Developing a Hazard Detection and Alert System to Prevent Incidents

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16. Abstract

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Abstract

The proposed project aimed to develop a cost-effective, user-friendly, and reliable hazard detection and alert system to prevent crashes between construction equipment/vehicles and workers on foot in work zones. The envisioned system includes wearable proximity sensors for the workers and an in-vehicle portable detection system for the operators. The system was designed to notify operators and workers promptly when equipment/vehicles are backing up and workers are nearby. The system employed Bluetooth Low Energy (BLE) beacon technology that enables a bidirectional detection and alert system to prevent crashes between equipment/vehicles and workers. However, the developed system had limitations associated with environmental and natural factors. The project concludes that BLE beacon technology is unsuitable for developing a safety detection and alert system for work zones.

Executive Summary

Work zones often create traffic conditions and road environments that are predisposed to incidents despite the presence of regulatory measures and various safety protocols. In the United States, work zone-related fatalities have persisted as a significant highway safety concern. Between 1982 and 2020, a total of 29,410 individuals, including both road users and workers, lost their lives within work zones, averaging approximately 774 fatalities per year. Moreover, the severity of work zone crashes has worsened in recent years, with the proportion of fatal crashes within total work zone incidents increasing from 1.8 percent to 2.2 percent between 2011 and 2020.

Work zone crashes exhibit considerable heterogeneity in location, contributing factors, and incident characteristics. Rear-end collisions are the most prevalent incident within work zones, often attributed to speeding. However, work zone accidents can also occur within the workspace designated for construction activities. Workers on foot face substantial risks, including the danger of being struck by operating equipment/vehicles in the workspace. A backing incident occurs when equipment/vehicles moving backward strike a worker on foot. Backing incidents are a critical work zone safety issue. For example, backing incidents accounted for 14.9 percent of worker fatalities in work zones in 2003-2010.

The project aimed to develop and test a cost-effective, user-friendly, and reliable hazard detection and alert system to prevent work zone crashes between construction equipment/vehicles and workers on foot. Workers on foot need help maintaining constant vigilance regarding the movement of equipment/vehicles in work zones. Also, the operators of heavy equipment/vehicles may find their awareness compromised due to various cognitive and physical impediments associated with work zone environments. These issues are particularly concerning when workers on foot are located outside the operator’s line of sight, such as within blind spots or behind barriers, increasing the potential crash risk. Even when drivers can visually identify workers on foot and attempt to alert them through conventional auditory or visual alarms, the efficacy of these warnings can be undermined by factors like ambient noise or inattention. These situations can have severe and, at times, fatal consequences.

This project uses Bluetooth Low Energy (BLE) beacon technology to develop a system to promptly notify workers and equipment/vehicle operators in motion or engaged in backing-up maneuvers, thereby effectively protecting workers on foot. The system developed had a bidirectional detection and alert system comprising wearable proximity sensor (WPS) tags for workers on foot and an in-vehicle portable detection (iVPD) system for equipment/vehicle operators. However, the field test results of the developed system indicate that the BLE beacon technology may not be usable for developing a bidirectional detection and warning system to prevent crashes involving workers on foot and construction equipment/vehicles in work zones. The system could not demonstrate an accurate and reliable capacity in detecting and alerting hazards. It is concluded that the BLE beacon technology cannot effectively control for various interferences associated with work zones' locational and environmental features.

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Chapter 1 Introduction

The project aimed to develop a cost-effective and reliable hazard and alert system for work zones to prevent backing incidents between construction equipment/vehicles and workers on foot. The system was designed to be a bi-directional detection and alert system that leverages advanced Bluetooth beacon technology that enables device-to-device direct communication.

1.1 Hazard Detection and Alert System Architecture

The proposed system has two major components:

- Wearable Proximity Sensor (WPS) Tags: These lightweight, wearable tag devices have a communication handler to provide sound warnings. They are designed for workers on foot and, thus, also referred to as Human Tags (HTs).

- In-Vehicle Portable Detection (iVPD) System: This component incorporates a Bluetooth Light Energy (BLE) beacon communication handler and an application that visualizes the locations of WPS tags tailored for equipment/vehicle operators.

In addition, the project team developed a Vehicle Proxy Tag (VPT), which can be attached to the back side of equipment/vehicles. This component was developed to improve direct signal advertising and scanning between WPS and iVPD.

The system employed advanced Bluetooth Low Energy (BLE) beacon technology for device-to-device direct communication between WPS and iVPD. The technology could provide a cost-effective solution for developing a positioning system without a GPS since it has been utilized for indoor positioning systems (Litum, 2021). Smartphones and tablets could be used for iVPD, which operates the application. The system was developed to provide real-time location of workers on foot for equipment/vehicle operators, and the workers were also informed of backing equipment/vehicles that pose safety risks.

A key innovation of this project is incorporating integrated operational concepts that use Vehicle-to-Crew (V2C) data between iVPD and WPS. These concepts serve two primary objectives:

- Decreasing Work Zone Incidents: This is achieved by a system hazard detection and alert system that provides positioning information without expensive communication devices and wireless communication technologies.

- Enhancing System Accuracy and Reliability: This is achieved by the system that delivers timely warnings of imminent collisions to workers on foot and construction equipment/vehicle operators, particularly those distracted. This enhancement is crucial in ensuring the system's effectiveness in real-world work zone environments.

