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Test and Evaluate a Bluetooth Based In-Vehicle Message System to Alert Motorists in Work Zones

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Final Report

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16. Abstract (Limit: 250 words)

Safe and efficient traffic flow in a work zone is a major concern for transportation agencies. To reduce risky behavior around work zones, we have developed a prototype system to investigate the feasibility of using in-vehicle messages to increase drivers' awareness of safety-critical and pertinent work zone information. Our previous effort focused on an inexpensive technology based on Bluetooth low energy (BLE) beacons that can be deployed in or ahead of the work zone. A smartphone app, called *WorkzoneAlert*, was developed to trigger non-distracting, auditory messages in a smartphone mounted in a vehicle within range of the BLE beacons. Messages associated with BLE beacons around the work zone can be updated remotely in real time and thus could provide significantly improved situational awareness about dynamic conditions in work zones, such as awareness of workers on site, changing traffic conditions, or hazards in the environment. We incorporated the recommended in-vehicle message elements and user interface from a human factors study previously conducted by the HumanFirst lab and deployed the in-vehicle work zone information system at three construction sites (CSAH 53, CSAH 112, and MN-65) in the Twin Cities metropolitan area (TCMA). Our field test results indicated that the *WorkzoneAlert* app is able to reliably detect the BLE beacon placed an average of 127 m away on traffic signs or portable radar speed signs and successfully announce the corresponding message associated with each BLE beacon.

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FINAL REPORT

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LIST OF ABBREVIATIONS

AV	Automated Vehicle
BLE	Bluetooth Low Energy
COTS	Commercial off-the-shelf
CSAH	Count State-Aid Highways
CTS	Center for Transportation Studies
DOT	Department of Transportation
DSRC	Dedicated Short Range Communication
FHWA	Federal Highway Administration
GATT	Generic Attribute
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAR	Highway Advisory Radio
IoT	Internet of Things
ITS	Intelligent Transportation Systems
ITS JPO	ITS Joint Program Office
LiPO	Lithium-Ion Polymer
MAC	Media Access Control
MTO	Minnesota Traffic Observatory
NEMA	National Electrical Manufacturers Association
RSI	Roadway Safety Institute
RSS	Received Signal Strength
RSSI	Received Signal Strength Indication
SD	Standard Deviation
SIG	Special Interest Group
TCMA	Twin Cities Metropolitan Area
TTC	Temporary Traffic Control
TTS	Text-to-Speech

UMN   University of Minnesota

WZDI   Work Zone Data Initiative

WZDx   Work Zone Data Exchange

EXECUTIVE SUMMARY

Safe and efficient traffic flow in a work zone is a major concern for transportation agencies. According to work zone injury and fatality data published by the U.S. Department of Transportation (USDOT), over 20,000 workers are injured in work zones each year. In the past, many intelligent transportation system (ITS) tools and applications, such as speed enforcement and variable speed-limit systems, have been developed and implemented to effectively mitigate traffic impacts caused by roadway construction. In addition, automated traffic information systems have been used to improve safety by informing motorists with timely updates on travel time, delay, and congestion. In recent years, challenges to work zone safety and mobility have been exacerbated by the growing issue of distracted driving. Many active work-safety technologies are available in the market to alert construction workers about intrusion and potential danger. There are also opportunities to alert motorists with timely and location-specific information as they are approaching work zones.

We previously developed a prototype system to investigate the feasibility of using in-vehicle messages to increase drivers' awareness of safety-critical and pertinent work zone information. Inexpensive Bluetooth low energy (BLE) tags were deployed in or ahead of a work zone. A smartphone app was also developed to trigger less-distracting auditory messages as compared to visual messages (Craig et al., 2017) from a smartphone or a vehicle's infotainment system when the drivers were approaching a work zone. We deployed several BLE tags and conducted field experiments at three work zones (CSAH 53, CSAH 112, MN 65) in Minnesota.

We tested the app running in the background on a smartphone using a sedan and a minivan at different times of day to evaluate the system's performance under different traffic conditions. Bluetooth detection rate, range, and available reaction time were used as performance measures for system evaluation. Vehicle location and timing of each triggered message were logged for data analysis. On average, the work zone alert system was able to detect the BLE tag and announce the associated auditory message when a vehicle was 106 m (348 ft) ahead of the work zone at the CSAH 53 site with a standard deviation of 55 m (180 ft). The results from the CSAH 112 site showed an average BLE detection range of 167 m (548 ft) with a standard deviation of 38 m (125 ft). Similarly, the results from the MN 65 site showed an average BLE detection range of 125 m (410 ft) with a standard deviation of 31 m (102 ft). At a posted work zone speed limit of 35 to 45 mph, our system on average allowed 5 to 9 sec of reaction time prior to the motorists approaching the location where the beacons were installed. The results indicated that our system is capable of providing location-specific and timely warning messages to alert motorists approaching work zones.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

According to work zone injury and fatality data published by the U.S. Federal Highway Administration (FHWA) in 2017, there were more than 158,000 crashes in work zones, resulting in 799 deaths and 61,000 injuries. More than 20,000 workers are injured in work zones each year, with 12% of those due to traffic incidents [Scriba & Atkinson, 2014; USDOT, 2015]. Despite a trend toward fewer work zone crashes from 2011 to 2013, the number of estimated work zone injuries actually increased in 2013 [USDOT 2015].

Promoting smarter work zones is one of the initiatives promoted by the 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 [USDOT, 2008]. 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 have been 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 to reduce risky behavior, associated with distraction.

1.2 OBJECTIVES

The objectives of the proposed project are to refine the BLE-based in-vehicle message system so that the deployed beacon incorporates a sustainable power source design, implements results from the human factors study to provide work zone information to motorists, and evaluates the system's performance. The proposed approach could establish an alternative to automatic speed enforcement to change the behavior in work zones by providing dynamic and timely work zone information. The results from this project will prepare us for a later field operation test.

1.3 LITERATURE REVIEW

1.3.1 Work Zone Speed Management

To improve work zone safety, speed enforcement, speed advisory systems, or variable speed limit systems are often used for work zone speed management. For example, Mattox et al. [Mattox et al., 2007] developed a speed-activated sign to inform vehicle drivers through a roadside visual cue when 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. [2007] 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 were less likely to comply with the variable speed limit if the posted speed was significantly different from the speed they would otherwise choose.

1.3.2 Automated Traffic Information System

In addition to work zone speed management, automated traffic information systems have been proposed to improve safety by informing motorists with timely updates on travel time, delay, and queue length [Ibrahim et al., 2013; Wegener et al., 2008; Marfia & Roccetti, 2010; Luttrell et al., 2008; Chu et al., 2005; FHWA, 2014]. Ibrahim et al. [2013] 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% was needed for the system to work.

Marks et al. [2017] conducted experimental evaluation of intrusion sensing technologies for work zone safety. Table 1.1 lists various active work zone safety technologies available in the market for alerting workers about work zone intrusion.

Table 1.1 Active Work Zone Safety Technologies

System Type	Technology	States Tested	Alert Type		
			Audible	**Visual**	**Vibratory**
Kinematic	SonoBlaster	New Jersey (Krupa 2010), Kansas(Novosel 2016), Oregon (Gambatese 2017)*	√	−	−
Infrared	Safety Line	None	√	√	−
Phenumatic and Microwave	Worker Alert System (WAS)	Oregon (Gambatese 2017)*, Colorado (Bauer 2017)*	√	√	√
	Intellistrobe	None	√	√	−
Radar	AWARE System	Missouri & Texas (Cleaver 2016)	√	√	√
Radio	Intellicone	Kansas (Novosel 2016), Oregon (Gambatese 2017)*	√	√	−
	Wireless Warning Shield	None	√	−	√

*Source: Marks et al. [2017], Table 3-1 p.8 (red font with * added)*

Recently, the FHWA and the Intelligent Transportation Systems Joint Program Office (ITS JPO) have been co-leading the early stages of the Work Zone Data Initiative (WZDI) to elevate the national state of practice regarding work zone activity data. The objective of the initiative is to develop and promote practices for generating such data to support work zone management within agencies and to advance the development of applications that enable data use among stakeholders. In supporting the WZDI, a

Work Zone Data Exchange (WZDx)[1] protocol has been proposed to address data exchange needs for automated vehicle (AV) integration. The WZDx project aims to develop a platform that provides harmonized, reliable, consistent, and real-time work zone data for third party use and facilitates the integration of AVs into the national transportation network.

1.3.3 Using Bluetooth Technology for Traffic Operations

Haseman et al. [2010] uses 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. The study suggests 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 [Martchouk et al., 2011; Stevanovic et al., 2015; Moghaddam & Hellinga, 2014]. Anonymous travel time monitoring is performed by matching the media access control (MAC) addresses of Bluetooth devices embedded in 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 [Quayle & Koonce, 2010; Wasson et al., 2008]. Dunlap et al. [2016] uses 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. The results suggest that the Bluetooth- and Wi-Fi-based methodology is reliable at providing a robust and detailed source of data for transit planning and operations analysis.

Liao [2014] 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 operating system was developed to provide 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 beacons 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

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[1] Work zone data exchange overview, https://www.transportation.gov/policy-initiatives/automated-vehicles/work-zone-data-exchange-overview

an action on the iPhone. Many articles, including Ashford [2015], quoted the Bluetooth Special Interest Group (SIG), which predicts that more than 90% of Bluetooth-enabled smartphones will support the low-energy standard[2].

