure 2-1. The system includes a spatial database, a middleware for data transactions, a smartphone app, and BLE tags. A work zone database for BLE tags was incorporated into the system to include location, sign, message content, and other necessary information associated with BLE tags in a work zone. A subset of the BLE work zone database is accessed by the smartphone based on the vehicle's current location. The Bluetooth scanning service on the smartphone is automatically activated as drivers approach the work zone using geo-fencing and based on direction of travel. Appropriate warning messages are referenced to each BLE tag when detected by an in-vehicle device (e.g., a smartphone app).

An Android smartphone application, called *Workzone Alert*, was developed for testing and data collection. The app was configured to run as a background service on the phone when the phone is turned on. The app constantly monitors a vehicle's location using the GPS sensor on the smartphone and periodically updates its local work zone database (stored on the phone) within a 50 miles (80 km) radius of the current vehicle location from a work zone database server. A continuous Bluetooth scan is initiated when a vehicle enters a geo-fenced work zone. When a work zone BLE tag is detected, the app projects an audible message which is supported by a visual display associated with the tag. When multiple work zone BLE tags are sensed, messages associated with the nearest BLE tag, i.e., the tag with the strongest signal, are announced to the driver. The current app includes several features, such as vibration, alerting tone, data collection, and graphical display, for testing in our field experiments.

If the BLE tag is configured to alert based on speeding, the app will announce "*You are speeding*" in addition to the work zone message that will be provided. When the vehicle leaves the geo-fenced work zone, the Bluetooth scanning service is terminated. Current messages attached to each BLE tag were selected for functional testing only.

The final message structure and content will be determined from the results of a human factors study currently being conducted by the HumanFIRST Laboratory at the University of Minnesota.

On account of privacy concerns [20], our system architecture includes a 3-tier implementation that improves the data security of communication between client devices and the database. We reprogramed the firmware of two commercial off-the-shelf (COTS) BLE long-range tags from two different sources that meet our application requirements. The BLE tags operate in discovery mode with minimal power consumption. The BLE tag and a battery were packaged in a NEMA enclosure for field-testing. Our app only recognizes the BLE tags that are programmed for our application. Other Bluetooth devices within the detection range are ignored.

In order to reduce the effort required in placing the Bluetooth beacons at a work zone, another smartphone app was developed for use by the work zone deployment contractors. This app allows the staff in the field to submit a request for message update at the location where a BLE tag is installed. This app automatically determines current latitude/longitude location of the smartphone beacon, scans for Bluetooth beacons in the vicinity, and then lists identified Bluetooth tags. After the staff selects the BLE tag and an authorized security code, the smartphone app then submits the message update request to the BLE database through the wireless network. This approach allows engineers or staff who are responsible for the work zone operation to update the in-vehicle messages in a timely manner.

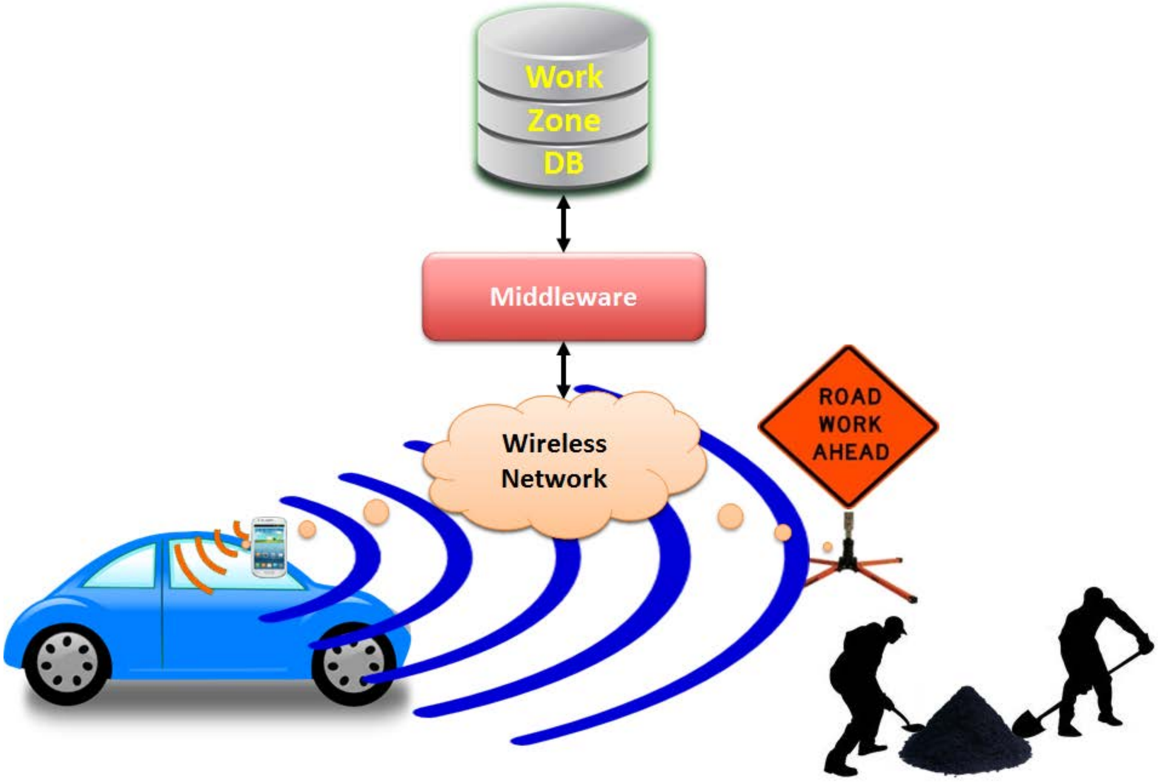

Figure 2-1 System Architecture of an In-Vehicle Work Zone Alert System

2.2 SMARTPHONE APP

In order to detect BLE tags while a vehicle is traveling at highway speed, we need to perform Bluetooth scans as frequently as possible. The Bluetooth scanning service on an Android smartphone can be configured in two different modes. In low power mode, the smartphone performs a Bluetooth scan every 4.4 second. Typical time between detections is about 100 ms (10 Hz) when the Bluetooth on an Android smartphone is configured in low latency mode. Table 1 lists the differences of scan rate and battery power consumption rate for the two Bluetooth scan modes. We use the low latency mode to detect BLE tags when a vehicle travels at highway speed. Further testing of the power consumption rate of the BLE modules were also conducted.

Table 1. Comparison of Bluetooth Scan Modes on Android Smartphones

Scan Mode	Low Power	Low Latency
Battery Level Change	-13%	-25%
Battery Drain Rate	268 mA	454 mA
Relative Battery Savings	41%	--
Typical time between detections	4400 ms	100 ms

2.2.1 App Design Requirements

A smartphone app for detecting Bluetooth Low Energy (BLE) modules was developed. The following design requirements were included in the software design.

1. Continuously scan Bluetooth Low Energy (BLE) devices in the environment when the smartphone app enters a geo-fenced zone (e.g., a work zone). The general Ray's algorithm (https://en.wikipedia.org/wiki/Point_in_polygon) will be implemented to determine whether a geo location with a given latitude-longitude exists inside a geo polygon (geofence) or not.
2. In addition to using geo-fence to trigger BLE scanning, the app will also compare the direction of traffic flow and direction of travel to ensure that a vehicle traveling though the overpass (or the underpass) of a geo-fenced work zone does not generate a false alarm.
3. Detect and identify BLE devices that belong to the work zone application. Note: The BLE tag was reprogrammed with our customized firmware.
4. Determine the nearest BLE device based on the received signal strength, if multiple BLE devices are detected.
5. Query messages based on the BLE MAC address from the work zone information database.
6. When a BLE module is detected, the phone can be configured to vibrate or beep or both, and announce the audible message thru the Text-to-Speech (TTS) interface.
7. Save collected data to local SD card for post analysis.
8. Block any incoming calls or switch the incoming call automatically to voicemail when speed is greater than a threshold (e.g., 5 MPH).

2.2.2 How the app works?

The app will use the GPS sensor on the smartphone to monitor a vehicle's location. The app will periodically update its local work zone database (stored on the phone) within a 50 mile radius of the current vehicle location from a work zone database server. As the vehicle moves toward the beginning of a work zone (using a geo-fencing technique), the Bluetooth service will initiate a continuous scan. When a work zone BLE tag is detected, the app will announce an audible message and/or provide a visual display associated with the tag. If the BLE tag is configured to alert speeding, the app will announce "*You are speeding*" in addition to the work zone message. When the vehicle leaves the geo-fenced work zone, the Bluetooth scanning service will be terminated. Please refer to the appendix for examples of the geo-fence database which defines the location of a work zone and the BLE tag database which defines the corresponding messages. Current messages attached to each BLE tag are selected for functional testing only. The final message structure and content will be determined from the results of a human factors study currently being conducted by the HumanFirst Lab.

The testing version of the app will allow users to select settings as illustrated in Figure 2-2. The deployment version of the app will be running in the background of the Android OS as a service. Some of the settings will not be enabled or available for the deployment version.

- The scanning period (testing version only) defines how long the phone will scan for BLE devices. For the deployment version, the app will trigger continuous BLE scans when a vehicle enters a geo-fenced work zone.
- The RSSI threshold (testing version only) setting allows the app to disregard detected BLE tags when the RSSI value is less than a specified threshold. That is, the app will ignore BLE tags if it's too far away.
- The vibration option enables the phone to vibrate for 2 seconds when a BLE tag is detected.
- The warning sound option will broadcast a tone on the phone for 2 seconds when a BLE tag id is detected. The vibration and alerting tone, when both options are selected, will start at the same time. They both are asynchronous procedureal calls which allow the vibrating effect and warning sound features to be independent of each other.
- The incoming/outgoing call option will disable the telephone service on the phone when a vehicle is traveling over a limit (currently, the limit is set at 5 MPH). That is, both outgoing calls and incoming calls are blocked if the vehicle's speed is above 5 MPH. Similarly, the driver won't be able to read the incoming message or send a text message if the vehicle's speed is over 5 MPH.
- The data collection option will collect the phone's GPS coordinate and speed when a BLE tag is detected for testing and data analysis.
- The display visual alert option will show a corresponding work zone image/sign on the screen of the smartphone if needed. See Figure 2-3 as an example. An image file can be assigned to a particular BLE tag in the cloud database.