1.2 System Design

The proposed system incorporates operational concepts that leverage Vehicle-to-Crew (V2C) data, aiming to reduce work zone incidents without needing costly communication devices or wireless technologies. This approach enhances the system's accuracy and reliability by providing timely warnings of potential collisions to workers on foot and operators. The technical aspects of the system design include the development of a beacon communication handler that utilizes embedded beacon stuffing technologies for BLE. The project team also devises an effective position detection algorithm for embedding into smart devices. Furthermore, the project team creates a visualization application package, iVPD, which can be deployed on smart devices. The iVPD app is implemented using a cross-platform integrated development environment (IDE), such as React Native, to facilitate iVPD visualization and neighbor discovery, including frequency, color, alert type, and more.

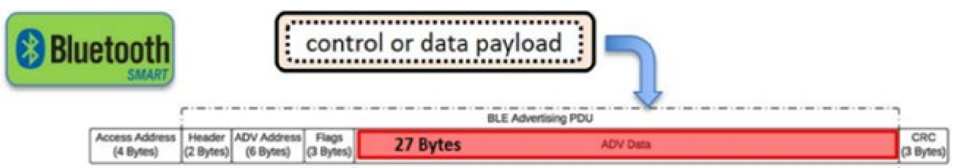


Figure 1.1 BLE Beacon Stuffing

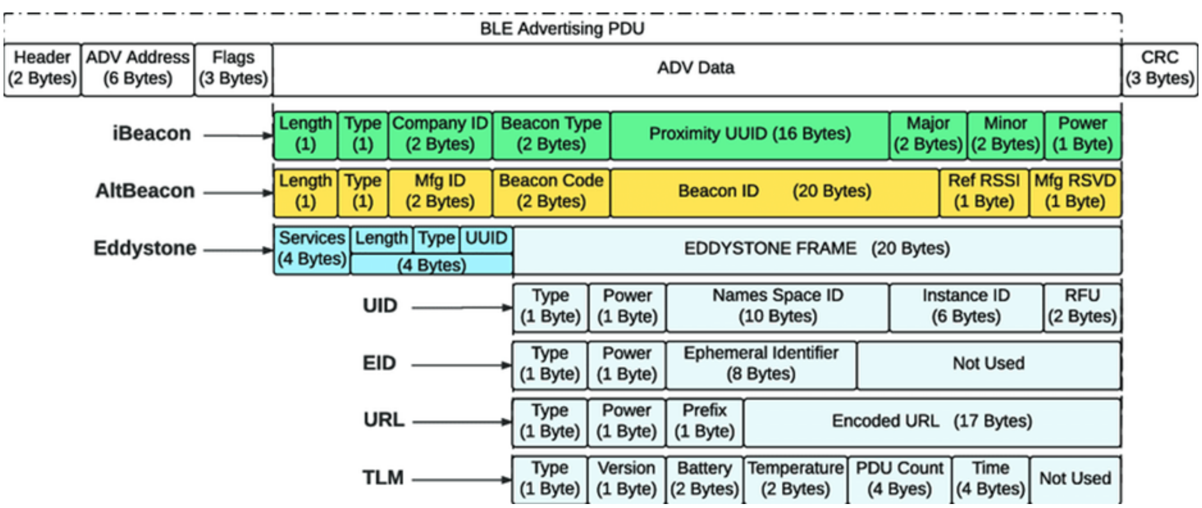


Figure 1.2 BLE Beacons' Packet Structures

The proposed system and its significance are outlined as follows: In pursuing a cost-effective and practical safety solution that does not rely on specialized communication devices, the system utilizes Bluetooth-enabled devices. Conventional wireless protocols have typically been unsuitable for issuing timely emergency alerts to mobile entities due to prolonged association delays and insufficient coverage ranges. To expedite warnings to both workers on foot and equipment/vehicle operators, the proposed approach eliminates the two to three-second BLE device connection overhead by introducing a concept known as "beacon stuffing."

Figure 1.1 illustrates the utilization of beacon frames to fulfill alert functions. These frames encapsulate vital information, including object identification, characteristics, geographic location, speed, and direction, within a beacon frame's Service Set Identifier (SSID). The SSID serves as a human-readable network identifier, with specifications varying (e.g., 27 bytes for Bluetooth protocol) (See **Figure 1.2**). The WPS and iVPD components actively detect periodic beacons to monitor nearby objects.

The system addressed challenges related to power consumption and potential congestion arising from the periodic broadcast of beacon messages. The project team proposed communication protocols based on specific Service Set Identifiers (SSID) to mitigate possible beacon congestion in densely populated areas. Despite mechanisms for spatiotemporal frequency isolation within beacon protocols, interference may still occur due to concealed nodes, periodic message delivery, and broadcast. The quest is to identify a more efficient beacon technology capable of reducing collisions and addressing issues related to power consumption.

Several theoretical studies have highlighted the high collision probability associated with periodic beacon transmission. One novel approach involves the utilization of SSID-based beacon probe requests and responses akin to the format of Wi-Fi beacon frames. However, the probe response is issued in direct response to a probe request, and it does not include the Traffic Indication Map (TIM) typically used to identify stations operating in power-saving mode. Rather than configuring tags to transmit beacon frames periodically, the proposed technology enabled tags to operate in a listening mode, responding only when prompted by a probe request initiated periodically by Proximity Alerts (PAs). Another innovative strategy in the proposed system development involved tags transmitting probe requests containing a specific SSID, thus eliciting only one probe response from the corresponding group of tags. This method helps control the level of concurrent probe responses, enhancing power efficiency and reducing the volume of beacon messages within the network.

Developing intelligent positioning algorithms to generate timely and accurate warnings is essential to this project. The project team also crafted relative positioning technologies for mobile entities to enhance the accuracy and efficiency of hazard alerts. However, location accuracy may be compromised as both objects move across quasi-random positions, accumulating positional errors. To mitigate these challenges, the project team designs an efficient relative positioning technology that primarily measures the changing distance and its trend between objects. The positional information with the calculated directions is used to determine the filtering range for unrelated beacon messages, reducing the likelihood of false positives. Given the critical importance of construction worker safety, the project team evaluated to reduce the chance of false positive alerts while ensuring no false negatives.