BLE technology typically has a wireless communication range up to 50 m based on line of sight, according to its specifications. Commercially available BLE beacons 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 beacon can "broadcast" its service name or other information. When the smartphone app receives the wireless signal from a BLE beacon, it will also get a received signal strength indicator (RSSI) value with the broadcast message. The RSSI can be used to evaluate distance from the beacon. Whether BLE beacons can be used to alert drivers of high-speed vehicles about work zones ahead is one of the key questions being addressed here.

1.3.4 Previous Work

In an attempt to reduce risky behavior around work zones, our previous effort examined the effectiveness of using in-vehicle messages to raise drivers' awareness of safety-critical and pertinent work zone information [Liao & Donath, 2016]. The objective of the previous project was to investigate 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 was 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.

A smartphone app, called *WorkzoneAlert*, was developed to trigger non-distracting, auditory messages in a smartphone mounted in a vehicle within range of the BLE beacons. Messages associated with BLE beacons around the work zone can be updated remotely in real time and thus 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 incorporated the recommended in-vehicle message elements and user interface from a human factors study previously conducted by the HumanFirst lab [Craig et al., 2017] and deployed the in-vehicle work zone information system at three construction sites in the Twin Cities metropolitan area (TCMA).

Experiment results from our previous work indicated that when a vehicle is travelling at 70 mph (113 km/h), our *WorkzoneAlert* app is able to successfully detect a long-range BLE tag placed more than 410 feet (125 meters) away on a traffic barrel or roadway shoulder. Several experiments were also conducted to validate the system's performance under different roadway geometry, traffic, and weather conditions.

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[2] Mobile Telephony Market, https://www.bluetooth.com/

There are commercially available products (Lombardo, 2018) that use sensors and beacons integrated with commercial navigation apps, such as Waze, to provide digital signage and warning to both workers and motorists. Our Bluetooth-based approach does not reply on GPS satellite reception and cellular network connection to deliver the information to travelers.

1.4 REPORT ORGANIZATION

The rest of this report is organized as follows. In-vehicle message and design of BLE beacon are presented in Chapter 2. Setup of field experiments and test results are discussed in Chapter 3 and 4, respectively. Finally, summary and discussion of this study are presented in Chapter 5.

Design of solar panel mounting assembly and additional field experiment results are included in Appendix A and Appendix B, respectively.

CHAPTER 2: SYSTEM DESIGN

This chapter summarizes the in-vehicle wok zone alert system previously developed [Liao & Donath, 2016] and describes the integration of a solar-power Bluetooth Low Energy (BLE) system using a commercial off-the-shelf (COTS) solar panel and charging system. A simple mounting system was also designed and developed for the solar panel.

2.1 IN-VEHICLE MESSAGE SYSTEM

The system architecture of the 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 beacons. A work zone database for BLE beacons was incorporated into the system to include location, traffic direction, message content, and other necessary information associated with each beacon in a work zone. A subset of the work zone database can be queried 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 the direction of travel. Appropriate warning messages are referenced to each BLE beacon when detected by an in-vehicle device (i.e., a smartphone app). The Bluetooth is configured in discovery mode and no pairing is required for our application.

An Android smartphone application, called *WorkzoneAlert*, was developed for field experiments 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 cloud server. A continuous Bluetooth scan is initiated when a vehicle enters a geo-fenced work zone. When a BLE beacon is detected, the app announces an audible message associated with the detected beacon. When multiple work zone BLE beacons are sensed, messages associated with the nearest BLE beacon, i.e., the beacon with the strongest Received Signal Strength (RSS), are announced to the traveler. The current app includes additional features, such as vibration, alerting tone, data collection, and graphical display, for testing in the field experiments. The app can potentially be integrated with the 511 or other navigation apps to receive work zone information statewide for broader adaption.

On account of data security concerns, our system architecture includes a 3-tier implementation that improves the data security of communication between client devices and the database. The research team reprogramed the firmware of the commercial off-the-shelf (COTS) long-range BLE sensors for high-speed applications (up to 80 mph). Each BLE beacon was configured operate in discovery mode with minimal power consumption. The BLE transmitter and a battery were packaged in a NEMA enclosure for field testing. The *WorkzoneAlert* app only recognizes the BLE beacons that are programmed for our application. Other Bluetooth devices within the detection range in the vicinity are ignored.

In order to reduce the effort required in placing the Bluetooth beacons at a work zone, another smartphone app (*WorkzoneDB*) was also developed for use by the contractors or construction

engineers. The *WorkzoneDB* allows the staff in the field to submit a request for message update at the location where a BLE beacon is mounted. This approach allows engineers or staff who are responsible for the construction operations to update the in-vehicle messages in a timely manner.
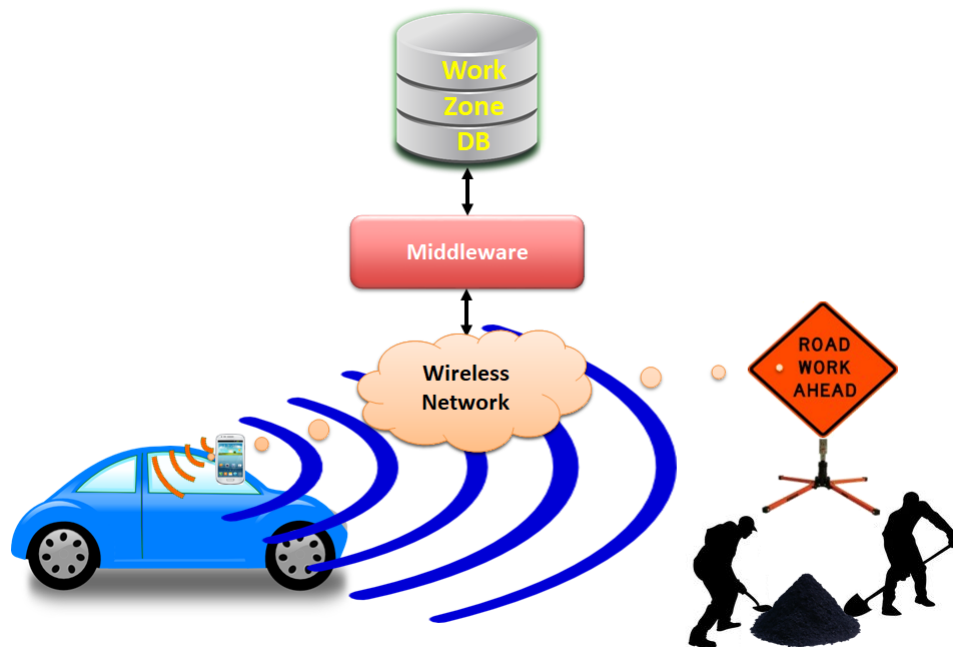

**Figure 2.1 System Architecture of an In-Vehicle Workzone Alert System.**

2.2 SOLAR CHARGER SYSTEM

In the literature, Jeon et al. [2016] identified the challenges of finite battery capacity for BLE beacons used in the Internet of Things (IoT) applications. They conducted a preliminary design of sustainable BLE beacons powered by solar panels. Their results indicated that a typical BLE beacon can be powered by a solar panel with a surface area of 300 cm^2 and a lithium-ion rechargeable coin cell battery. In addition, Spachos and Mackey [2018] evaluated the energy efficiency and accuracy of the solar-powered BLE beacons by comparing the solar vs. battery powered BLE beacons. Their results indicated that the solar-powered BLE beacon is a promising solution with minimum energy requirement and high accuracy.

A solar charging system was integrated and packaged in a National Electrical Manufacturers Association (NEMA) polycarbonate enclosure as illustrated in Figure 2.2. The solar charging system is comprised of a 3.7V 6600 mAh Lithium-Ion Polymer (LiPo) battery, a Li-Ion / Li-Polymer battery charge circuit board based on Microchip MCP73833, and a 6V solar panel. The battery charging system is configured to have a maximum charging rate of 500 mA. The design was designed to draw the most current possible from a solar cell, up to the max charge rate. It's also capable of autonomous power source selection between an input (from DC, USB, or solar) or a battery.

There are three status LEDs on the LiPo charger. The red PWR LED indicates that there is good power connected to the charger. The orange CHRG LED indicates current charging status. When this LED is lit, the charger is working to charge up a battery. It also acts as a low battery indicator (fixed at 3.1V) when no power is connected. That is, when the battery voltage drops below 3.1V, the orange LED will come on. The green DONE LED indicates the battery is charged when it's lit up.