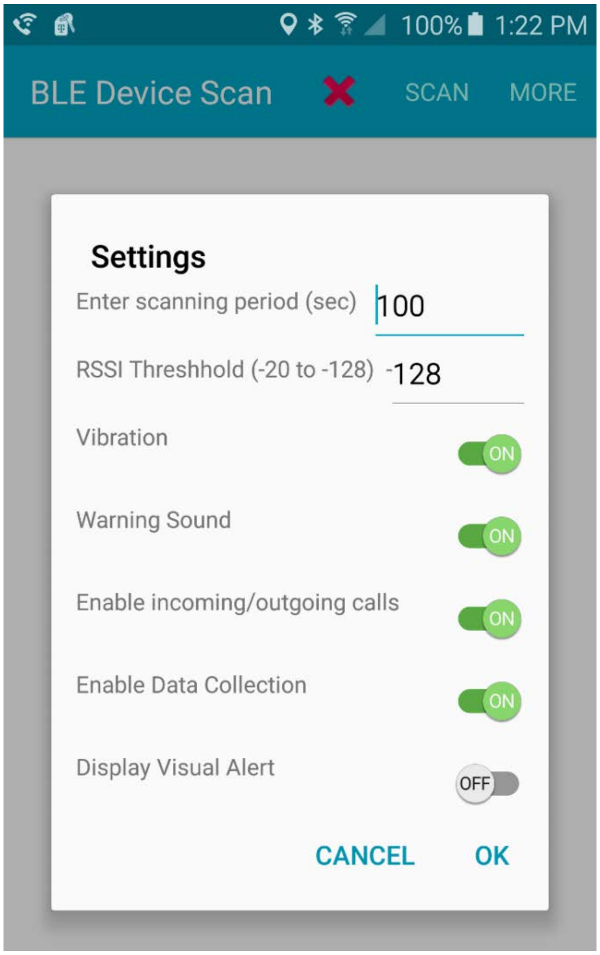

Figure 2-2 Interface to Change Users Settings

Figure 2-3 Display of a Work Zone Alert Display

2.3 BLUETOOTH LOW-ENERGY BEACON

We purchased and reprogramed the firmware of two commercial off-the-shelf (COTS) BLE long range modules from two different sources that meet our application requirements. The BLE modules are operating in discovery mode with minimal power consumption around 30 mA. As displayed in Figure 2-4, the BLE module and a battery were packaged in a NEMA enclosure for field testing. The size of the NEMA enclosure is 3.5” W x 4.5” L x 2.25” H. Our app will only recognize the BLE tags that are programmed for our application. Other BLE tags within the detection range will not be considered by our app.

Figure 2-4 A BLE long-range module with battery packaged in a NEMA enclosure

2.3.1 BLE Module Programming

We modified the firmware of the BLE module using the CC debugger (as shown in Figure 2-5) from Texas Instrument (http://www.ti.com). The CC Debugger is a small programmer and debugger for the TI Low Power RF System-on-Chips (SoC) including the BLE devices. The customized BLE firmware allows our smartphone app to recognize workzone specific BLE modules and ignore the other BLE devices in the environment. The CC debugger user's guide is available at http://www.ti.com.cn/cn/lit/ug/swru197h/swru197h.pdf.

Figure 2-5 TI CC Debugger

We used the BGScript language provided by from BlueGiga (https://www.bluegiga.com/en-US/) to program the firmware of each BLE module. BGScript is a scripting language intended for programming of simple applications. BGScript applications can be used to automate application functionalities such as opening a connection, listening for General Purpose Input/Output (GPIO) interrupts, and even for reading and writing data via interfaces such as Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI), Inter-Integrated Circuit

(I2C) or GPIO [22]. Each BGScript xml file contains tags that define inputs files (Generic Attribute Profile (GATT), hardware, script usb_main) and an image output file. An example of the BGScript project file is illustrated in Figure 2-6. Additional programming guide, please refer to the BlueGiga software web site (https://www.bluegiga.com/en-US/products/software-bluegiga-bluetooth-smart/).

```xml
<?xml version="1.0" encoding="UTF-8"?>
<project>
    <device type="ble121lr-m256k" />
    <gatt in="gatt.xml" />
    <hardware in="hardware.xml" />
    <script in="script.bgs" />
    <image out="out.hex" />
</project>
```

Figure 2-6 Sample BGScript Project File

A BGBuild.exe command from the BGScript software is used to compile the codes and generate the BLE firmware image (as illustrated in Figure 2-7).

```
Command Prompt

E:\Chenfu\BLE Project\BGScripts\iBeacon_BLE121LR_firmware>e:\Bluegiga\ble-1.3.2-
122\bin\bgbuild.exe project.xml

RAM Memory
-------------------------------------------------
Core RAM end                      @ 0x00a44    2628
Top of RAM                        @ 0x01f00    7936
RAM left for data                 = 0x014bc    5308
Attribute RAM                     - 0x00000       0
Connections                     1 - 0x00196     406
Script Variables                  - 0x00026      38
RAM for packet buffers        124 - 0x012e4    4836

Flash Memory
-------------------------------------------------
Core flash reserved               @ 0x18000   98304
Top of flash                      @ 0x3f800  260096
Flash left for data               = 0x27800  161792
Common configuration              - 0x00070     112
16 bit UUIDs                      - 0x00018      24
128 bit UUIDs                     - 0x00000       0
Attribute database                - 0x0006c     108
Constant attributes data          - 0x000a2     162
BGScript                          - 0x0015f     351
Flash for PS Store             78 - 0x27000  159744

E:\Chenfu\BLE Project\BGScripts\iBeacon_BLE121LR_firmware>_
```

Figure 2-7 Compile BGScript

The compiled BLE firmware can be loaded to the BLE devices using the flash programmer tool (see Figure 2-8) provided by the TI or using the BLE SW update tool (see Figure 2-9) from the BlueGiga.

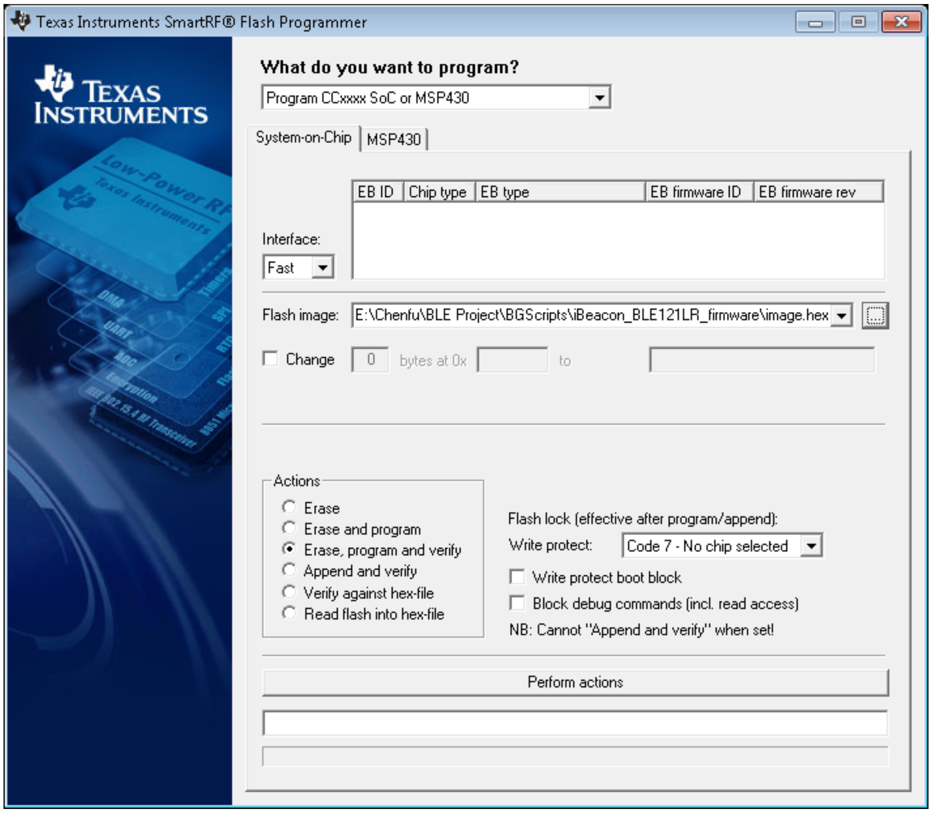

Figure 2-8 TI SmartRF Flash Programmer Interface

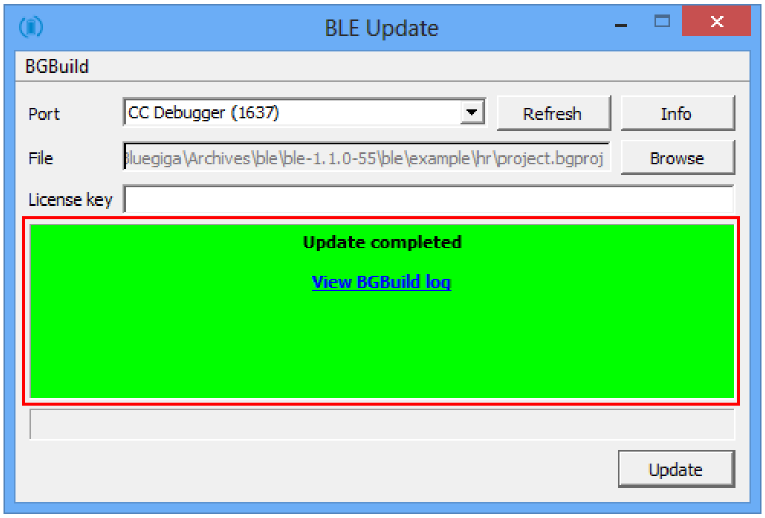

Figure 2-9 BlueGiga BLE Software Update Tool

2.3.2 BLE Module Testing

We first evaluated the BLE signal strength detected by different smartphones. Figure 2-10 and 2-11 display the RSSI values over time measured by Samsung Galaxy S5 and S6 smartphones when a BLE module was placed at an equal distance between the phones. The RSSI signal received by the S5 smartphone (-68.4 dBm) is slightly higher than the RSSI signal received by the S6 phone (-70.0 dBm).