As for WPS tags, the project team designed the alert system to be bi-directional, cost-effective (less than sixty dollars per tag with no maintenance costs), flexible regarding form factors, and power efficient. The project team uses the ESP32 chipset, which offers a small form factor and integrates low-cost, low-power, systems-on-a-chip microcontrollers with built-in dual-mode Bluetooth 4.2 communication capabilities and antenna switches.

WPS tag comprises a BLE beacon module, a rechargeable battery, and auditory alerts. It can be attached to a helmet for practical use. These WPS tags broadcast periodic beacon messages every 100 milliseconds, containing device identification, location, and travel information, including speed and direction. The project team designs and develops a reliable method for embedding information into these beacons using beacon stuffing technology. The beacons are updated when there is a significant change in the device's speed and direction of travel, allowing for the precise computation of direction vectors for each object. The iVPD generates a spatiotemporal awareness of the surrounding environment by visualizing object locations.

WPS incorporates a beacon communication handler and offers auditory alerts. At the same time, iVPD includes a beacon communication handler and a software application for visualization and warnings. The beacon communication handler continuously monitors its surroundings by emitting periodic messages at 100-millisecond intervals. These beacons contain essential information, such as device identification and geographic location. The project team implements reliable information embedding techniques using beacon stuffing technology (Chandra et al., 2007; Choi et al., 2018; Song et al., 2018). Beacons are updated whenever a significant change in the device's speed and direction occurs. This information is harnessed to compute precise direction vectors for each object. iVPD plays a pivotal role in generating a spatiotemporal understanding involving equipment/vehicles and workers on foot. The system actively alerts equipment/vehicle operators through sounds and display screens. Simultaneously, WPS is designed to detect approaching equipment and vehicles to workers on foot and alert them via audio warning.

A key finding from preliminary system testing was a design issue that led to significant variation in distance measurements associated with the presence of substantial obstacles (e.g., a dump truck, as shown in **Figure 1.3**). Due to the considerable cargo length of construction vehicles, the size of obstacles encountered may exceed the range capabilities of the BLE signal to and from the nearby WPS or HT harnessed to safety helmets. It needs to be noted that interfering obstacles can also include manufactured and natural features and humans affecting or blocking BLE beacon signals. Consequently, the signals exhibit uncontrollable levels of variation and accuracy. Also, the project team occasionally experienced limited signal reachability when imposing distance restrictions, whereas allowing unrestricted length results in significant signal variation.

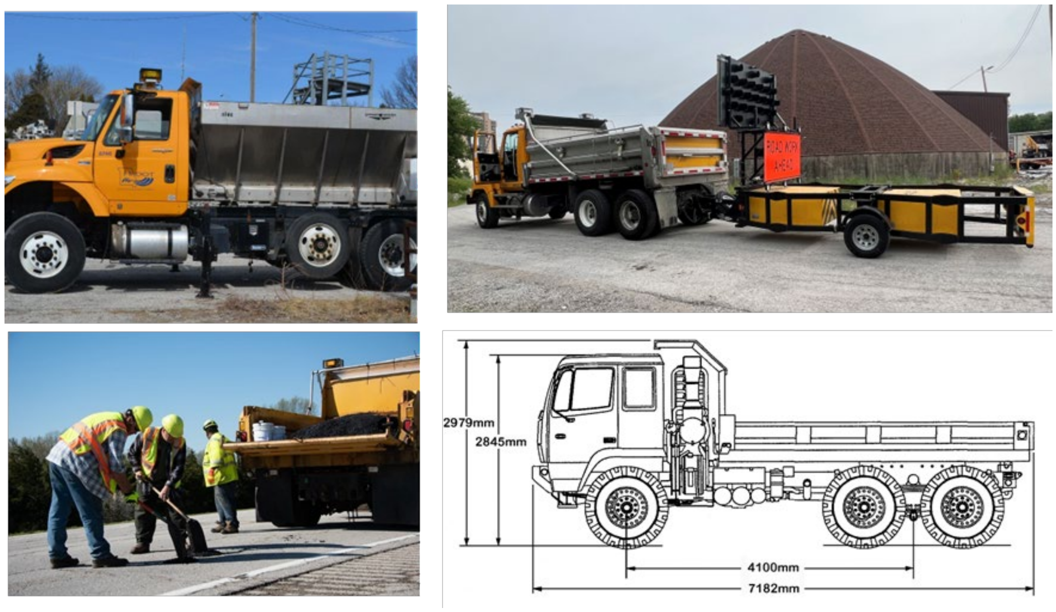


Figure 1.3 Construction Vehicle Form Factors

The project team addressed obstacles' interference with the system with Vehicle Proxy Tag (VPT) to mitigate the problem. VPT was designed to mitigate the limitations of iVPC associated with obstacles by extending signal advertising and scanning. The iVPC app establishes communication with the VPT and performs scanning operations. By leveraging this setup, the VPT can advertise beacon signals to the receiving HT, overcoming the issues related to signal variation and accuracy arising from large obstacles. In the proposed approach, a VPT is attached to the rear end of equipment/vehicles, as illustrated in **Figure 1.4**. **Figure 1.4**. shows the system hardware and configuration designed for the project.