The smart load sharing function automatically uses the input power when available to keep the battery from constantly charging or discharging. The LiPo charger is both charging a battery and providing power to the BLE beacon at the same time.
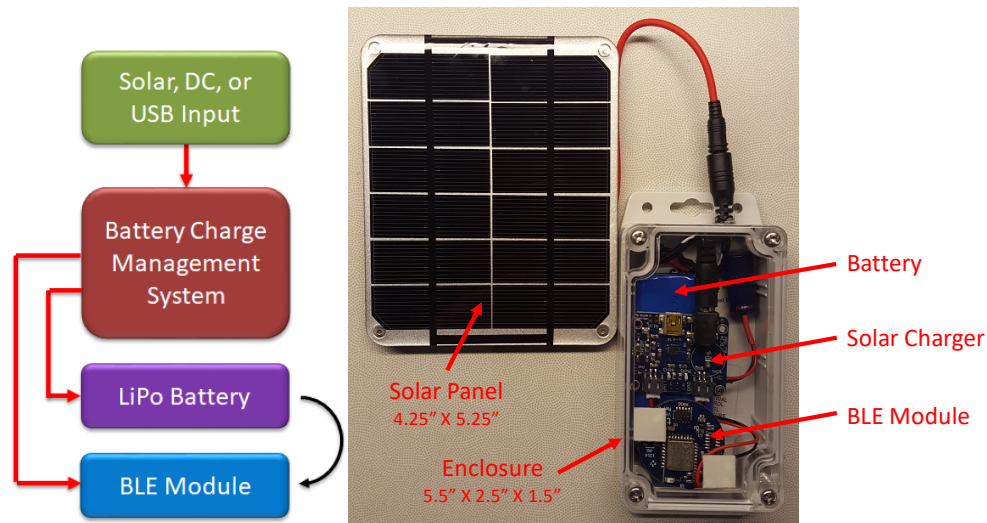
Figure 2.2 Solar Charger System.

A solar panel mounting system was designed and created using aluminum angle bars. The fixture design allows installers to easily adjust the tilt angle of the solar panel for maximum energy yield. As displayed in Figure 2.3, the solar panel with the customized mounting fixture was attached to a street lamp post using a stainless steel clamp. Detailed design drawings of the mounting fixtures are included in Appendix A.

Figure 2.3 Solar-powered BLE on a street light post.

CHAPTER 3: FIELD EXPERIMENTS AND SYSTEM EVALUATION

We worked with the Hennepin County and MnDOT construction engineers to identify 3 construction sites for the field experiments. Roadway construction sites on CSAH 53 in Richfield, CSAH 112 in Long Lake, and MN-65 in East Bethel were identified for deploying and testing the BLE-based in-vehicle work zone information system. Four BLE sensors were deployed on the 66th St (CSAH 53) in Richfield, MN, two beacons were installed on Wayzata Blvd (CSAH 112) in Long Lake, MN, and two more beacons were deployed on State Highway 65 (MN 65) in East Bethel, MN.

Experiments were performed by running the Workzone Alert app in the background on an Android smartphone which was mounted on the dashboard of a vehicle. Two vehicles, a sedan and a minivan, were separately used to travel through the test sites and collect data in different time of day. In order to capture when and where the in-vehicle message was triggered when a vehicle is approach a work zone, a data collection feature was added the *WorkzoneAlert* app. Vehicle location, speed, and auditory message triggering time were recorded for analysis.

Experiment setup and additional information of each test site are discussed as follow.

3.1 EXPERIMENT SETUP

To setup a field experiment, we first worked with the project lead and construction engineers at each site to identify locations for mounting BLE beacons. The BLE beacons were installed on traffic sign posts at CSAH 53 and MN 65 sites. At CSAH 112, BLE beacons were mounted on portable radar speed signs due to the nature of construction configuration. All beacons were mounted at least 6 feet above the ground for better signal detection.

After the installation of BLE beacons, a separate smartphone app, called *WorkzoneDB*, was used at each installation site to capture beacon location and specify a desired message (e.g. "*Workzone ahead, lane shift ahead, use caution!*") associated with the beacon. The *WorkzoneDB* app captured the beacon location using the GPS position on the smartphone and submitted the message to a cloud server. The *WorkzoneDB* app was previously developed to assist contractors and field engineers update the beacon information onsite from the smartphone device. The password protected *WorkzoneDB* app only allows authorized users to submit and update beacon messages.

After installing the beacons and updating corresponding message for each beacon, we mounted a smartphone with the *WorkzoneAlert* app running in the background on the dashboard of a passenger vehicle as illustrated in Figure 3.1. For each experiment, we drove back and forth through the construction zone instrumented with our BLE beacons multiple times to test the app and collect data. Bluetooth scanning times on the smartphone and the time when a roadside Bluetooth beacon is detected are collected. Vehicle speed and trajectory (latitude and longitude coordinates) are also recorded on the phone for post analysis.

Figure 3.1 A Smartphone Mounted on the Dashboard of a Passenger Vehicle.

3.2 CSAH 53 IN RICHFIELD

Four BLE beacons were installed on traffic signs along CSAH 53 (West 66th Street) in Richfield as illustrated in Figure 3.2. CSAH 53 is an urban arterial with a mix of signalized and un-signalized (including roundabouts) intersections. The first 2 BLE sensors installed at Logan and Pleasant Ave were configured to provide in-vehicle messages for the EB traffic and the other 2 beacons deployed at Chicago Ave and Richfield Parkway were configured for alerting only the WB traffic. The battery-powered BLE beacons were mounted on traffic signs (see Figure 3.3) about 1.2 meters above ground over a 7-week of experiment period at this construction site.
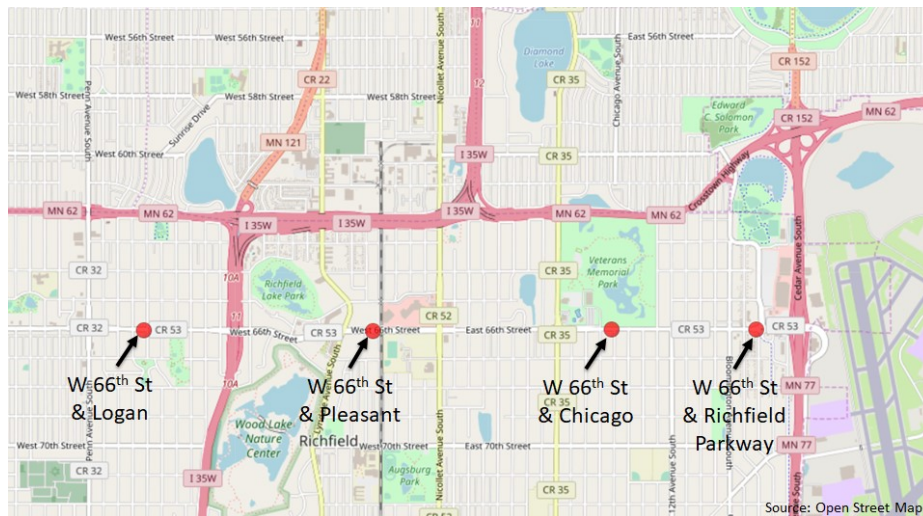
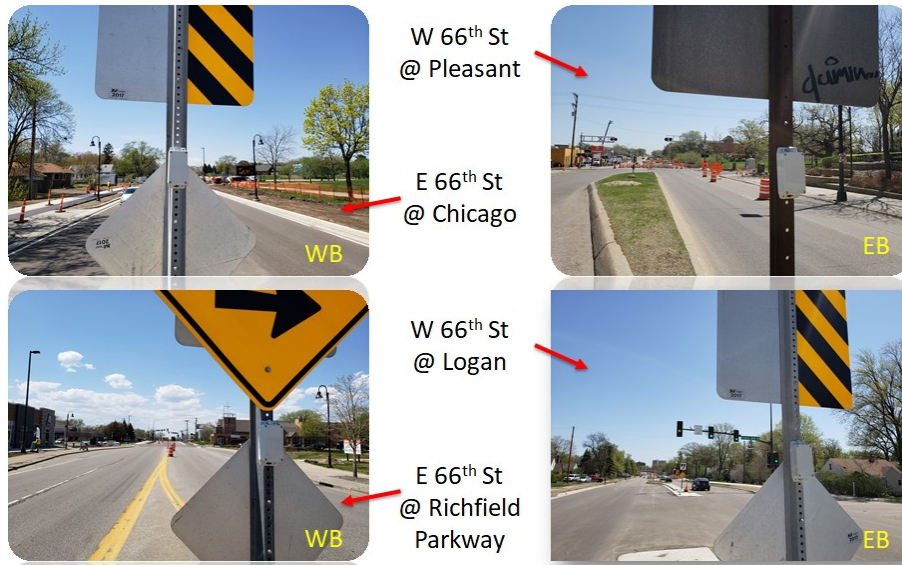Figure 3.2 Four BLE Beacons Deployed Along CASH 53 in Richfield.

Figure 3.3 Images of BLE Beacons Mounted on Traffic Signs at CASH 53.