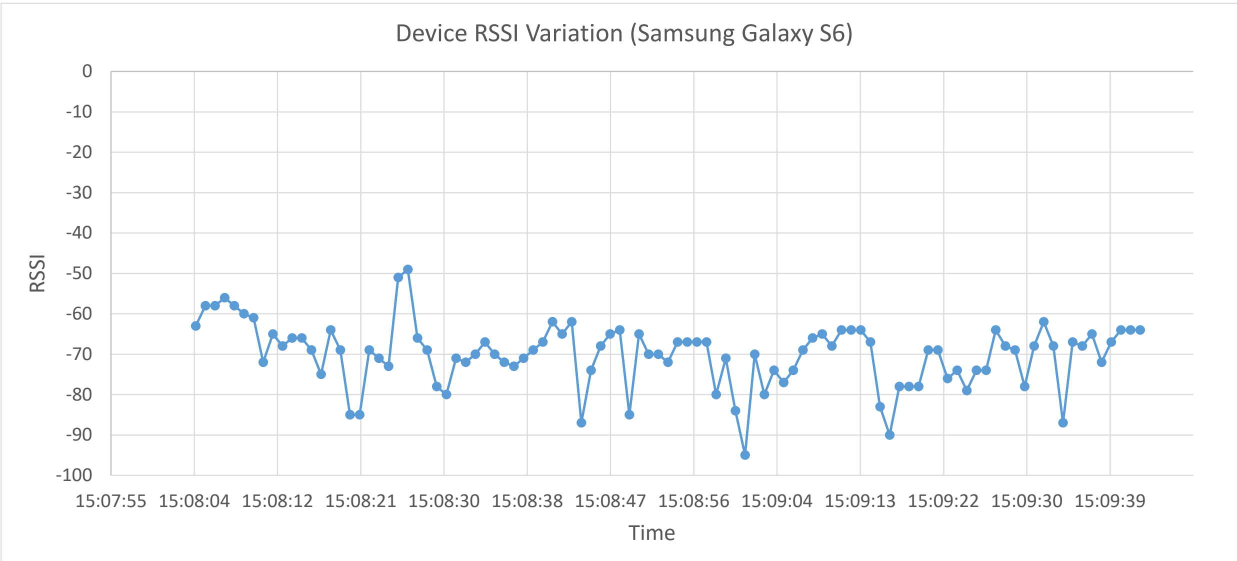

Figure 2-10 RSSI Variation of a Samsung Galaxy S6 Phone (AVG=-70.0, SD=7.9)

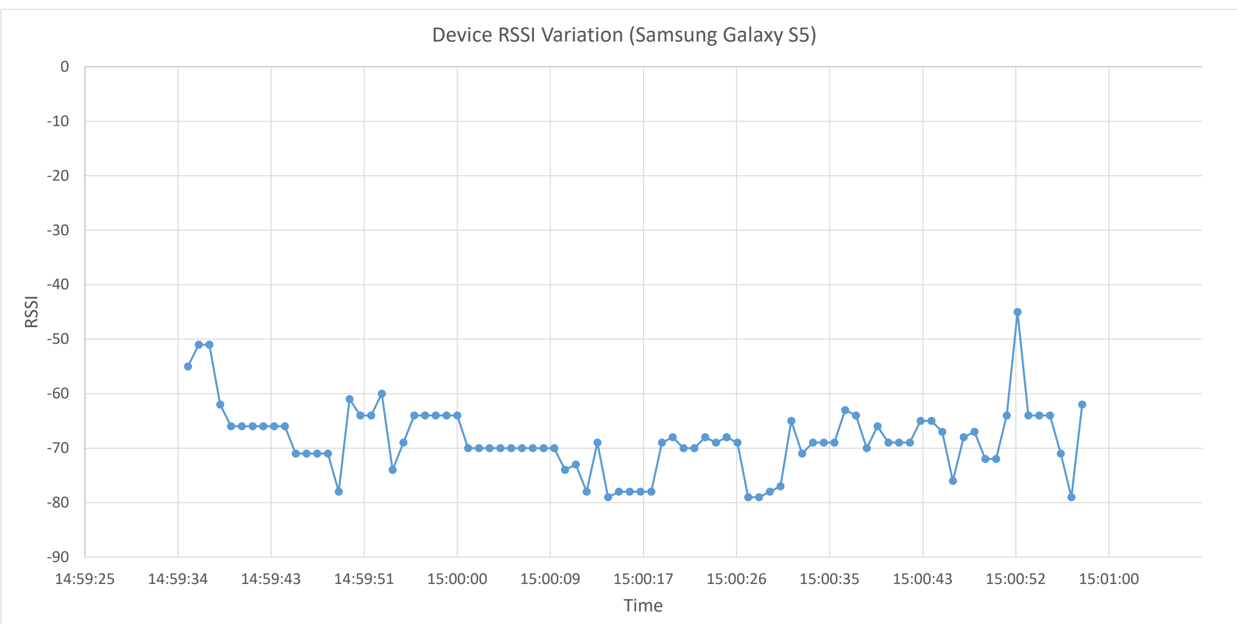

Figure 2-11 RSSI Variation of a Samsung Galaxy S5 Phone (AVG=-68.4, SD=6.3)

In addition to the RSSI signal strength comparisons, we compared the detection range of two BLE long range modules (from Ambient Sensors and BETZTechnik) when a vehicle was traveling at different speeds (30 to 80 MPH). Figure 2-12 displayed the results of RSSI detection range at different speeds. The BLE module from Ambient Sensors has a better detection range (60 m longer on average) than the BLE module from BETZTechnik. For each sensor, the detection range and speed relationship is not necessarily negative linear. The fitted R square values for both BLE modules are relatively small (less than 0.1).

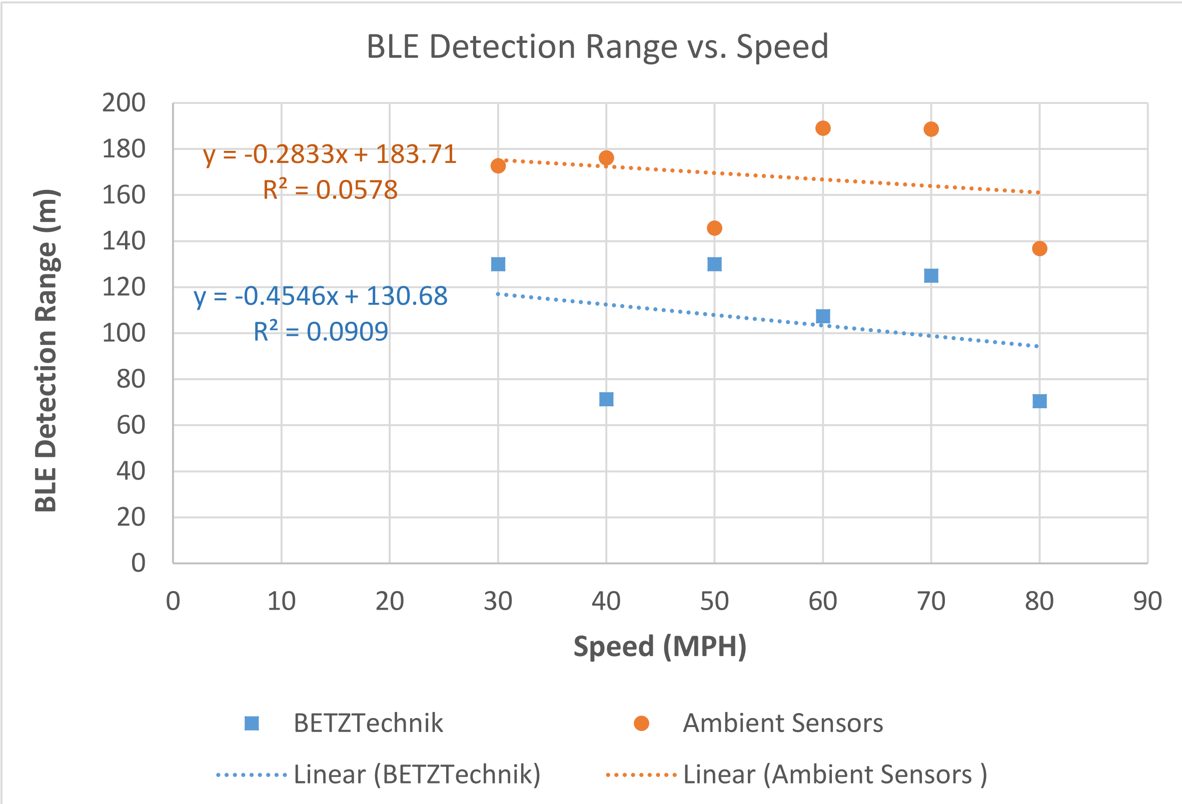

Figure 2-12 BLE Detection Range versus Speed

CHAPTER 3: EXPERIMENT AND DATA ANALYSIS

In order to reduce risky behavior around work zones, this project examines the effectiveness of using in-vehicle messages to heighten drivers' awareness of safety-critical and pertinent work zone information. The investigation centers around an inexpensive technology based on Bluetooth Low Energy (BLE) tags that can be deployed in or ahead of the work zone. A smartphone app was developed to trigger non-distracting, auditory-visual messages in a smartphone mounted in a vehicle within range of the BLE work zone tags. Messages associated with BLE tags around the work zone can be updated remotely in real time and as such may provide significantly improved situational awareness about dynamic conditions at work zones such as: awareness of workers on site, changing traffic conditions, or hazards in the environment.

We conducted several experiments at different speeds and locations to evaluate the robustness of the detection of BLE tags. We also implemented a geo fencing technique to automatically trigger Bluetooth scanning when a vehicle approaches a work zone. Selected experiment results are discussed in the following section. A TAP meeting was scheduled on 4/18/2016 to discuss results from task #1 to #3.

Our field experiment parameters include,

- Test the system at different speeds,
- Trigger Bluetooth scanning automatically when a vehicle enters a geo-fence zone,
- Test different mounting locations of BLE tags (height, orientation, etc.),
- Test different mounting locations of Smartphone (dash, seat, etc.) in a vehicle,
- Examine the detection rate when a BLE module is blocked by nearby trucks or vehicles, and
- Conduct experiments under different weather conditions (rain, snow, temperature, etc.).