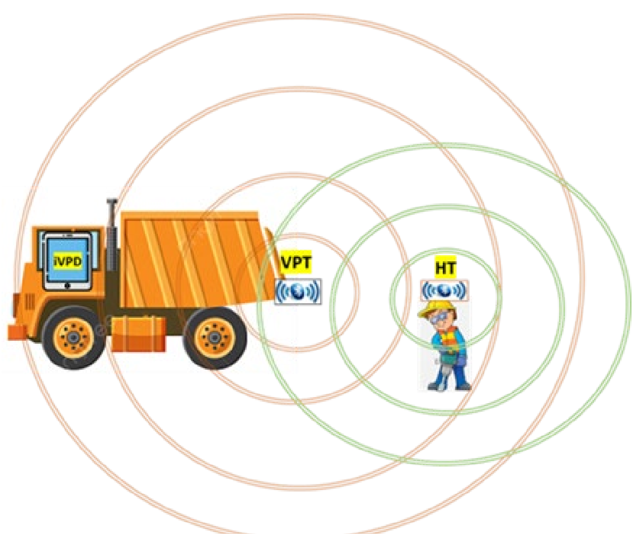


Figure 1.4 Proposed Hazard Detection and Alert System for Work Zones

Chapter 2 Literature Review

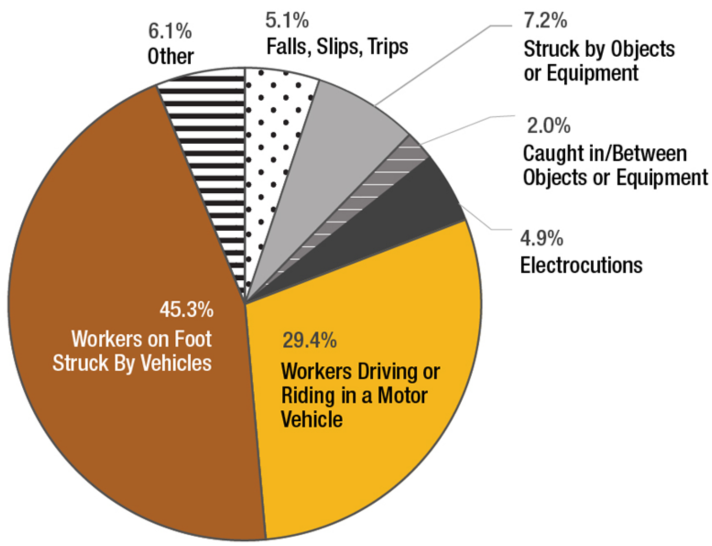
Work zones often create traffic conditions and road environments prone to crashes (Ullman et al., 2018). Work zone crashes have remained a significant highway safety concern despite various regulations and safety measures. In the United States, from 1982 to 2020, a total of 29,410 lives were lost within work zones, averaging approximately 774 fatalities per year, as reported by NIOSH (2022, n.d.-a) and NWZSIC (2022a). Notably, there was a decline in work zone fatalities during the 2000s after reaching a peak of 1,186 deaths in 2002. However, between 2011 and 2020, the number of work zone fatalities increased by 45.2 percent, from 533 to 774 deaths, as reported by NWZSIC (2022a). This increase in work zone fatalities significantly outpaced the 19.9 percent increase in total traffic fatalities during the same period (Stewart, 2022). Furthermore, the severity of work zone crashes worsened, with the share of fatal crashes in total work zone incidents increasing from 1.8 percent to 2.2 percent between 2011 and 2020, as noted by Stewart (2022).

Work zone incidents exhibit notable heterogeneity in location, contributing factors, and vehicle crash characteristics. Rear-end collisions are the most frequently occurring incident in work zones, often with speeding as a contributing factor (Stewart, 2022). Work zone crashes are not confined to interactions with passing vehicles but also extend into the workspace reserved for construction workers and equipment used for field activities. Highway workers, particularly those on foot, face substantial risks, including the potential for injury from passing vehicles and the movement of heavy equipment, such as construction equipment and vehicles entering and exiting the work zones. National work zone safety statistics indicate that workspace incidents are frequently associated with mobile equipment backing up (FHWA, n.d.; NIOSH, n.d.-a.; Pegula, 2013). Consequently, a comprehensive understanding of backing incidents within the workspace and implementing measures to safeguard workers on foot are paramount in enhancing work zone safety.

2.1 Crashes Involving Workers on Foot in Work Zones

2.1.1 Backing Incidents in Work Zones in the US

A backing incident occurs when equipment moving backward strikes a worker on foot. A study reported that 14.9 percent of worker fatalities in work zones from 2003-2010 were related to mobile equipment backing up (Pegula, 2013). Among those crashes, dump trucks had the highest involvement rate of 58.7 percent.



Source: National Work Zone Safety Information Clearinghouse (NWZSIC), 2022b

Figure 2.1 Average Highway Worker Fatalities in Work Zones in 2017-2019

BLS work zone crash data for 2017-2019, as shown in **Figure 2.1**, estimated that 9.2 percent of the highway worker fatalities were related to either being struck (7.2 percent) by equipment/objects or caught (2.0 percent) in/between equipment/objects (NWZSIC, 2022b). However, all those fatally injured workers were not necessarily on foot, though most might have been. While crashes involving equipment backing up in work zones are not uncommon, there is a shortage of detailed data and studies on incidents involving workers on foot in these areas, leading to an incomplete understanding of such incidents. In addition, detailed statistics and information on non-fatal work zone backing incidents are unavailable. Despite incomplete information, the existing work zone fatality data still implies that backing incidents are a substantial work zone safety issue that needs to be addressed.