3.3 CSAH 112 IN LONG LAKE

CSAH 112 (i.e., Wayzata Blvd) is a suburban arterial in the western metro area. Figure 3.4 illustrates the location of 2 BLE beacons deployed at the CSAH 112 construction site. The first BLE beacon installed Tealwood Pl was configured to provide in-vehicle messages for the EB traffic and the other beacon deployed near Lindawood Ln was configured for alerting only the WB traffic. The BLE beacons were mounted on portable radar speed signs (see Figure 3.5) about 2.5 meters above ground at this construction site.
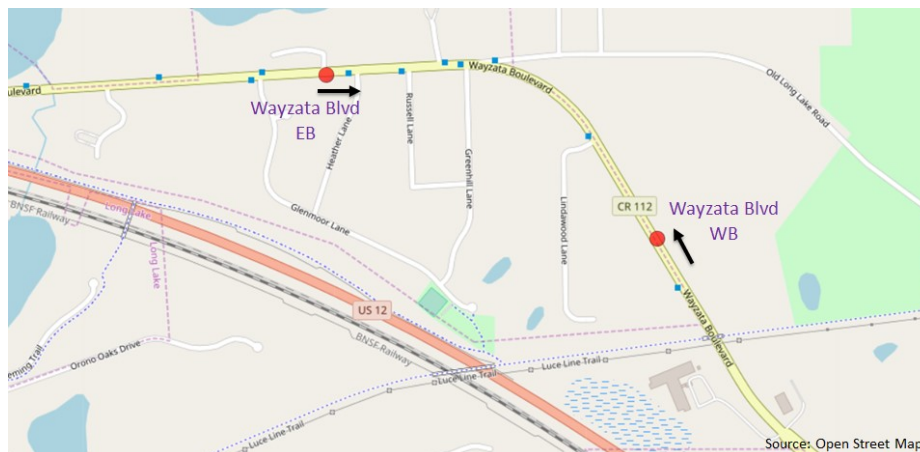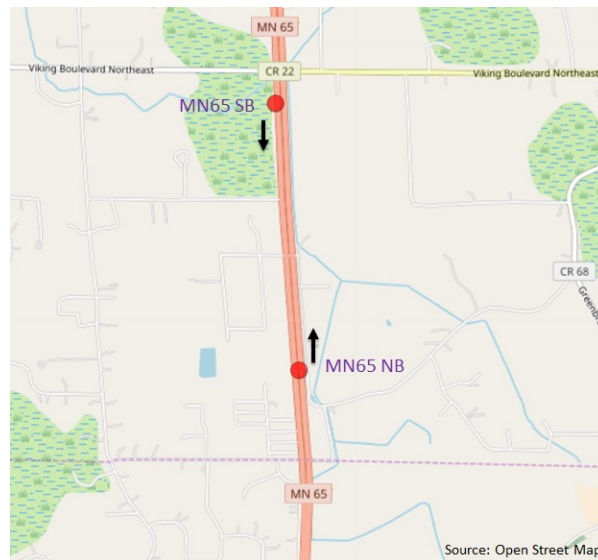

Figure 3.4 Two BLE Beacons Installed Along CASH 112 in Long Lake.

Figure 3.5 Images of BLE Beacons Mounted on Portable Radar Speed Signs at CASH 112.

3.4 MN 65 IN EAST BETHEL

Two BLE beacons were installed on traffic signs along MN 51 in East Bethel, MN as illustrated in Figure 3.6. A number of signalized intersections were involved in this construction site on state highway MN 51. The BLE beacons were placed about 1 mile apart to alert drivers in each direction. The first BLE beacon installed at Viking Blvd was configured to provide in-vehicle messages for the SB traffic and the other beacon mounted at 187th Ln was configured for alerting the NB traffic. Both battery-powered BLE beacons were mounted on traffic signs (as shown in Figure 3.7) about 1.5 meters above road surface over the experiment period at this construction site.

Figure 3.6 Two BLE Beacons Installed Along MN 65 in East Bethel

MN65 NB @ 187th Ln (East Bethel)   MN65 SB @ Viking Blvd (East Bethel)

Figure 3.7 Images of BLE Beacons Mounted on Traffic Signs at MN 65.

3.5 EVALUATION METHODOLOGY

To evaluate the system performance, the smartphone app was programmed to collect timestamp, vehicle speed and trajectory data when a Bluetooth beacon was detected by the app. Bluetooth detection rate, range and available reaction time are selected to evaluate system performance at different traveling speed.

The detection range is used to evaluate the performance of Bluetooth communications under different traffic conditions, particularly when the direct line of sight is obstructed by vehicles ahead and in the adjacent lane. Bluetooth detection range is computed as the network distance from the installation location of a roadside beacon to the location where an in-vehicle message is triggered as a vehicle is traveling toward a work zone.

The available reaction time measure the time from an in-vehicle message is triggered to the time when the motorist passes the location where a roadside beacon is installed. The available reaction time could vary depending on the posted work zone speed limit and motorist's actual traveling speed.

CHAPTER 4: RESULTS AND ANALYSIS

Several runs of experiments were conducted at each test site using a minivan and a sedan during under different traffic conditions. The research team conducted experiments on 2 County roads (CSAH 53 & CSAH 112) and a state highway (MN 65) in urban and suburban areas. A few sets of results are included in this chapter for discussion.

4.1 SITE #1 – CSAH 53

The research team performed 18 experiments at this test site. On average, the work zone alert system was able to detect the BLE tag and announce associated auditory message when a vehicle is 106 m (348 ft) ahead of the work zone at CSAH 53 site with a standard deviation of 55 m (180 ft). At posted work zone speed limit of 35 mph, our system averagely allows 6.8 sec of reaction time prior to the motorists approaching the location where a roadside beacon is installed.

Figure 4-1 displays the speed profile of a test vehicle traveling EB on CSAH 53 toward a closed roadway segment near Pleasant Ave where traffic was redirected to a lane in the opposite direction. An auditory in-vehicle message (*Attention! Lane shift ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 129 m (425 ft) away from the location where the BLE beacon was mounted. The auditory message was programmed based on the message elements recommended by the results from the human factors study (Craig et al., 2017). The red dots in Figure 4-2 illustrate the GPS coordinates of the vehicle after the work zone message was triggered.
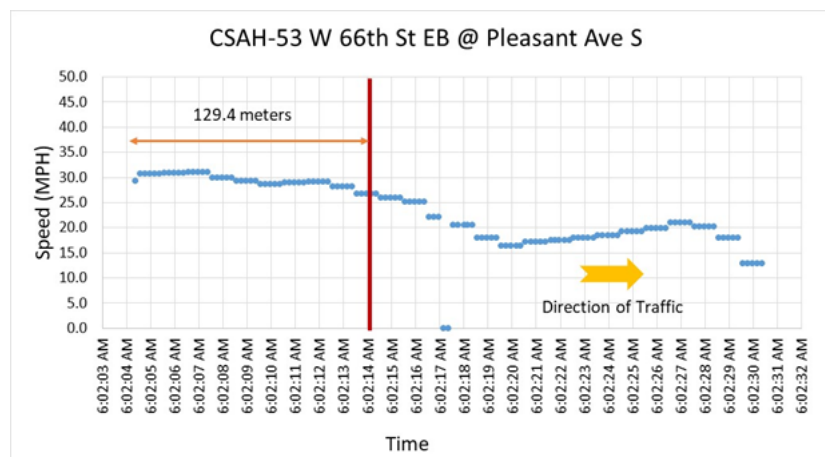

Figure 4.1 Speed Profile of a Test Vehicle Traveling EB on CSAH 53 at Pleasant Ave.
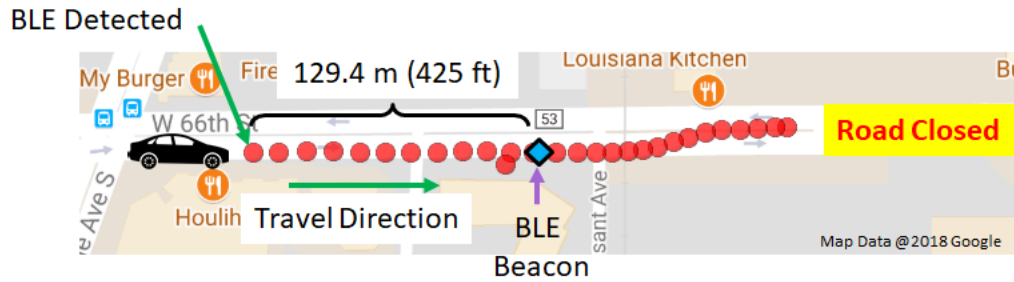
Figure 4.2 Trajectory of a Test Vehicle Traveling EB on CSAH 53 at Pleasant Ave.