3.1 EXPERIMENTS AND DATA ANALYSIS

We conducted experiments on a residential street (traveling at 45-50 MPH) and at the MnROAD facility (traveling up to 70 MPH) by placing a traffic barrel on the shoulder of a roadway. The BLE module was placed on top of the barrel with its antenna facing toward the incoming traffic as shown in Figure 3-1, or on a lamp post (Figure 3-2) about 8 ft above the ground for our experiments. A smartphone running our work zone alert app is mounted near the middle of the dashboard of a minivan as illustrated in Figure 3-3.

Figure 3-1 Placement of a Bluetooth Low-Energy Module on a Traffic Barrel

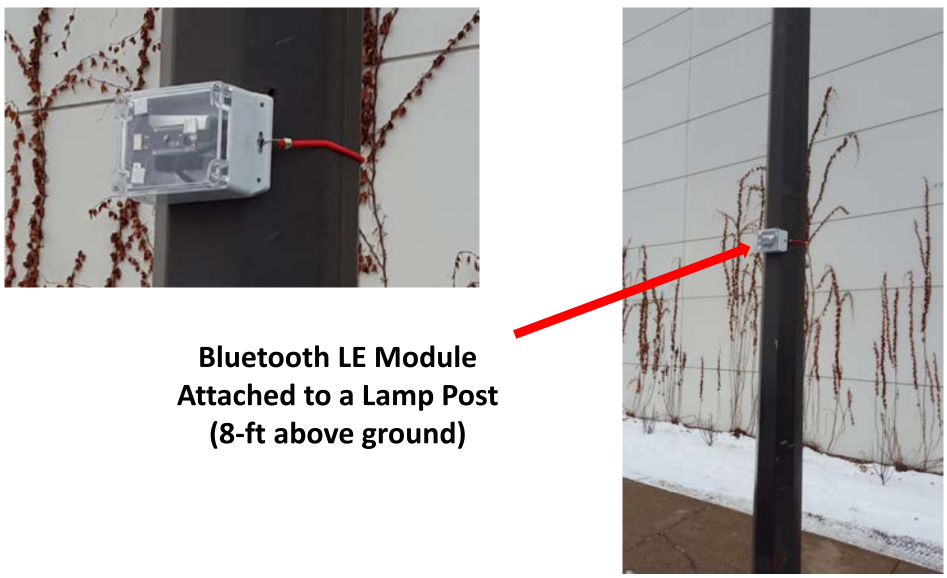

Figure 3-2 Placement of a Bluetooth Low-Energy Module on a Lamp Post

Figure 3-3 Placement of a Smartphone in a Minivan

Experiment results indicated that while travelling at speeds up to 70 MPH, the smartphone app is able to successfully detect a long-range BLE tag placed more than 100 m away on a traffic barrel on a roadway shoulder for experiments #1 to #5. To validate the system performance in a real work zone setting, experiment #6 was conducted on I-35E NB near County Road E East in Vadnais Heights, MN using a passenger vehicle. A long-range Bluetooth tag was mounted on a speed limit sign. Results from each experiment are described as follows.

Experiment 1:

As illustrated in Figure 3-4, a test vehicle (Toyota Corolla) travels at 45 MPH on a residential street northbound from the starting point toward a BLE module placed on a traffic barrel on the shoulder of the test roadway. The app starts recording the GPS coordinates when the BLE module is detected. The plot shows the speed profile of the test vehicle passing by the BLE module at 1:09:05 pm. The estimated range of Bluetooth detection at 45 MPH is about 160 meters.

Experiment 2:

As illustrated in Figure 3-5, a test vehicle (Toyota Corolla) travels on a county highway at 55 MPH from the green circle dot in the northbound direction toward a BLE module placed on a traffic barrel. The test app only logs the GPS latitude/longitude coordinates when the BLE module is detected. The plot shows the speed profile of the test vehicle passing by the BLE module around 1:21:41 pm. The estimated range of Bluetooth detection at 55 MPH is about 150 meters.

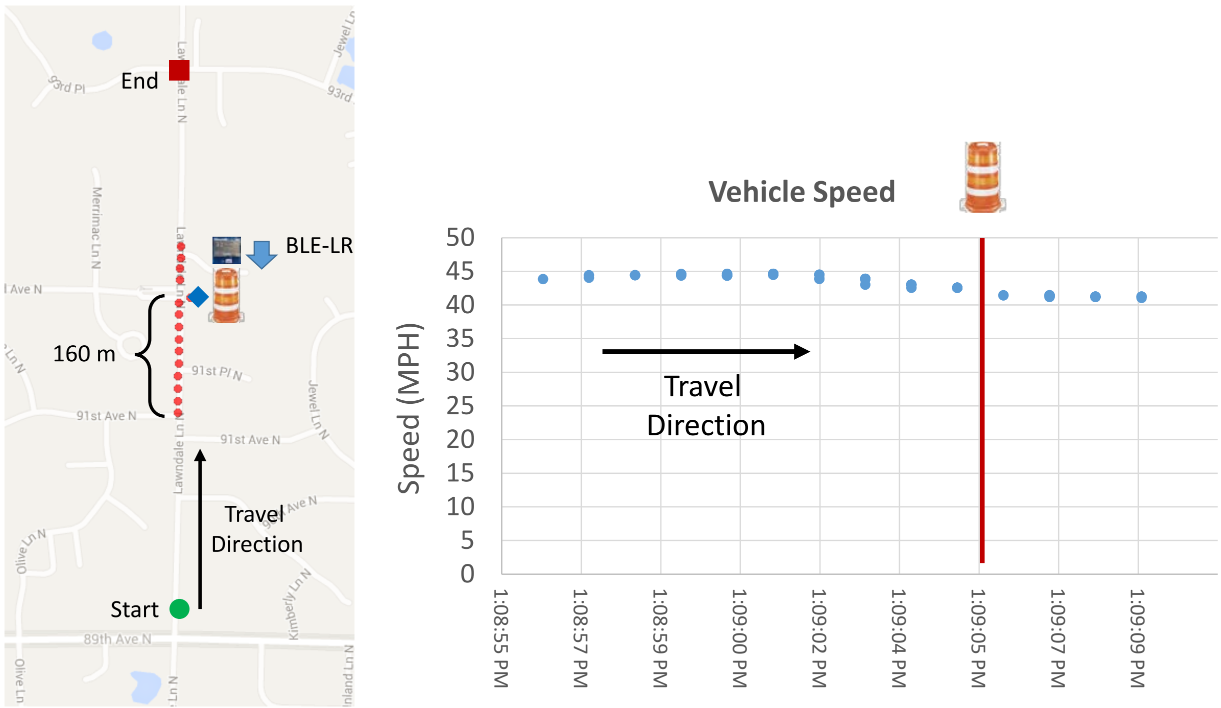

Figure 3-4 Illustration and Results of an Experiment on a Local Street at 45 MPH

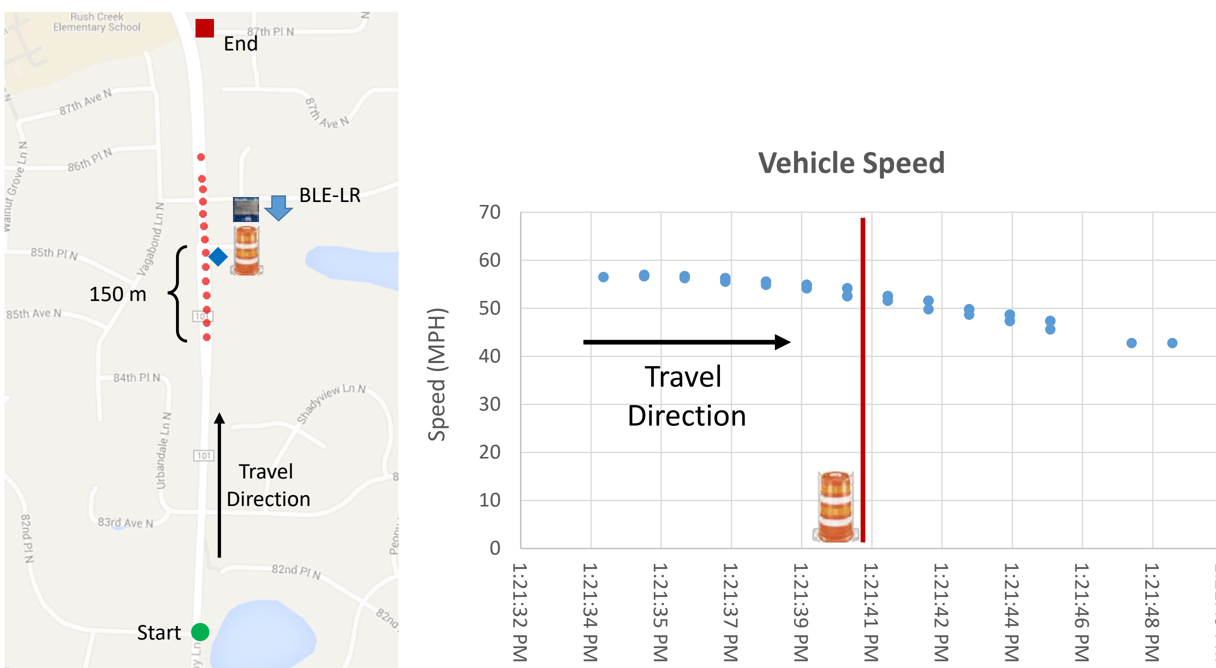

Figure 3-5 Illustration and Results of an Experiment on a Local Street at 55 MPH

Experiment 3:

As illustrated in Figure 3-6, a test vehicle (Toyota Corolla) travels at 70 MPH on the MnROAD test facility in Albertville, MN. The test vehicle travels in the inner loop (in the northwest direction) toward a BLE module placed on a traffic barrel at the shoulder of the MnROAD. The smartphone app records the GPS latitude and longitude coordinates when the BLE module is detected. The plot in Figure 6 shows the speed profile of the test vehicle passing by the BLE module around 9:37:51 am. The estimated Bluetooth detection range at 70 MPH is about 125 meters.