2.1.2 Backing Incidents in Missouri's Work Zones

The Missouri Department of Transportation (MoDOT) provided a database of backing crashes involving MoDOT equipment for this project. The database included 1,156 reported crashes that occurred between 2012 and 2021. It contains a brief description and date for each crash. **Figure 2.1** provides annual trends of backing crashes, including those involving third parties ("Claim") and those not involving third parties ("Event"). However, it should be noted that the database includes crashes that occurred in work zones and non-work zone areas. **Figure 2.2** shows that the number of backing crashes has declined overall, even though the number significantly spiked in 2019. The decrease in backing crashes is attributed mainly to reduced crashes among MoDOT equipment or personnel without third-party involvement. However, this crash database indicates that backing crashes are still a substantial work zone safety issue in Missouri. Over the past decade, on average annually, more than 100 backing crashes involving MoDOT equipment occurred, although the crash frequency has declined overall.

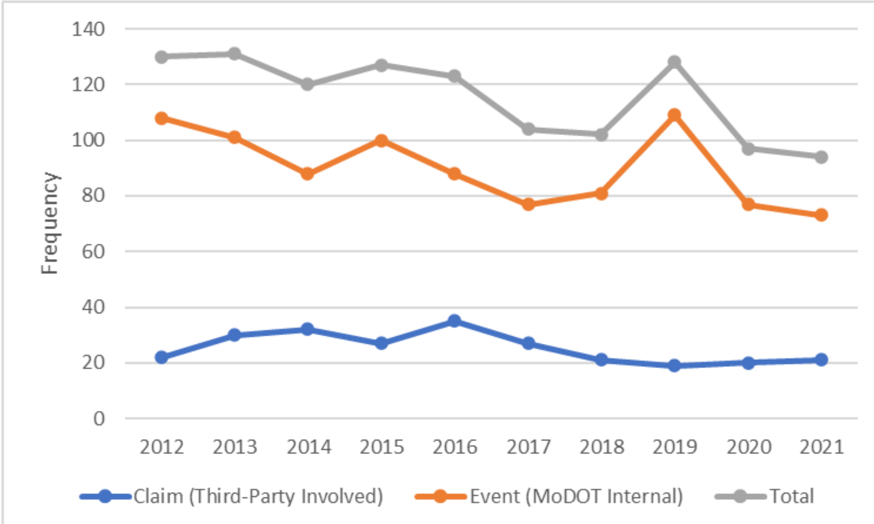


Figure 2.2 Backing Crashes MoDOT's Equipment or Personnel Involved in 2012- 2021

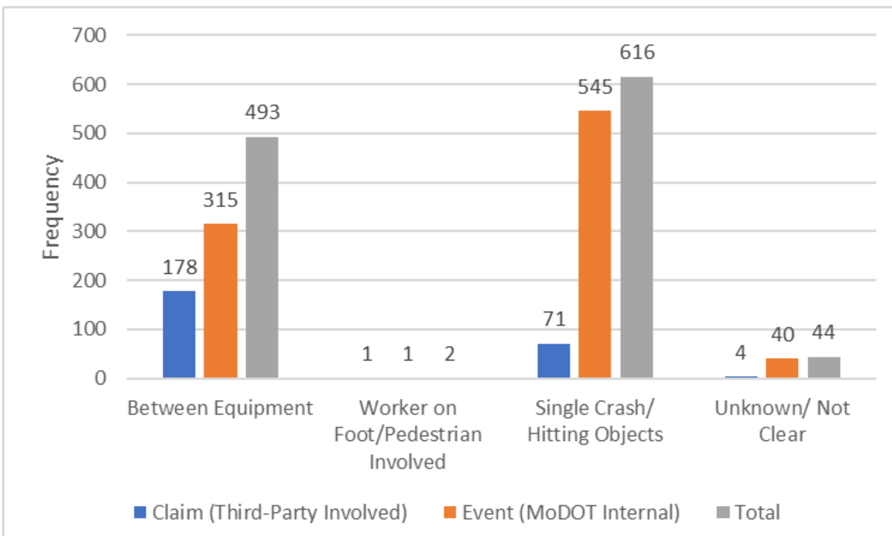


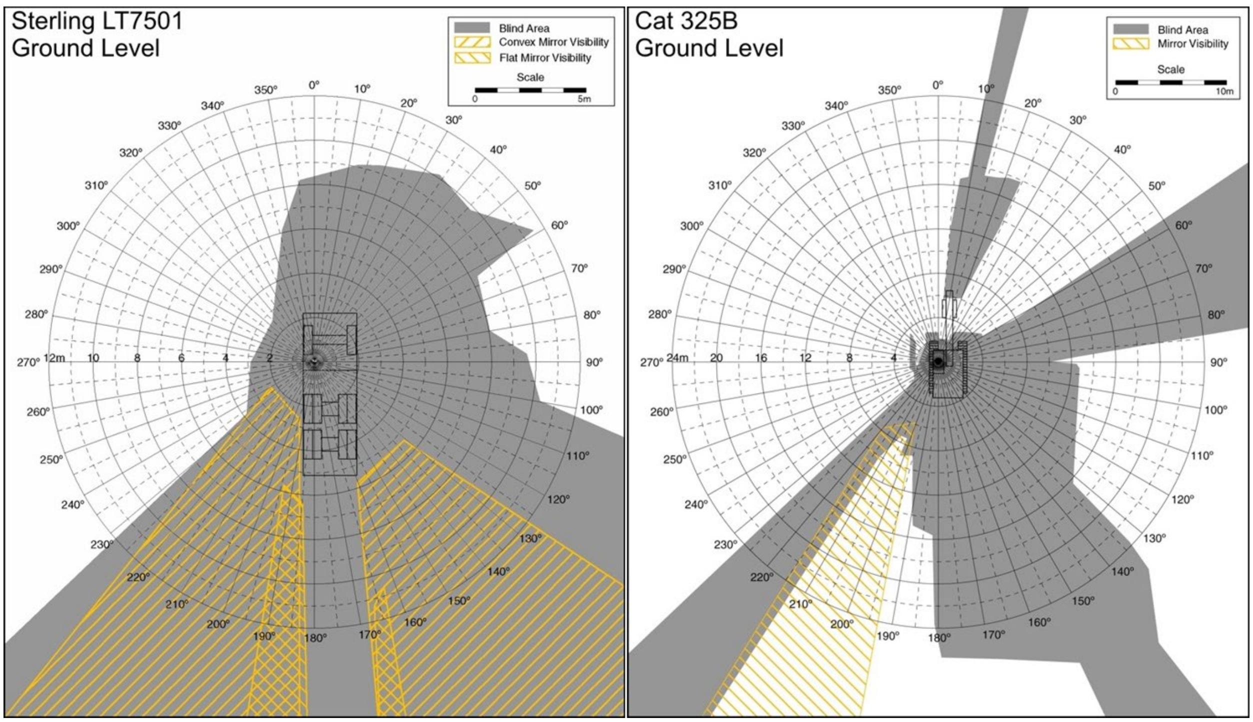
Figure 2.3 Types of Backing Crashes Reported to MoDOT in 2012-2021