Figure 4-3 displays the speed profile of a vehicle traveling WB on CSAH 53 toward a roundabout where construction activities occurred on the west of Richfield Parkway. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 117 m (383 ft) away from the location where the BLE beacon was mounted. The speed of the test vehicle prior to entering the roundabout was about 30 mph. The speed was reduced to around 15 mph in the roundabout then increased to 30-35 mph after leaving the roundabout. The red dots in Figure 4-4 illustrate the GPS coordinates of the vehicle after the work zone message was triggered.
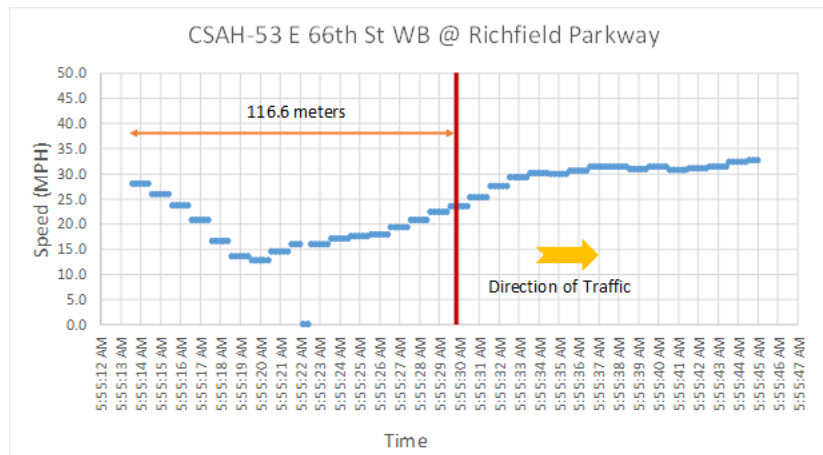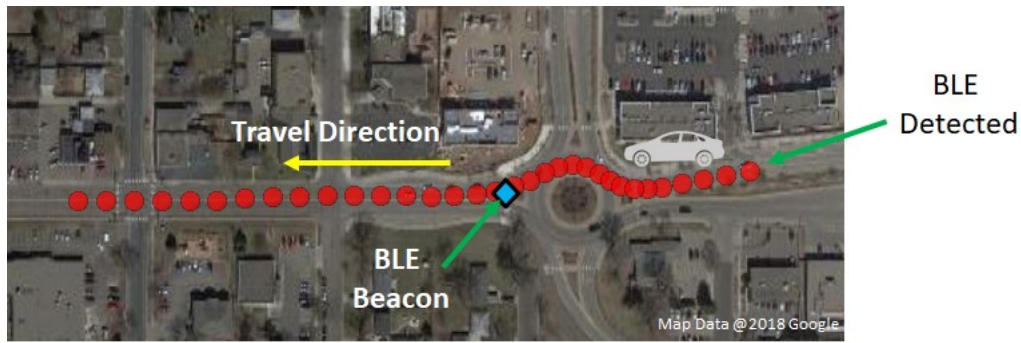

Figure 4.3 Speed Profile of a Test Vehicle Traveling WB on CSAH 53 at Richfield Parkway.

Figure 4.4 Trajectory of a Test Vehicle Traveling WB on CSAH 53 at Richfield Parkway.

Each BLE beacon can be programed to trigger in-vehicle messages depending on the direction of travel. The research team also conducted experiments to verify if any in-vehicle auditory message was triggered for traffic in the unintended directions. Figure 4-5 illustrates the vehicle trajectory of a sedan traveling in EB then making a U-turn around the roundabout at CSAH 53 and Richfield Parkway. The BLE beacon was mounted on a sign post as indicated in blue diamond in the figure. The beacon was programmed for WB traffic only. As shown in Figure 4-5, the BLE beacon was detected by the app on the test vehicle initially when the vehicle was traveling in the EB direction. However, the auditory in-vehicle message was not triggered because of the vehicle heading did not matched the direction programmed in the beacon. The auditory message was triggered after the test vehicle turning around the roundabout with heading in the WB direction. Similarly, experiments were also conducted at other locations on CSAH 53 to verify and validate the directional configuration of the BLE beacons.
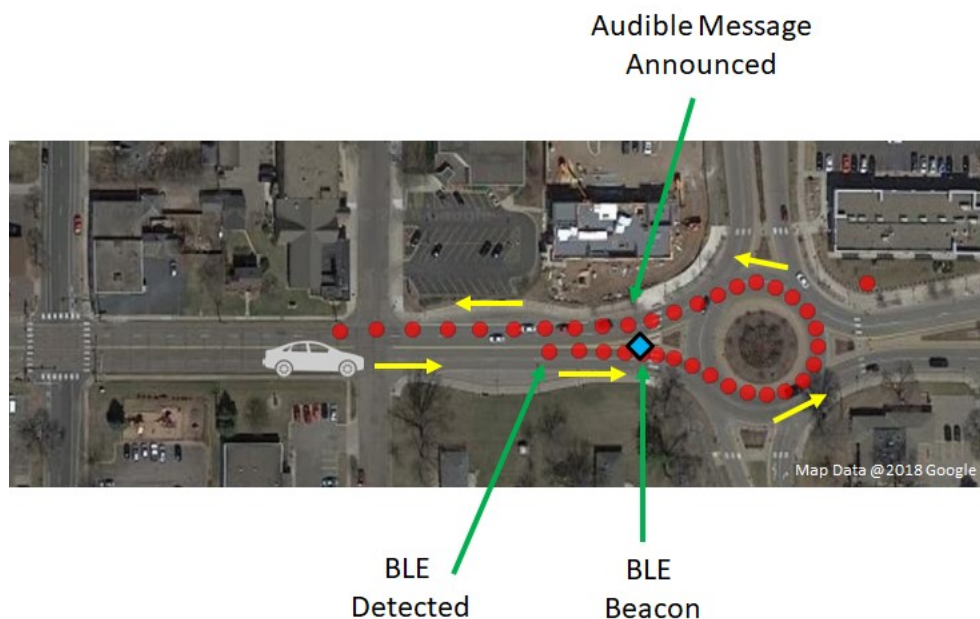
Figure 4.5 Trajectory of a Test Vehicle Traveling EB then Turning Around at a Roundabout.

The research team conducted 10 experiments at test site #2. On average, the work zone alert system was able to detect the BLE tag and announce associated auditory message when a vehicle is 167 m (548 ft) with a standard deviation of 38 m (125 ft) ahead of the work zone at CSAH 112 site. At posted work zone speed limit of 35 mph, our system averagely allows 10.7 sec of reaction time prior to the motorists approaching the location where a roadside beacon is installed.

Figure 4-6 displays the speed profile of a test vehicle traveling WB on CSAH 112 toward a work zone where heavy construction activities occurred on the west of CSAH 112. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 235 m (770 ft) away from a portable radar speed sign where the BLE beacon was mounted. The average Bluetooth detection range is longer at this location as compared to the CSAH 53 test site. The contributing factors may include: (1) Bluetooth beacons were mounted at a higher location (2.5 m above ground) on portable radar speed signs, and (2) traffic was lighter in this suburban location where traffic is lighter during the construction period. The posted speed limit at this work zone is 35 mph. Figure 4-6 indicates that the test vehicle traveled around 30-35 mph while entering the work zone. The red dots in Figure 4-7 illustrate the trajectory of the smartphone mounted in the test vehicle after the work zone message was triggered and announced.
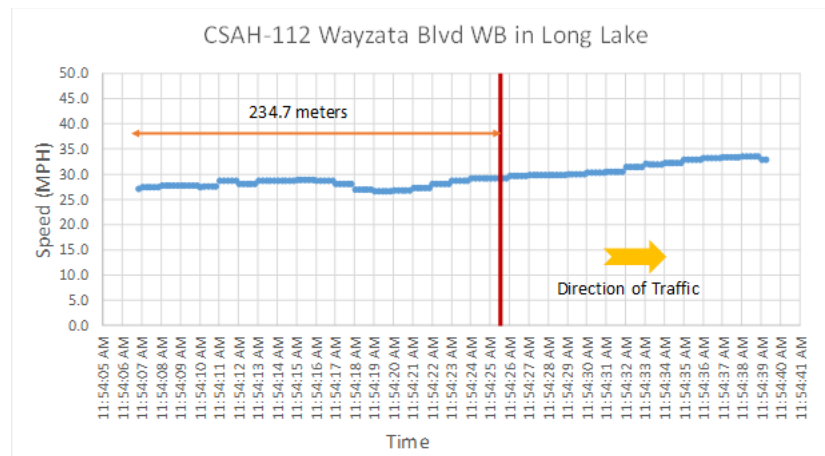

Figure 4.6 Speed Profile of a Test Vehicle Traveling WB on CSAH 112 in Long Lake.
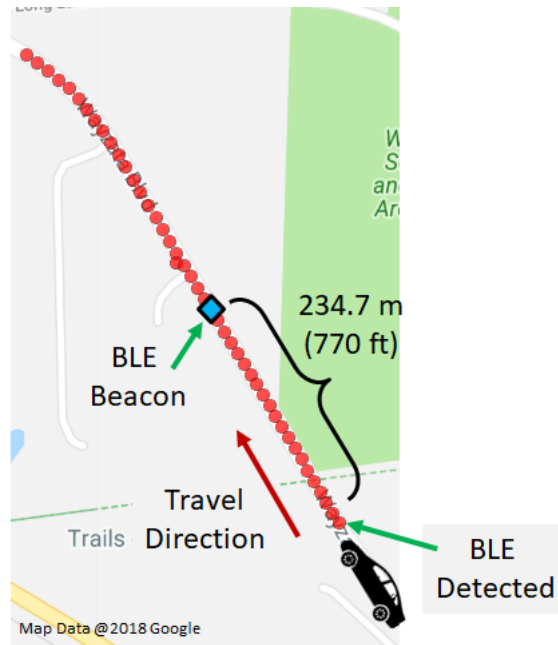
Figure 4.7 Trajectory of a Test Vehicle Traveling WB on CSAH 112 in Long Lake.

4.3 SITE #3 – MN 65

The research team performed 16 experiments at test site #3. On average, the results from the MN 65 site has an average BLE detection range of 125 m (410 ft) with a standard deviation of 31 m (102 ft). At posted work zone speed limit of 55 mph, our system averagely allows 5.1 sec of reaction time prior to the motorists approaching the location where a roadside beacon is installed.