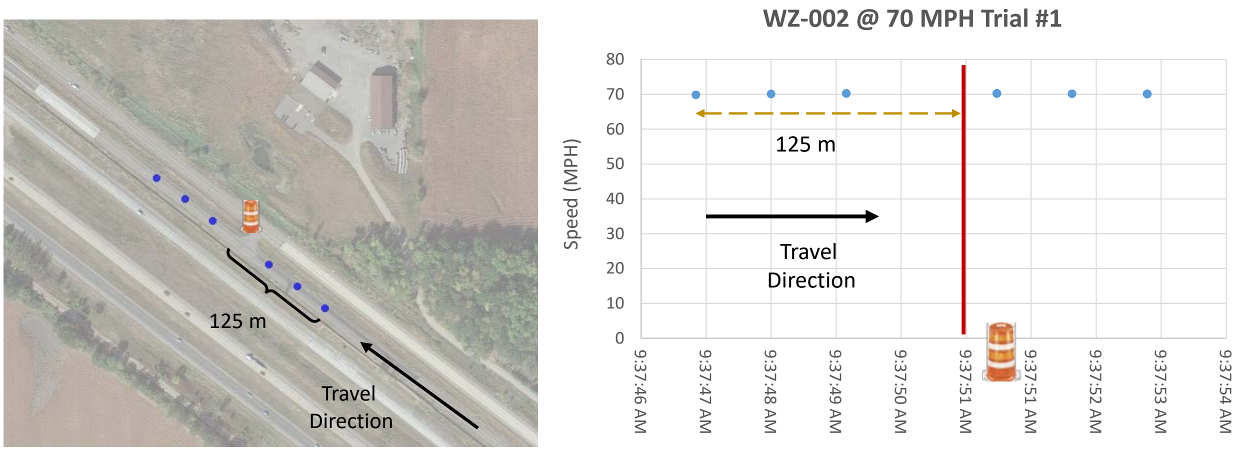

Figure 3-6 Illustration and Results of Experiment at 70 MPH on MnROAD

Experiment 4:

As illustrated in Figure 3-7, a minivan (Toyota Sienna) travels at 50 MPH on a residential street northbound from the starting point toward the BLE module on a winter day in January 2016. The app starts recording the GPS coordinates when the BLE module is detected. The plot shows the speed profile of the test vehicle passing by the BLE module at 11:42:57 am. The estimated range of Bluetooth detection at 50 MPH is about 172 meters.

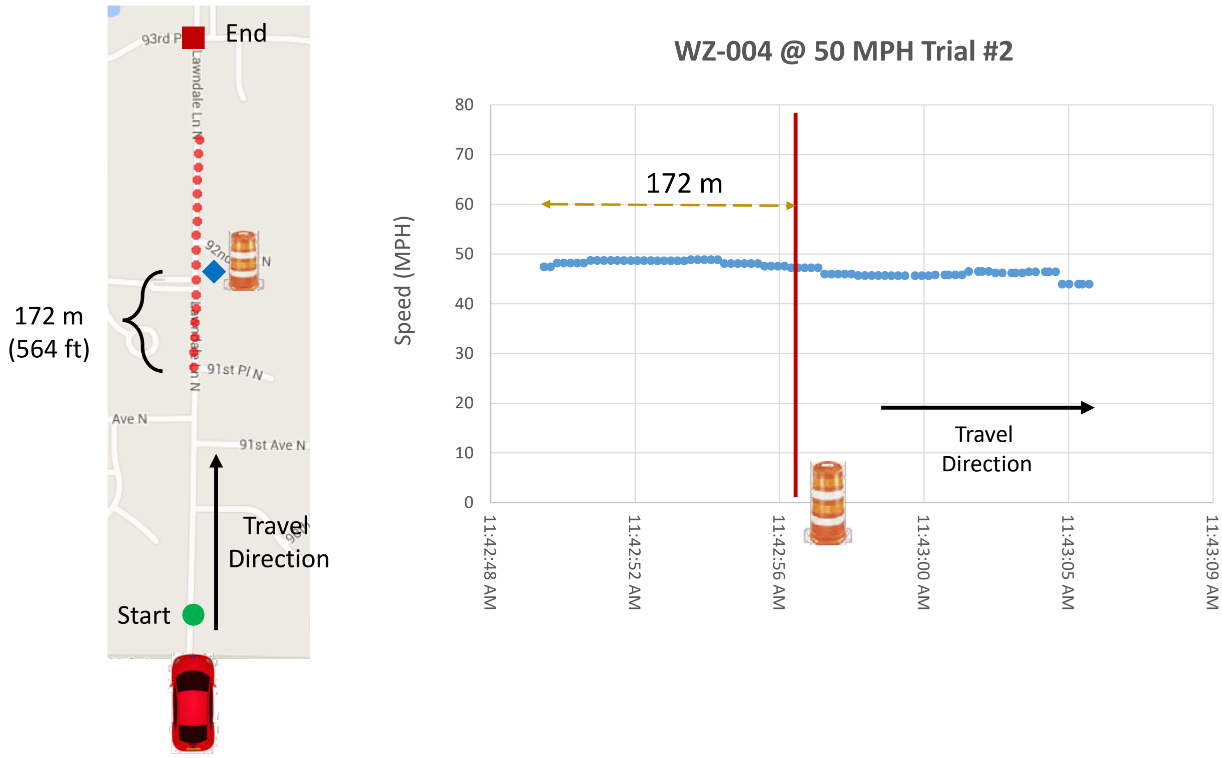

Figure 3-7 Illustration and Results of an Experiment on a Local Street at 50 MPH (Snow on ground)

<u>Experiment 5</u>:

As illustrated in Figure 3-8, a minivan (Toyota Sienna) travels at 50 MPH on a residential street northbound from the starting point toward the BLE module, a geo-fencing approach was used. Bluetooth scanning on the smartphone starts immediately after the test vehicle enters the geo-fence zone. The app performs a geo-fence check whenever a GPS location change is detected. The app started recording the GPS coordinates when the vehicle entered the geo-fenced zone. The plot shows the speed profile of the test vehicle passing by the BLE module at 10:17:05 am. The estimated range of Bluetooth detection at 50 MPH is about 281 meters.

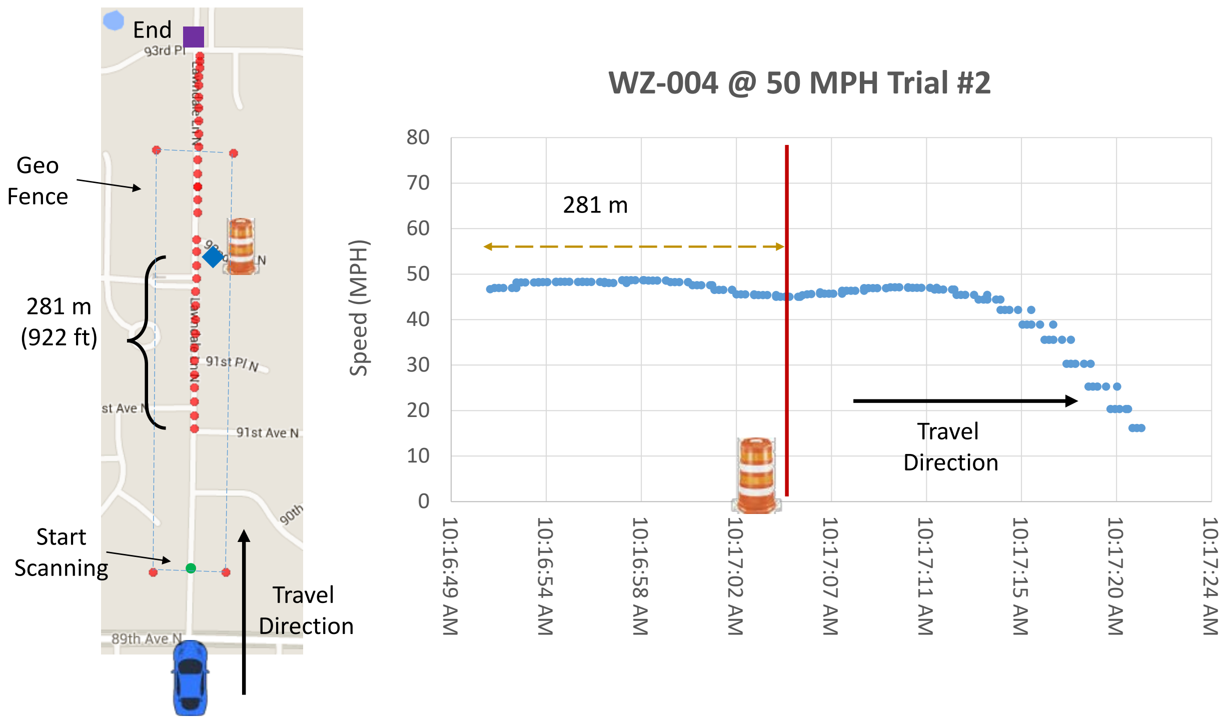

Figure 3-8 Illustration and Results of an Experiment on a Local Street at 50 MPH (Auto Scan)

Experiment 6:

Another experiment was conducted on I-35E NB near County Road E East in Vadnais Heights, MN using a passenger vehicle. A long-range Bluetooth tag was mounted on a speed limit sign as shown in Figure 3-9. As illustrated in Figure 8, the test vehicle travelled at 50 MPH (80 km/h) on I-35E NB from downtown St Paul toward the BLE tag. A geo-fencing technique was used here as well. The Bluetooth scanning service on the smartphone was activated immediately after the test vehicle entered the geo-fenced zone (dash-lined polygon on the left showing the map in Figure 3-10). The speed profile plot, as displayed in Figure 3-10, shows that the test vehicle passed by the BLE module at 10:51:44 am. The estimated range of Bluetooth detection at 50 MPH (80 km/h) is about 525 feet (160 meters) ahead of this work zone.