Based on the descriptions provided in the database, 1,156 reported crashes were classified into three major categories. As shown in **Figure 2.3**, the most common type of backing crashes was single crashes involving MoDOT equipment hitting an object (e.g., bay/garage door, mailbox, utility pole/line) or leaving the roadway (e.g., ditching). In addition, there was one backing incident involving a pedestrian and another involving a worker on foot. The pedestrian crash in 2020 occurred when a MoDOT operator backed up at a traffic stop. The 2018 crash involving a MoDOT worker on foot occurred when a MoDOT operator tried to hook up a plow to a truck. Even though there was visual contact between the operator and the spotter, the worker on foot was bumped by the backing truck. The database did not include any injury information of the worker on foot. However, it is worth noting that the presence of a spotter did not prevent the backing incident.

2.2 Backing Incidents and Prevention Efforts

2.2.1 Equipment Blind Area

Workers on foot in the workspace are vulnerable since they often work close to heavy construction equipment and vehicles with large blind areas. A blind area is a crash hazard, and workers in the area are invisible to the operators, even with internal and external rearview mirrors. Each equipment unit has a unique blind area, and the size of the area varies significantly. In general, the larger the equipment, the larger the blind area. For workers on foot, it is difficult to figure out each equipment unit's unique blind area.



Source: National Institute for Occupational Safety and Health (NIOSH) (n.d.-b.)

Figure 2.4 Ground Level Blind Area Diagrams of a Dump Truck (Sterling LT7501) and a Hydraulic Excavator (Caterpillar 325B)

Figure 2.4 illustrates the ground-level blind area of a dump truck and an excavator, which are often used in work zones. When workers on foot are in blind areas (in grey) not covered by mirror visibility areas (in yellow), operators cannot see them. For operators, blind areas are more prevalent behind vehicles. Thus, backing movements can potentially endanger workers on foot in blind areas. In addition, work zone noises and workers on foot not being able to pay attention to their surroundings increase the danger even more without a spotter and hazard detection/alert equipment.

2.2.2 Safety Systems to Prevent Backing Incidents

2.2.2.1 Conventional Systems to Prevent Backing Incidents

Various systems have been implemented to prevent backing incidents in work zones. They are low-tech but still prevalent measures and used by highway agencies. The summary of these systems is described below.

Internal Traffic Control Plan (ITCP): Preventing backing incidents in the workspace has various forms, from an ITCP and spotter to mobile sensing devices designed to detect nearby workers. An ITCP is a temporary traffic control plan typically developed for a specific work zone and involves the development of schematic diagrams for the movements of equipment and workers. An ITCP can also be used to separate workers on foot from operating equipment (ARTBA, 2016). As a critical component of work zone safety, an ITCP coordinates the flow of equipment and workers operating and working in proximity within a work zone (Pratt et al., 2001). It also informs all parties operating within the workspace about the locations of others.

An ITCP also includes the following (ARTBA, 2016):

- Define the chain of command and the role of the on-site ITCP coordinator.
- Designate safe areas for workers to separate moving vehicles from workers on foot.
- Designate and mark appropriate paths for work vehicles and equipment with a speed limit.
- Develop an operational communication plan, including communication methods.
- Define specific operating procedures for trucks delivering materials in the workspace.

Spotter: Employing a spotter in the workspace has been a critical component of work zone safety. Spotters inform and warn equipment operators about workers nearby. The spotter should always remain visible to equipment operators (ATSSA, n.d.). The operator should stop moving if the spotter is not visible until visual contact is established again. Spotters can play a significant role in preventing backing incidents, though human errors can still happen.

Back-up Alarm: Backing alarms are popular in-vehicle systems that prevent backing incidents in work zones. The Occupational Safety and Health Administration (OSHA) requires a back-up alarm or a spotter for construction vehicles when backing up with an obstructed view to the rear at ground level (OSHA, n.d.). Each state can have additional regulations on the requirement. However, Missouri is a federal OSHA state that only needs to comply with the OSHA requirement. Despite their popularity, back-up alarms were reported inoperable in 28 percent of OSHA-investigated fatal incidents (FHWA, n.d.).

Video Camera: An equipment-mounted video camera with an in-vehicle display monitor can prevent backing incidents by eliminating blind spots that the rearview mirrors cannot capture (OSHA, n.d.). Rearview cameras have been effective preventing backing crashes among passenger vehicles. For example, video cameras reduced police-reported backing crash involvement rates by 17 percent (Cicchino, 2017). Such effectiveness could be realized in work zones. However, the video cameras can easily have mud/dust/dirt buildup, which may limit the effectiveness and use of video cameras to prevent backing incidents.