Figure 4-6 displays the speed profile of a test vehicle traveling WB on CSAH 112 toward a work zone where heavy construction activities occurred on the west of CSAH 112. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 235 m (770 ft) away from a portable radar speed sign where the BLE beacon was mounted. The posted speed limit at this work zone is 35 mph. Figure 4-6 indicates that the test vehicle traveled around 30-35 mph while entering the work zone. The red dots in Figure 4-7 illustrate the trajectory of the smartphone mounted in the test vehicle after the work zone message was triggered and announced.
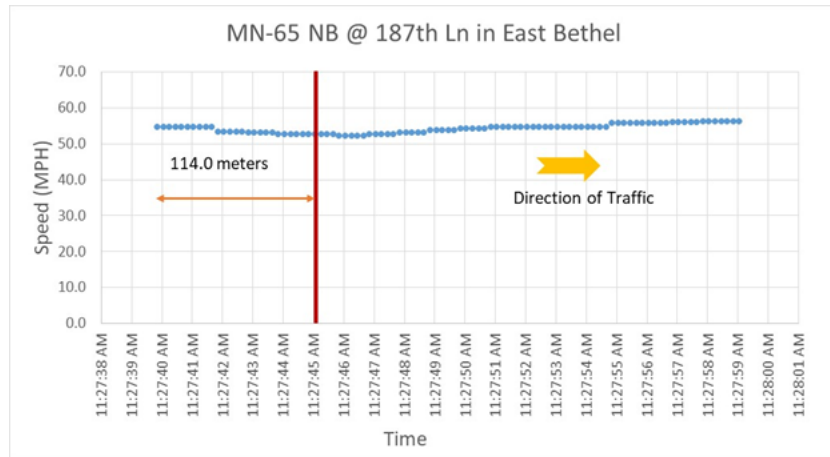
Figure 4.8 Speed Profile of a Test Vehicle Traveling NB on MN 65 in East Bethel.
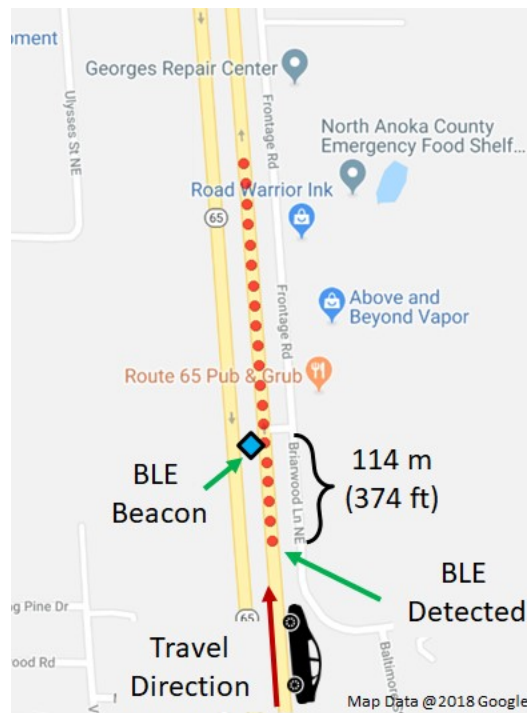

Figure 4.9 Trajectory of a Test Vehicle Traveling NB on MN 65 in East Bethel.

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CHAPTER 5: DISCUSSION AND SUMMARY

We have developed a Bluetooth low-energy (BLE)-based system that can be placed in a work zone or at key locations to provide in-vehicle warning messages to drivers. It has the capability to provide timely work zone information to motorists. A smartphone app (*WorkzoneAlert*) was developed to perform Bluetooth scanning and to announce the appropriate message corresponding to a Bluetooth tag when it is detected. The app automatically runs as a service in the background when a phone is turned on. A continuous Bluetooth scan is initiated when a vehicle enters a geo-fenced work zone. We chose the auditory in-vehicle message structure and content based on the results of a human factors study.

Another smartphone app was also developed for work zone deployment contractors to submit message updates. 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.

We deployed several BLE tags and conducted field experiments at three work zones (CSAH 53, CSAH 112, MN 65) in Minnesota. Experiments were conducted by installing the app on a smartphone mounted on a sedan or a minivan at different times of day and under different traffic conditions to evaluate the system performance. Vehicle location and timing of each triggered message were logged for data analysis. Table 5.1 lists 44 experiments that were conducted among the three construction sites. On average, the work zone alert system was able to detect the BLE tag and announce an associated auditory message when a vehicle was 106 m (348 ft) ahead of the work zone at the CSAH 53 site. The results from the CSAH 112 site showed an average BLE detection range of 167 m (548 ft). Similarly, the results from the MN 65 site showed an average BLE detection range of 125 m (410 ft). The average detection range at site 2 was longer than at the other two sites, which was probably partly due to the mounting height of the Bluetooth beacons and the lighter traffic condition during the construction period at this site.

Table 5.1 Summary of Experiments by Test Site

Corridor	CSAH 53	CSAH 112	MN-65
City	Richfield	Long Lake	East Bethel
Beacon Mounting Height (m)	1.2	2.5	1.5
Average Detection Range (m)	106.1	166.7	124.9
Detection Range SD (m)	54.9	37.6	30.8
Number of Experiments	18	10	16
Posted Work Zone Speed Limit (mph)	35	35	55
Average Reaction Time (sec)	6.8	10.7	5.1

The variation in the detection ranges of the beacons from site to site were largely influenced by beacon mounting height and traffic conditions (i.e., other vehicles around the test vehicle during each experiment). The Bluetooth wireless signals may be deflected or obstructed by vehicles nearby the test vehicle.

Previous experiment results on an interstate highway also suggested that it is feasible to receive BLE signals at highway speed.

Our test results indicated that the Bluetooth-based work zone information system is capable of providing in-vehicle messages for motorists approaching a work zone using the BLE technology. It can provide dynamic and location-based in-vehicle work zone information for motorists.

In the future, there is a need to develop guidelines for engineers and operational staff to select auditory information elements of in-vehicle messages that are compliant with standards. The app can potentially be integrated with the 511 or other navigation apps to receive work zone information statewide. Currently, there are crowdsourcing-based solutions (such as Waze) in the market. However, the information availability and description of these solutions are inconsistent. In addition, the crowdsourcing-based solution has no information quality check and validation, which could cause driver distractions.

In rural areas where cellular reception is spotty, our system can provide a default work zone message when a BLE tag is detected and no message update associated with the detected beacon is available. In areas where GPS signal reception is poor and a positioning solution is not available, the Bluetooth scanning on the smartphone can be initiated automatically to continuously look for work zone beacons within the range of BLE communications.

We believe a timely warning message tailored to the individual driver's behavior can improve the situation awareness of the driver and his or her response to the work zone, particularly when there are workers on site and construction work is in progress.