Figure 3-9 Installation of a Bluetooth Beacon at a Highway Work Zone

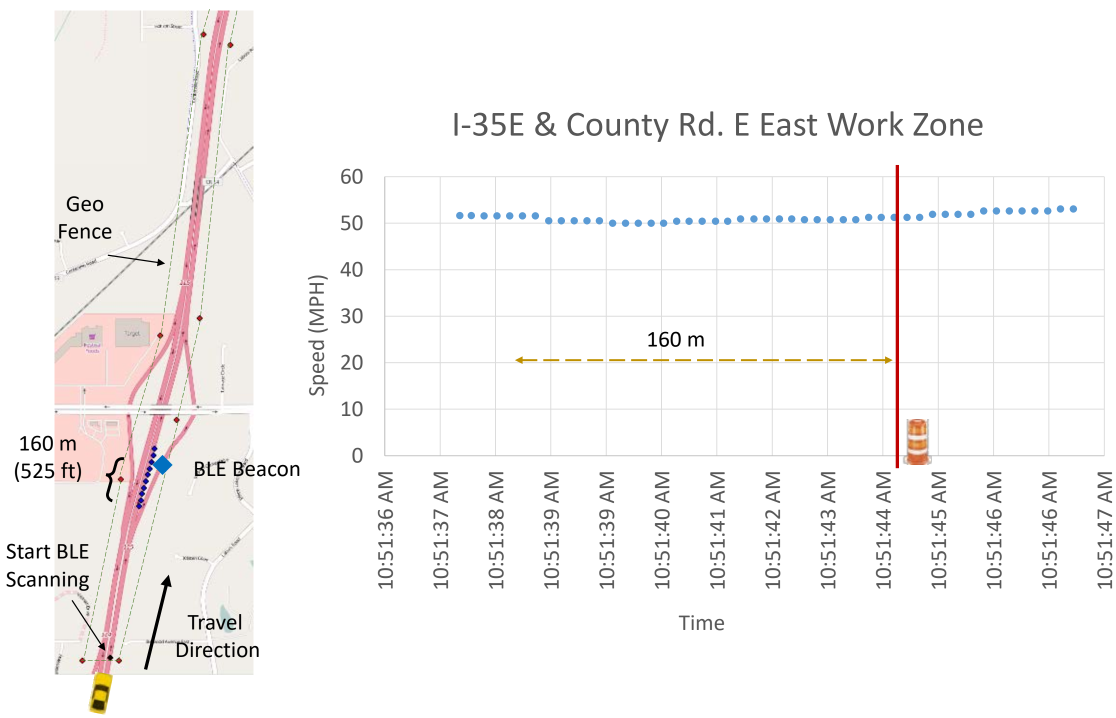

Figure 3-10 Speed Profile of a Test Vehicle at I-35E & County Road E East Work Zone

3.2 POWER CONSUMPTION ANALYSIS

We used a DC inline watt meter and power analyser [23], to measure the smartphone battery power consumption rate. As shown in Figure 3-11, our test smartphone (a Samsung S6 model) draws 196 mA per hour without running the *Workzone Alert* app.

This battery power consumption rate is used as a baseline. The test phone consumes 209 mA per hour when the work zone app is running without Bluetooth scanning. When the Bluetooth scanning is running continuously, the test phone will draw 325 mA per hour. For a smartphone with 3000 mAh battery capacity, for example, the smartphone with a fully charged battery will respectively last 15, 14, and 9 hours for the baseline, work zone app without Bluetooth scanning, and work zone app with continuous Bluetooth scanning scenarios.

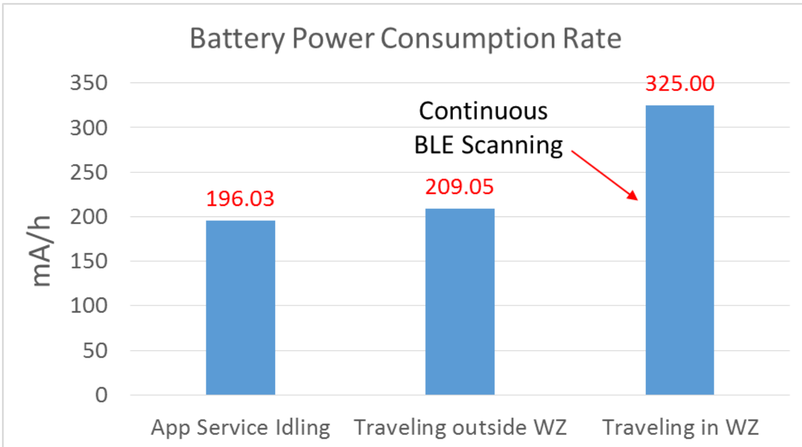

Figure 3-11 Comparison of Smartphone Battery Consumption

The BLE tag consumes about 10, 33, and 36 mA while in idling, receiving (RX), and transmitting (TX) modes, respectively. Currently, the BLE tag is powered by a 2700 mAh portable charger. It will last about 3 to 3.5 days if the BLE module is in TX/RX mode continuously. A commercially available solar panel can be integrated into the existing rechargeable battery system to power the BLE tags.

CHAPTER 4: SUMMARY AND CONCLUSION

4.1 SUMMARY

We have developed a Bluetooth Low-Energy (BLE) system that can be placed in a work zone or at key locations to provide in-vehicle warning messages to a driver. A smartphone app was developed to perform Bluetooth scanning and to announce the appropriate message corresponding to a Bluetooth tag when it is detected. A continuous Bluetooth scan is initiated when a vehicle enters a geo-fenced work zone. Current messages attached to each BLE tag were selected for functional testing only. The final message structure and content will be determined from the results of a human factors study.

In addition, another smartphone app was developed for work zone deployment contractors to request message updates (Figure 4-1). This approach allows work zone staff to easily reconfigure any changes in a work zone by submitting message updates through the smartphone app. After receiving a message update request, engineers or staff who manage the work zone operation can update the audible messages in a timely manner.

The current system demonstrated that it is capable of providing in-vehicle messages for motorists approaching a work zone using the Bluetooth low-energy technology. Our experiment results indicated that communication between a smartphone and BLE tags at high speed is feasible. Our future effort will focus on validation of the proposed system in a real work zone environment under different traffic conditions.

4.2 POTENTIAL IMPACT

The objective of this study is to investigate the feasibility of using inexpensive Bluetooth low-energy technology to trigger in-vehicle messages for motorists in work zones. We believe the proposed approach can establish an alternative to automatic speed enforcement to change behavior in work zones by providing dynamic work zone information. The research findings of this study will help us understand the communication performance (latency, scanning rate, power consumption, etc.) of long-range BLE tags in a work zone. Based on the proposed approach, the experimental results indicate that communication between a smartphone and BLE tags at high speed is feasible. It is anticipated that this project will provide guidelines for engineers and operations staff to determine the placement of tagged landmarks at work zones for triggering in-vehicle messages. The app can potentially be integrated with a 511 system or other navigation apps to dynamically receive relevant workzone information.

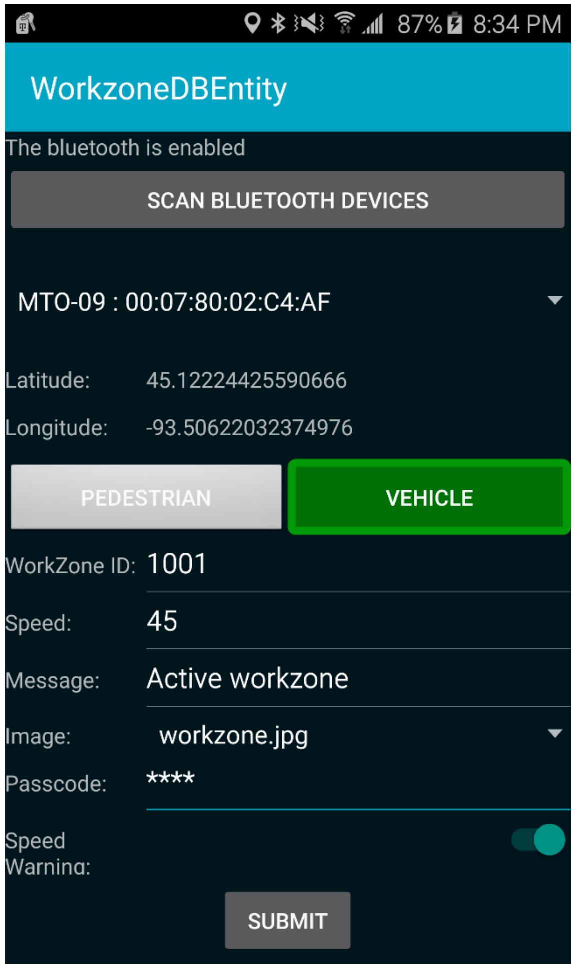

Figure 4-1 Smartphone App to Update Work Zone Database Onsite

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APPENDIX A
BLE DATABASE SCHEMA

The geo-fence and the BLE tag data schema are described as follows.

1. Workzone geofence table: **geofences**

Table A.1 Workzone Database for Genfencing

Name	wz_id	point_id	lat	lon
data type	integer	integer	double	double
Example	1001	1	45.266551	-93.716759
Example	1001	2	45.266046	-93.71751
Example	1001	3	45.260853	-93.708054
Example	1001	4	45.261382	-93.707496
Example	901	1	44.98032	-93.2307
Example	901	2	44.97936	-93.2313

Example	901	3	44.9784	-93.2287
Example	901	4	44.97952	-93.2279
Example	902	1	45.12345	-93.5031
Example	902	2	45.11753	-93.5032
Example	902	3	45.11753	-93.5017
Example	902	4	45.1234	-93.5016
Example	903	1	45.12315	-93.5071
Example	903	2	45.12177	-93.507
Example	903	3	45.12175	-93.5058
Example	903	4	45.12308	-93.5051

Notes: point_id for each work zone will be in sequential order that defines a work zone buffer in a polygon.

2. BLE tag table: **ble_tags**

Table A.2 Database for Bluetooth Tags

Name	**wz_id**	**ble_mac**	**lat**	**lon**	**speed_limit**	**Traffic_dir**	**message**	**flag**	**image_file**
Data type	integer	char(18)	double	double	integer	integer	text	short	text
Description	Workzone ID	BLE MAC Address	Latitude	Longitude	Speed Limit	Traffic Direction	Workzone Message	Flag	Image File
Sample #1	1003	00:07:80:02:BA:2E	45.263702	-93.712407	45	90	"road work ahead, 1.5 miles"	1	"wz.jpg"
Sample #2	1003	00:07:80:02:BA:2F	45.263714	-93.712503	35	120	"active work zone, no passing zone"	0	NULL

Notes:

Flag = 1 - Check if the vehicle exceeds speed limit and announce "*You are speeding*" message if speeding

Traffic_dir is expressed in degrees. 0 degree is the north direction, 90 degrees is east direction, and 270 degrees is in west direction.

APPENDIX B
ADDITIONAL RESULTS FROM EXPERIMENTS CONDUCTED AT MNROAD

Experiment results of a test vehicle traveling at speeds from 30 to 70 MPH at the MnROAD facility are included as follows. Section B.1 presents the experiment results using BLE long-range module from BETZTechnik (http://www.betztechnik.ca/store/c1/Featured_Products.html). Section B.2 includes the experiment results using BLE long-range module from Ambient Sensors (https://www.tindie.com/stores/ wa7iut/).