Work Zone Intrusion Alarm (WZIA): Though they have limited effects on backing incidents by design, WZIA systems have been used for work zone safety. WZIAs are alarm systems that warn unauthorized vehicles and errant motorists entering the workspace to protect highway workers (Gambatese et al., 2022). Enhanced safety effects of commercially available WZIA systems have been reported (e.g., Awolusi and Marks, 2019; Ozan et al., 2020). However, a study for the New Jersey Department of Transportation (NJDOT) reported that the sound produced by a WZIA system ("SonoBlaster") might not be fully effective during jack hammer operations, and the system's set-up procedures are often complicated (Krupa, 2010). The NJDOT study concluded that the alarm system was ineffective, given the quality control and reliability issues and the cost.

2.2.2.2 Advanced Systems to Prevent Backing Incidents

Advanced proximity detection and alert devices can prevent backing incidents (OHSA, n.d.). Three major detection systems for work zone safety have been commercially available: sonar-based, radar-based, and tag-based. All those proximity detection devices alert equipment operators about workers on foot in blind areas. In addition, infrared sensors and thermal imaging systems have been explored (Ruff, 2007). Infrared sensors transmit an invisible infrared light beam and detect reflections from nearby objects. Infrared video cameras (or thermal imagers) detect the thermal signature radiated from a person and provide an enhanced image. However, the commercial applications of infrared-sensing technologies and thermal imaging for work zone safety have been minimal.

Ruff (2007) identified several criteria for selecting a particular proximity detection and warning system that can be applied to highway work zone safety. The criteria are listed below (pp. 38-39).

- What is the acceptable frequency of false and nuisance alarms?
- What detection range is desired—close-in for slow-moving situations only or long detection ranges?
- Is additional functionality desired? Two-way or one-way?
- What types of equipment is outfitted with the proximity warning system? A system that has adjustable detection ranges and zone widths will be easier to fit into differing equipment.
- What areas should be monitored around the mining equipment?
- Should multiple technologies be combined?

An alarm from the proximity warning system can prompt the operator to check the video monitor so that a potential collision does not go unnoticed. The combination of cameras and a proximity warning system could potentially overcome the drawbacks of any single system operating alone. **Table 2.1** summarizes proximity detection and alert systems based on the criteria.

Table 2.1 Proximity Detection and Warning Systems for Work Zone Safety

Feature	Sonar (or ultrasonic) systems	Radar systems	Magnetic field tag-based systems	Radio frequency tag-based systems
	Transmit pulsed sound waves and detect echoes from nearby objects. The sound frequency is above human hearing (greater than 20KHz). Sensitive to particles in the air (dust, snow, and rain) and debris buildup on the face of the sensor.	Transmit a radio signal from a directional antenna mounted on the equipment to detect moving objects. Typically operated in the microwave (300 MHz - 40 GHz) portion of the radio spectrum	Use electronic tags that workers wear. Tag detectors or readers are installed on the equipment. Two-way communication between the reader and the tag allows alarms to be generated at the tag also.	Use electronic tags that workers wear. Tag detectors or readers are installed on the equipment. Two-way communication between the reader and the tag allows alarms to be generated at the tag also.
Adjustable detection ranges	No	Yes	Yes	Yes
Maximum detection range	3 m (10 ft)	7.6 m (25 ft) to 17 m (55 ft) depending on system	18 m (60 ft)	80 m (260 ft)
Minimum number of sensor units required for front and rear coverage	4 or more depending on system	2 to 4 or more depending on system	1 or 2 depending on system	2
Two-way alarming	No	No	Yes	Yes
Relative frequency of false alarms	Medium	Medium	Low	Low
Relative frequency of nuisance alarms	High	High	Medium	Medium
Tolerance to mud/dust/dirt buildup	Low	Medium	High	High
Installation and setup difficulty	Low	Low	Medium	Medium
Cost per piece of equipment: (High > $10,000 Low < $5,000)	Low	Low to Medium	Medium to High	High

Source: Edited based on Ruff (2007) *Recommendations for Evaluating and Implementing Proximity Warning Systems on Surface Mining Equipment*.

Given the criteria, tag-based systems have several advantages over others. The advantages include detection range adjustment, maximum detection range, two-way alarming, frequency of false alarms, and tolerance of mud/dust/dirt buildup. Among these advantages, the two-way alarming capability between operator and worker is a critical safety improvement even though it adds cost (Ruff, 2007).

Tag-based systems need a mobile sensing device for detection, transmitter sets, and software (Lee et al., 2009). Therefore, tag-based systems could potentially be more expensive than other systems. However, given several advantages, tag-based proximity detection and alert systems have more potential to be effective in protecting workers from backing incidents in work zones, while innovations in communication technologies in recent years have lowered the cost of the systems.

2.3 Survey Analysis on State DOTs' Use of Safety Devices to Prevent Backing Incidents

The project team conducted a survey in June 2022 of state DOTs' experiences using proximity detection devices to protect workers on foot from backing incidents involving construction equipment in work zones. The survey also asked about the elements to consider in using the devices. This survey was reviewed by the Institutional Review Board (IRB) of the University of Missouri–Kansas City. MoDOT personnel helped the project team to solicit survey participation through a listserv North American Association of Transportation Safety & Health Officials (NAATSHO) members. Twelve traffic safety engineers and occupational safety professionals who work at 10 state DOTs participated in the survey. Those participating state DOTs were Arkansas, Connecticut, Georgia, Iowa (two responses), Kansas, Kentucky, Mississippi, Missouri, South Carolina (two responses), and South Dakota.