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APPENDIX A

DRAWINGS OF SOLAR PANEL MOUNTING ASSEMBLY

Figure A.1 is the drawings for two 1-in angle bars that were directly attached to the solar panel. Another two ¾ in angle aluminum bars (as illustrated in Figure A.2) were used for adjusting the tilt angle of the solar panel. And, the mounting L bracket shown in Figure A.3 was used for attaching the entire assemble to a lamp post using a stainless steel worm gear clamp (Figure A.4).
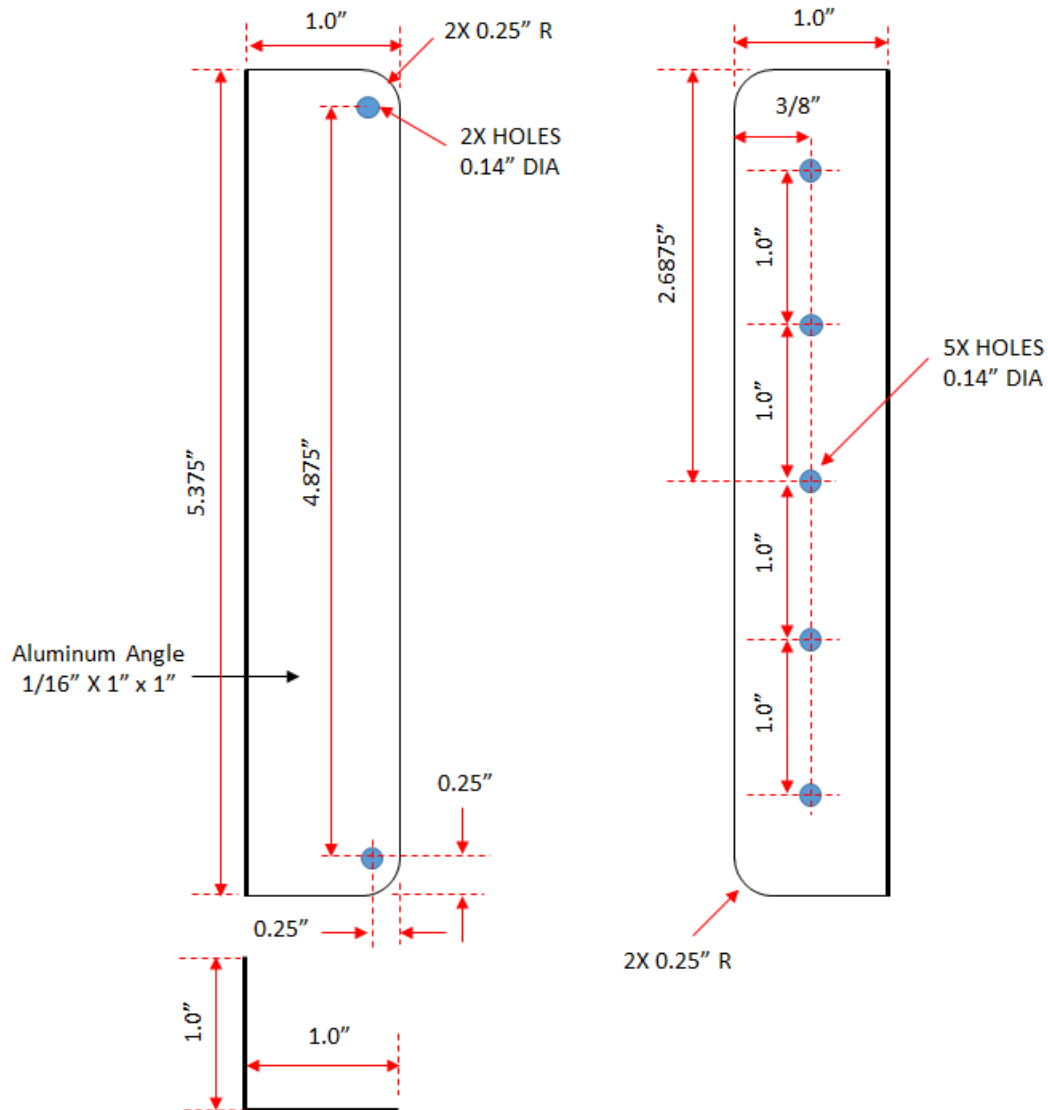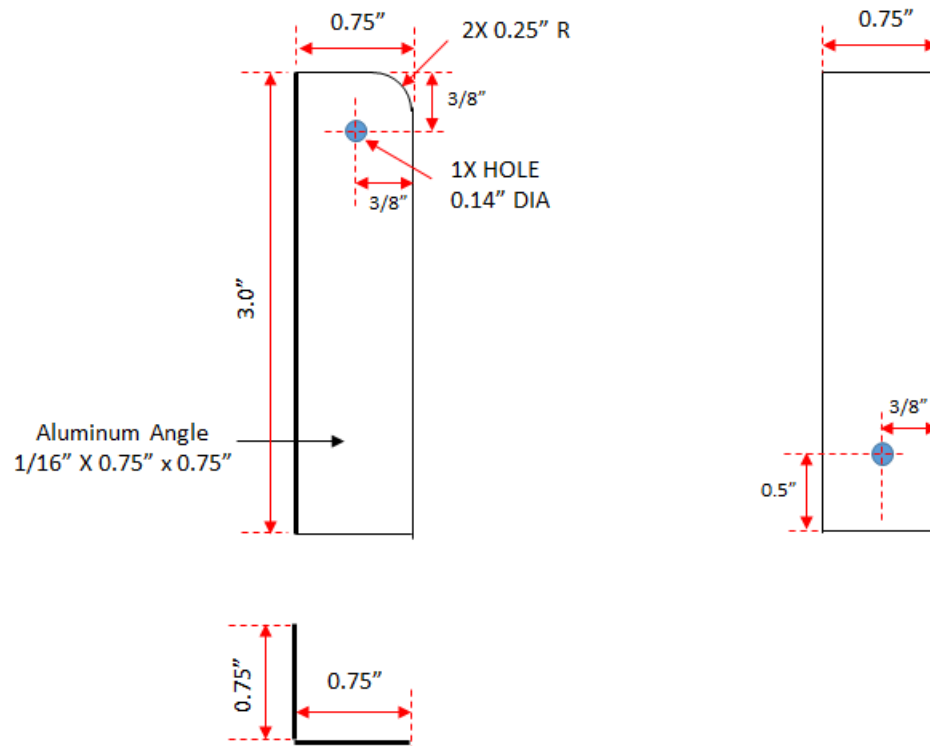

Figure A.1 Drawings of Angle Bar for Holding Solar Panel
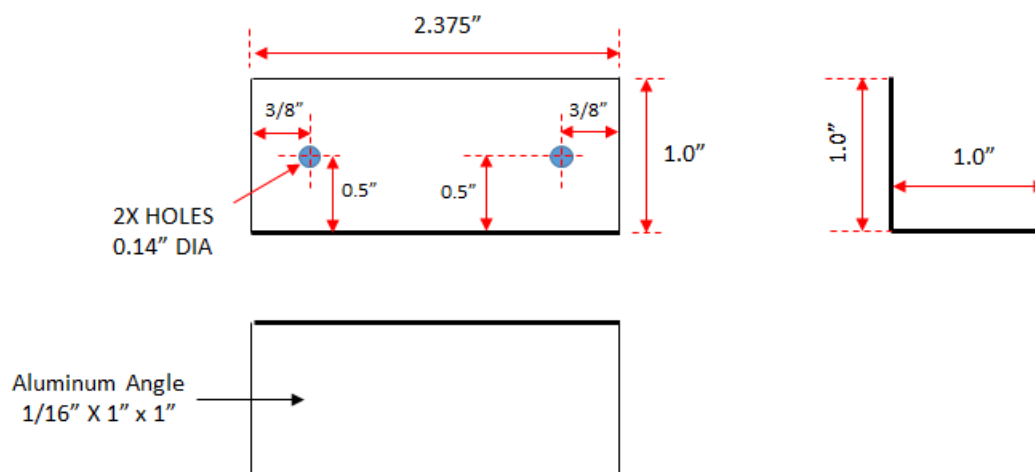
Figure A.2 Angle Bars for Tilt Angle Adjustment

Figure A.3 Mounting L-Bracket

Figure A.4 Solar Panel Mounting Assembly

APPENDIX B

ADDITIONAL EXPERIMENT RESULTS

Figure B.1 displays the speed profile of a test vehicle traveling EB on CSAH 53 toward a work zone near Logan Ave S. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 91 m (297 ft) away from the location where the BLE beacon was mounted. The red dots in Figure B.1 illustrate the GPS coordinates of the vehicle after the work zone message was triggered.
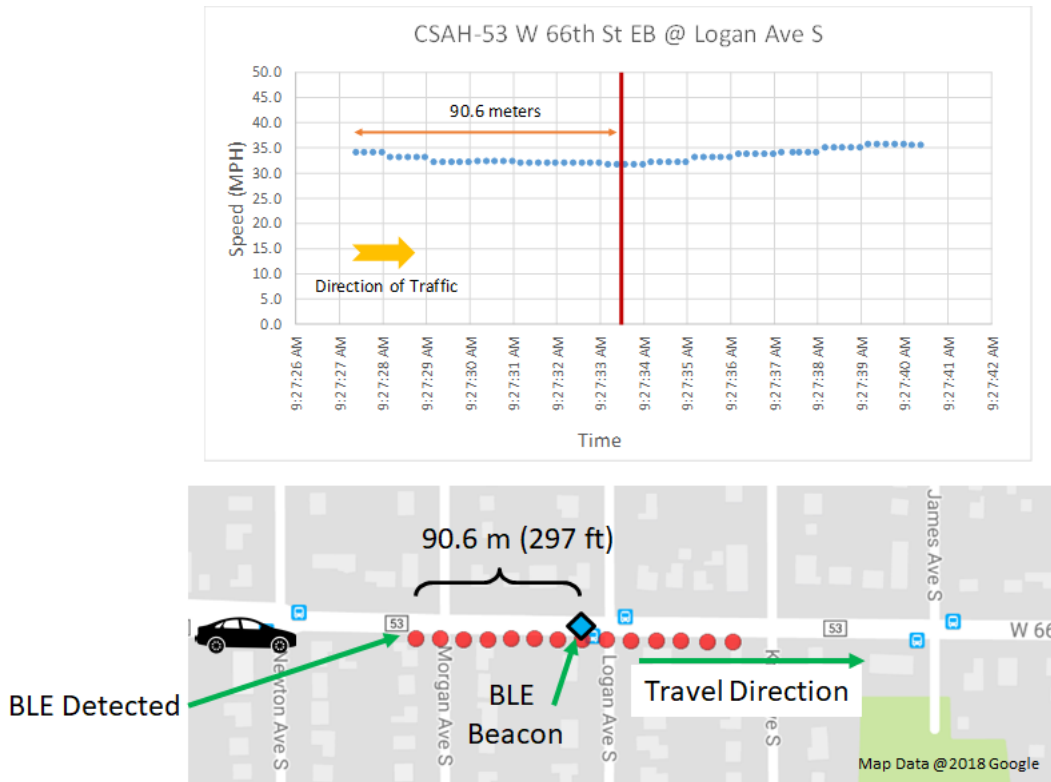

Figure B.1 Speed Profile and Trajectory of a Test Vehicle on CSAH 53 EB at Logan Ave S.

Figure B.2 displays the speed profile of a test vehicle traveling WB on CSAH 53 toward a work zone near Chicago Ave S. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 175 m (575 ft) away from the location where the BLE beacon was mounted. The red dots in Figure B.2 illustrate the GPS coordinates of the vehicle after the work zone message was triggered.