B.1 BLE long-range module from BETZTechnik

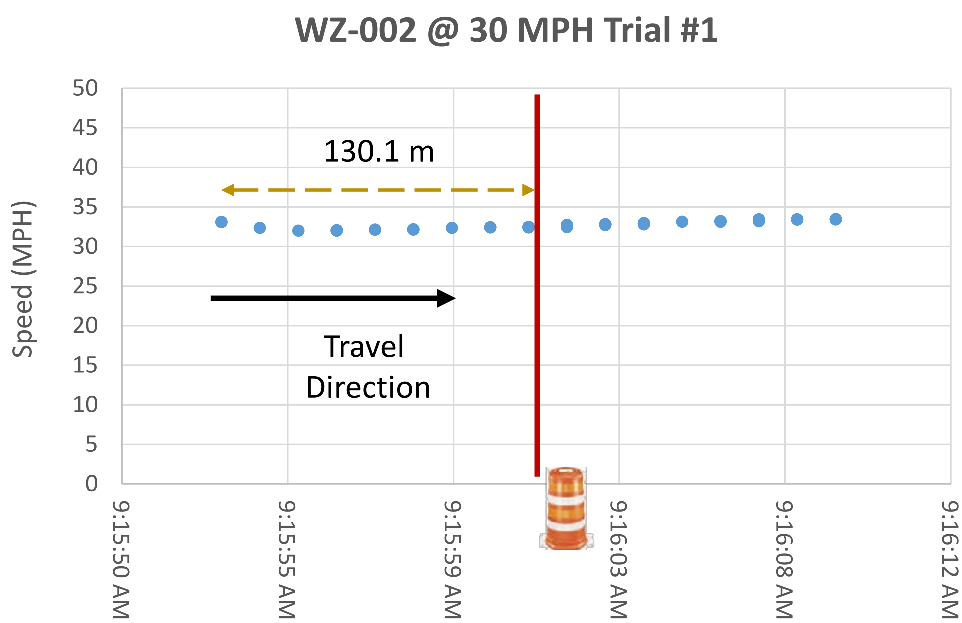

Figure B.1 Vehicle Traveling at 30 MPH

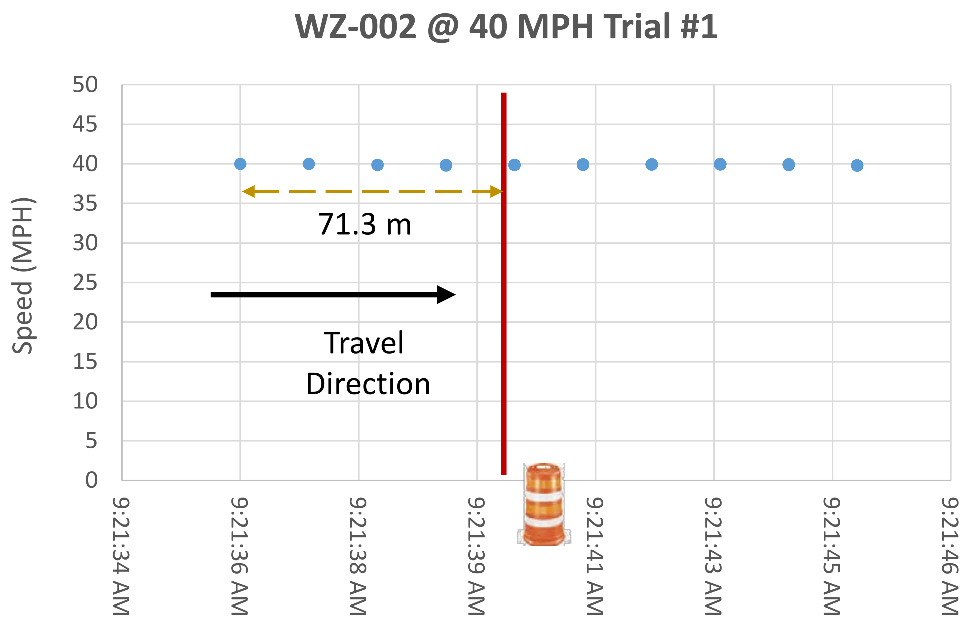

Figure B.2 Vehicle Traveling at 40 MPH

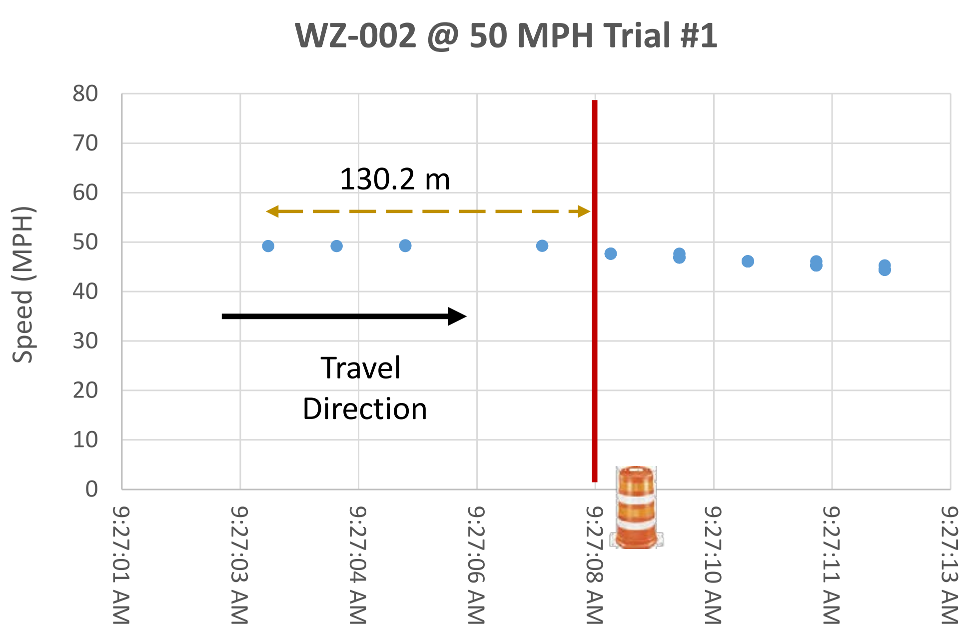

Figure B.3 Vehicle Traveling at 50 MPH

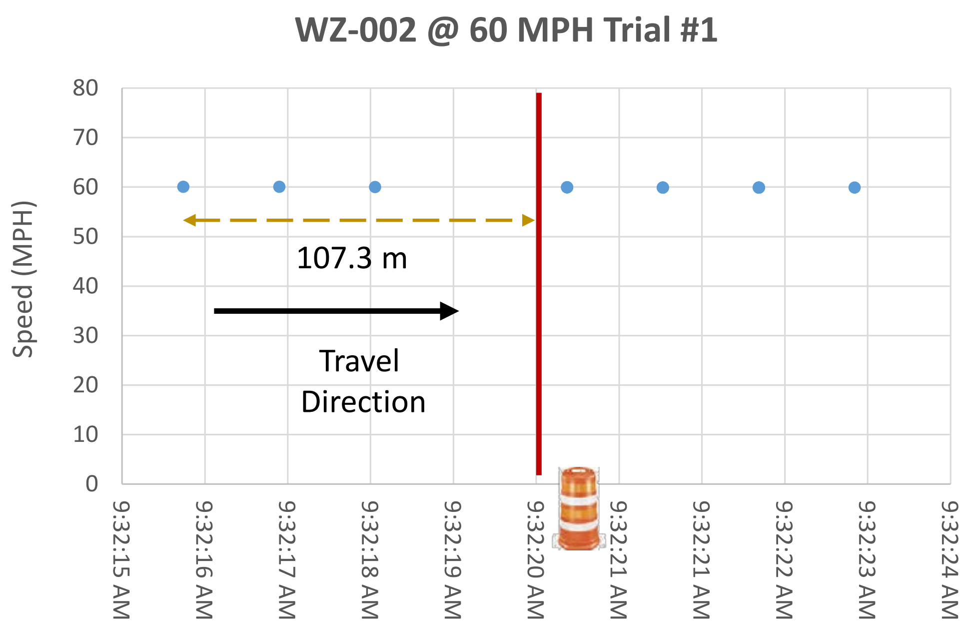

Figure B.4 Vehicle Traveling at 60 MPH

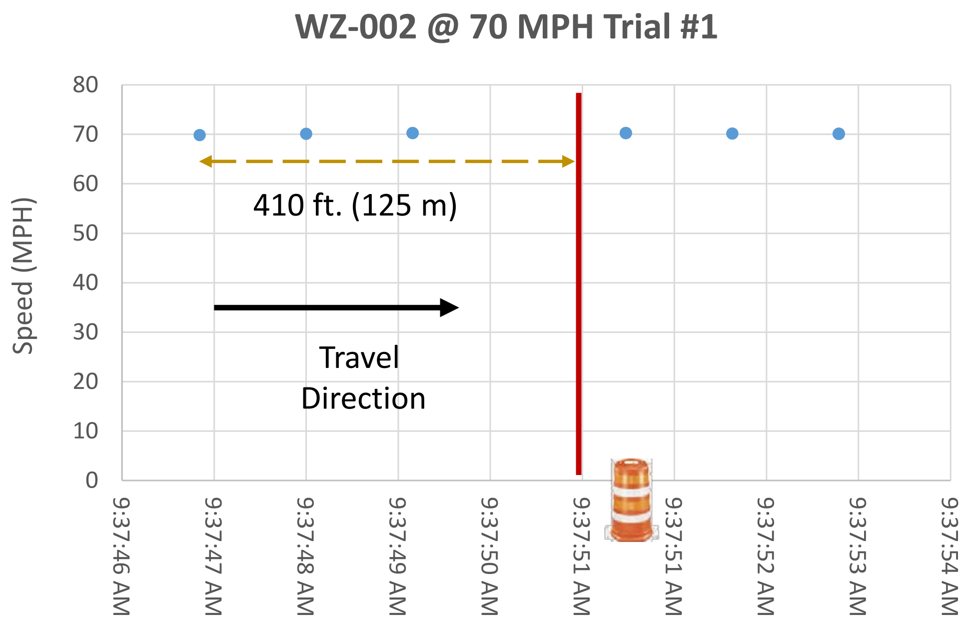

Figure B.5 Vehicle Traveling at 70 MPH