Figure B.3 displays the speed profile of a test vehicle traveling WB on CSAH 112 toward a work zone in Long Lake, MN. The BLE beacon was mounted on a portable radar speed sign. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 204 m (668 ft) away from the location where the BLE beacon was mounted. The red dots in Figure B.3 illustrate the GPS coordinates of the vehicle after the work zone message was triggered.
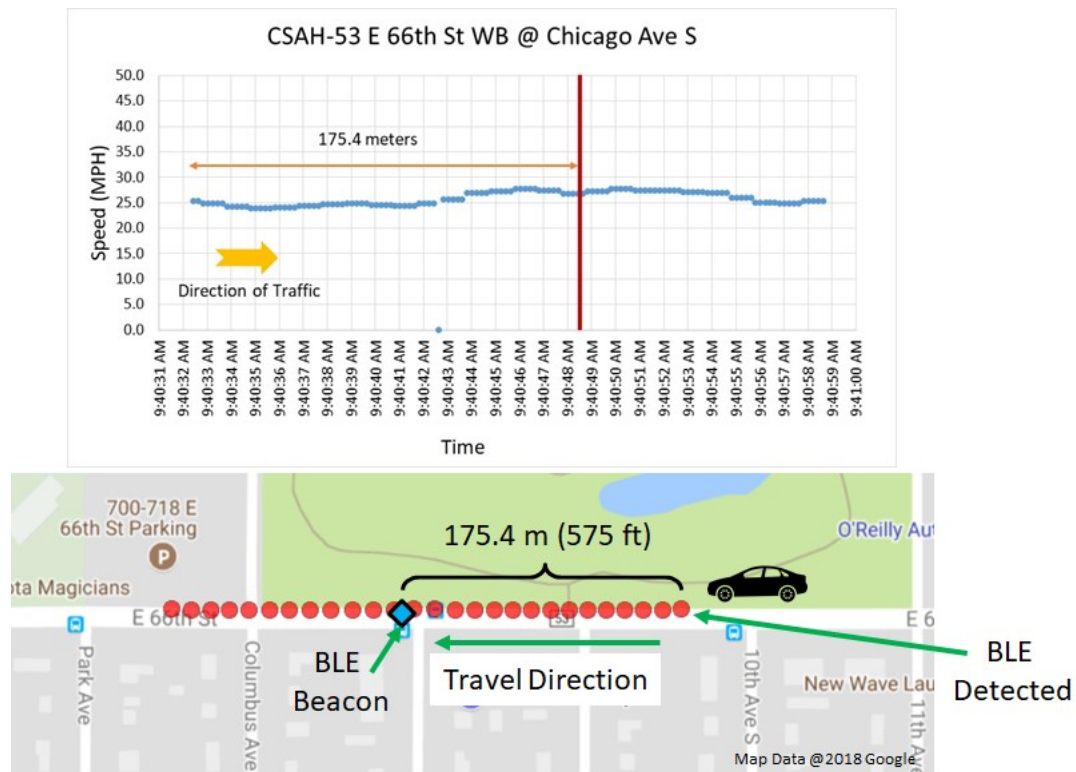
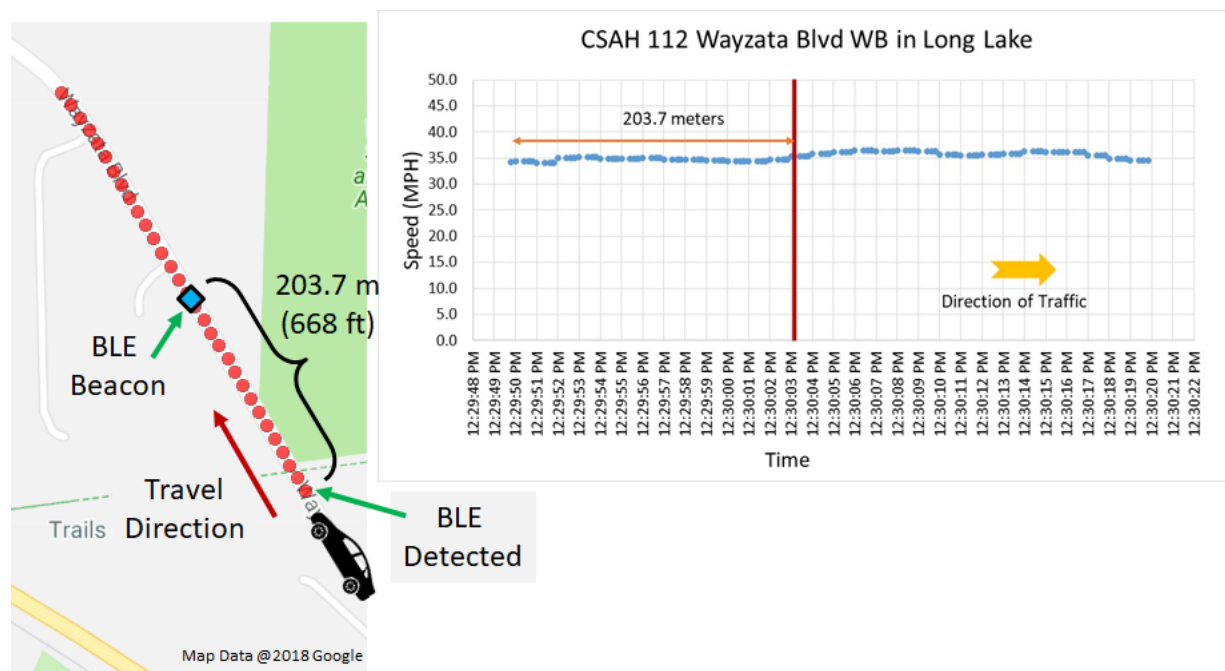Figure B.2 Speed Profile and Trajectory of a Test Vehicle on CSAH 53 WB at Chicago Ave S.

Figure B.3 Speed Profile and Trajectory of a Test Vehicle on CSAH 112 WB in Long Lake.

Figure B.4 displays the speed profile of a test vehicle traveling SB on MN 65 toward a work zone south of Vikings Blvd in East Bethel, MN. The BLE beacon was mounted on a traffic sign. An auditory in-vehicle message (*Attention! Work zone ahead. Use caution!*) previously programmed and stored in the cloud was triggered and announced about 144 m (472 ft) away from the location where the BLE beacon was mounted. The red dots in Figure B.4 illustrate the GPS coordinates of the vehicle after the work zone message was triggered.
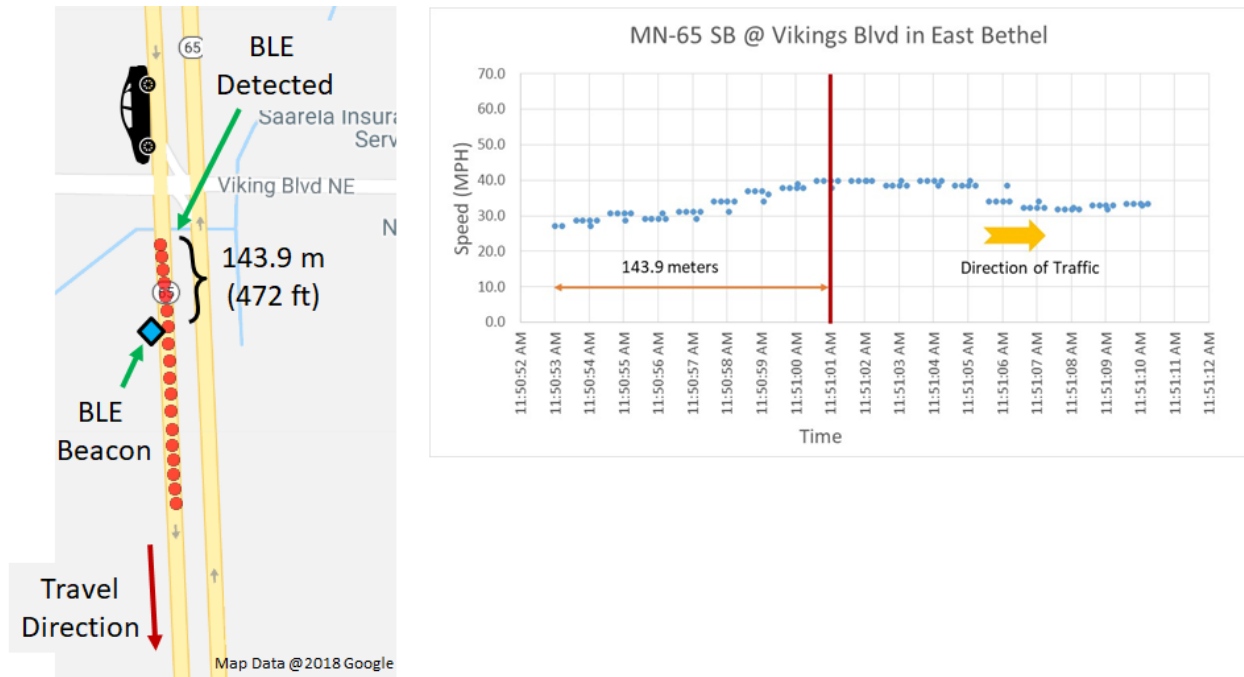

Figure B.4 Speed Profile and Trajectory of a Test Vehicle on MN 65 SB in East Bethel.