B.2 BLE long-range module from Ambient Sensors

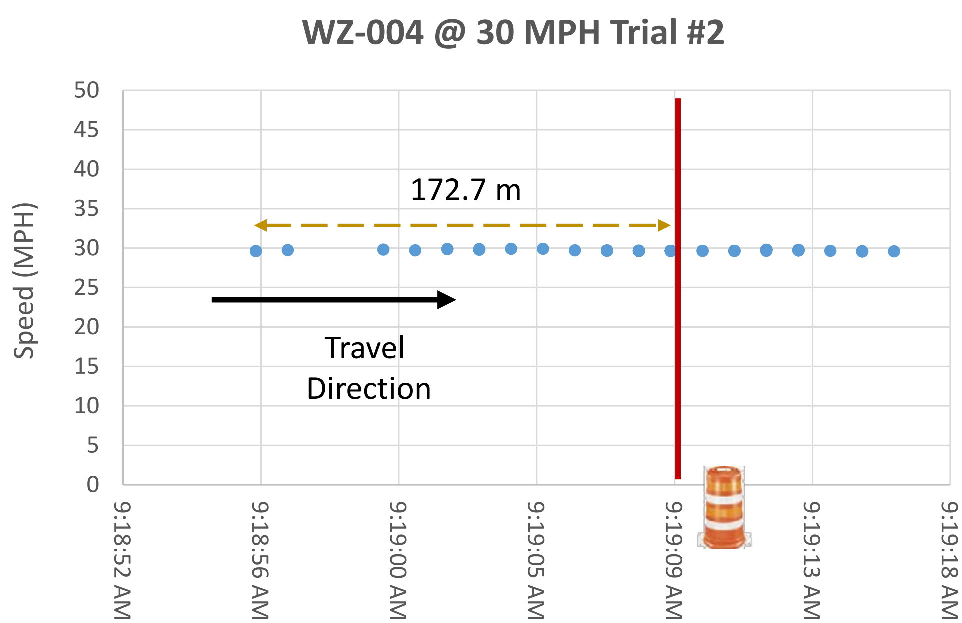

Figure B.6 Vehicle Traveling at 30 MPH

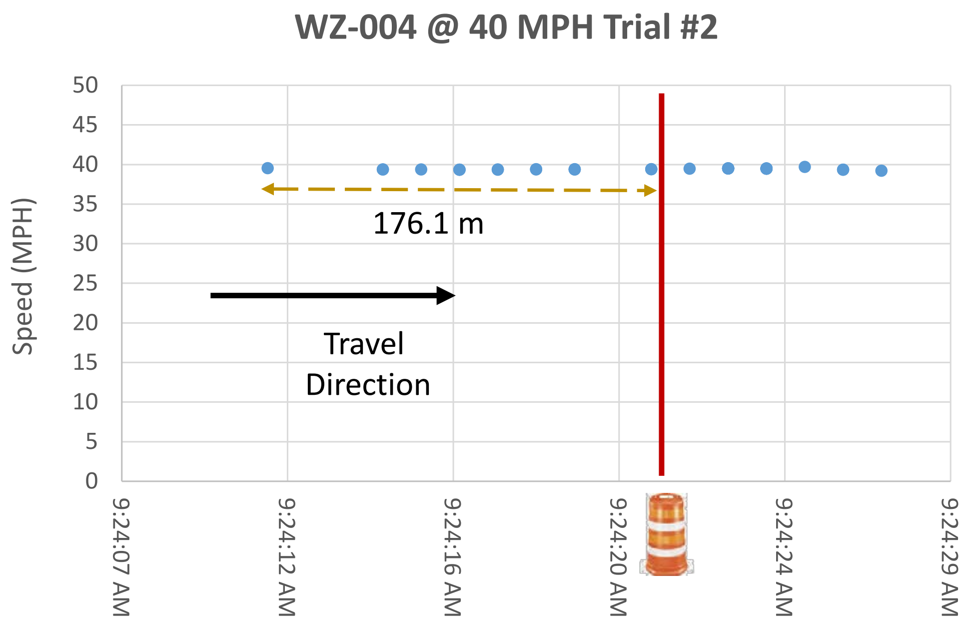

Figure B.7 Vehicle Traveling at 40 MPH

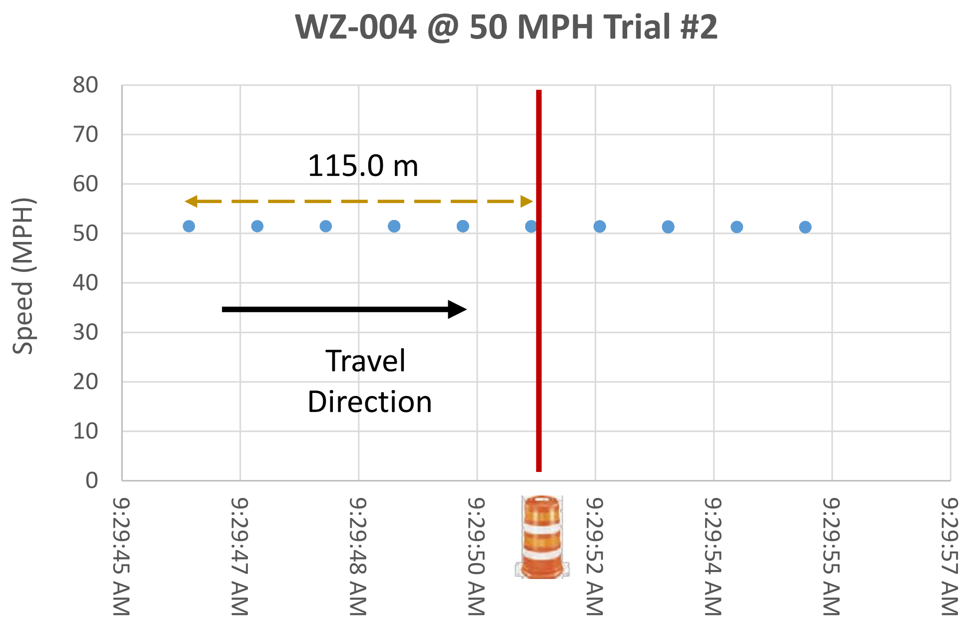

Figure B.8 Vehicle Traveling at 50 MPH

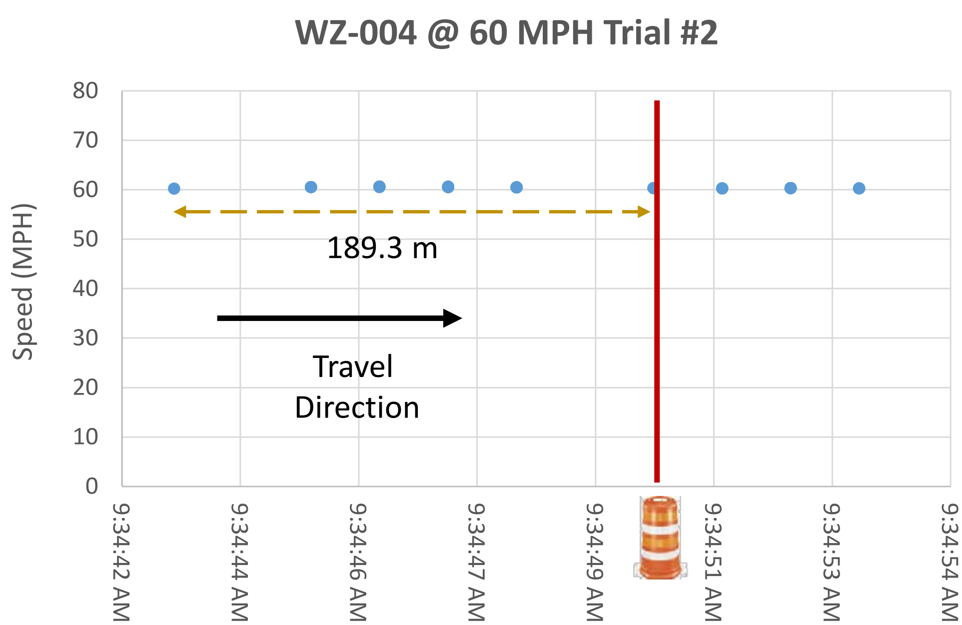

Figure B.9 Vehicle Traveling at 60 MPH

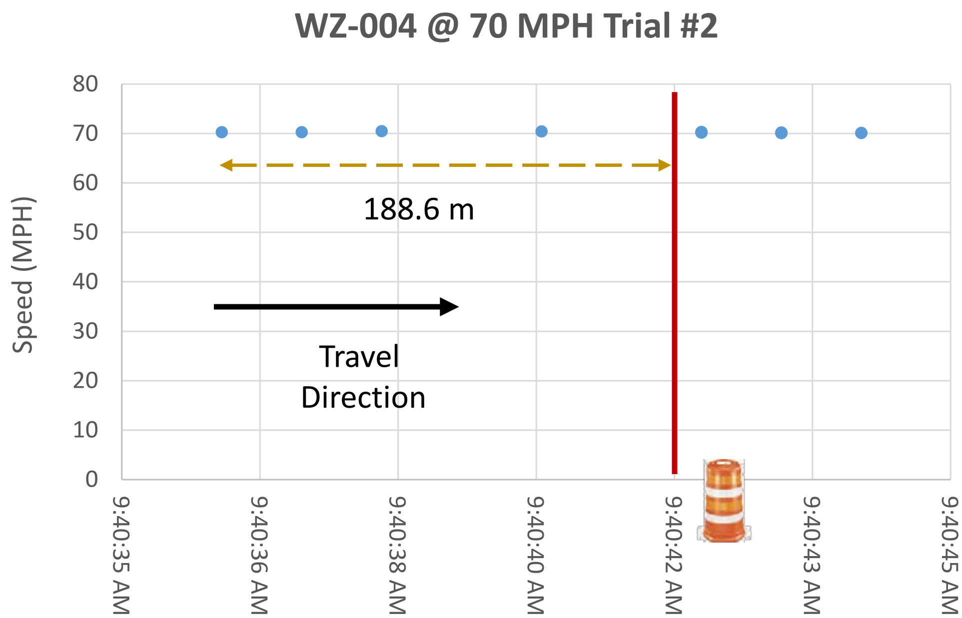

Figure B.10 Vehicle Traveling at 70 MPH