Table 2.2 Use and Considerations of Safety Equipment to Prevent Backing Incidents

		Frequency	Note
Q. Please identify your department's safety equipment or device that has been used to protect ground workers from backing incidents in work zones. (Mark all that apply) (Please mark all that apply)	A) Tag-based systems (which alert drivers and ground workers when ground workers are behind or near the truck or equipment using wearable communication tags)	0	
	B) Back-up video cameras (with an in-vehicle display monitor)	9	
	C) Infrared/thermal camera detection devices	0	
	D) Radar/sonar-based detection devices	0	
	E) Intrusion alarm	1	
	F) A system not listed above (Please specify)	4	All four answers were back-up alarm.
Q. What has been the primary consideration(s) for using the equipment or device your department has used? (Please mark all that apply)	A) Cost	5	
	B) Ease of use	5	
	C) Ease of maintenance	5	
	D) Construction workers' demand	0	
	E) Safety benefits/effectiveness	9	
	F) Other (Please specify)	2	Two responses were hooking up trailer and winter equipment operation.

Backing video cameras were used by nine of the ten state DOTs surveyed while backing alarms were used by four, as shown in **Table 2.2**. One state had also used an intrusion alarm. However, any proximity detection systems that employ advanced technologies have not been used at all by 10 state DOTs. Regarding state DOTs' consideration in employing safety devices to curb backing incidents, "Safety benefits/effectiveness" was answered most frequently. Cost, ease of use, and ease of maintenance were also considered.

The survey results indicate that state DOTs consider the "Safety benefits/effectiveness" of devices more than any other factor, though "Cost," "Ease of use," and "Ease of maintenance" were also important. The efficacy of sophisticated proximity detection and warning systems remains unclear. No use of those systems by 10 state DOTs may reflect this deficiency.

Table 2.3 Elements to Consider for Future Adoption of Safety Equipment to Prevent Backing Incidents

		1st	2nd	3rd
What will be the most critical factors in employing any safety equipment or device in the future to protect ground workers from backing incidents in work zones? Please rank the top three.	A) Cost	2	2	5
	B) Ease of use	0	2	2
	C) Ease of maintenance	0	1	2
	D) Construction workers' acceptability	1	2	1
	E) Proven safety benefits	7	2	0
	F) Legal mandates	1	1	0
	G) Other	0	0	0

Note: Based on 12 survey responses from 10 state DOTs. Some responses chose less than three answers.

The survey also asked about considerations for the future adoption of safety equipment to prevent backing incidents. As **Table 2.3** shows, "Proven safety benefits" will be the most critical elements to consider. "Cost" and "Construction workers' acceptability" were also ranked relatively high. The importance of proven safety benefits shown in Table 3 is consistent with the findings in **Table 2.2**. Again, the survey results from 10 state DOTs clearly indicate that proven safety benefits are necessary to adopt a new safety system to curb backing incidents. In addition, the survey results show that the new system should be affordable and well received by workers in work zones. The acceptability by workers may also be reflected in the ease of use.

Table 2.4 Mitigation Plan and Vulnerability Assessment for Backing Incidents

		Frequency	Note
Q. Does your department have an explicit mitigation plan or vulnerability assessment regarding backing incidents in work zones?	Yes	1	
	No	8	
	Not clear	1	Two responses from one state DOT were conflicting between Yes and No.

The survey also asked about state DOTs' use of a mitigation plan or vulnerability assessment for backing incidents. Only one state had an explicit plan or vulnerability assessment for the incidents, as shown in **Table 2.4**. This survey result indicates that there is room to curb backing incidents through safety planning efforts in addition to new safety equipment with proven safety benefits, affordability, and ease of use.

2.4 Assessment of Existing Proximity Detection and Alert Systems

Existing work zone safety approaches can be described as geo-fenced work zones separating passing vehicles from the work area to provide positive protection. The physical separation technologies and equipment have been enhanced and automated, including an autonomous truck-mounted attenuator (ATMA), a Mobile Barrier, and an Automated Flagger Assistance Device (AFAD), as shown in **Figure 2.5**. Also, many alert systems have been deployed outside work zones to prevent crashes (to reduce speed and intrusion), including Dynamic Message System/Sign (DMS) and Queue Warning System (QWS), as shown in **Figure 2.6**. Furthermore, smart work zone intrusion alarm (WZIA) systems or intrusion alert systems (IAS) in **Figure 2.7**. have been developed using various technologies, including radar (e.g., AWARE), cone/barrel-mounted kinematic sensors (e.g., SonoBlaster), networked RF sensors (e.g., Intellicone, iCone, Bluetooth beacon), pneumatic tubes (e.g., Worker Alert System - WAS), and computer vision and ranging (e.g., SmartCone). When the IAS detects an intrusion, it gives audible, visual, and vibratory alerts.

Figure 2.5 Autonomous Truck Mounted Attenuator (ATMA) Mobile Barrier and Automated Flagger Assistance Device (AFAD)

Figure 2.6 Dynamic Message System/Sign (DMS) and Queue Warning System (QWS)

Figure 2.7 Intrusion alert systems (IAS)

The cost, sensor type, and alert methods of active work zone safety technologies are described in **Table 2.5**.

Table 2.5 Active Work Zone Safety Technologies

Method	Technology	Sensor Type	Alert Type	Cost
Advanced physical zone separation	Autonomous truck-mounted attenuator (ATMA)	N/A		Approximately around $330,000, which increased to $410,000 with the upgrades
Advanced physical zone separation	Mobile Barrier	N/A		$20,000/yr the MBT-1. Also, the purchase cost is approximately $330,000
Advanced physical zone separation	Automated Flagger Assistance Device (AFAD)	N/A		$34,000 for 2 units
Smart work zone prevention systems	Dynamic Message System/Sign (DMS)	Radar to detect driver's speed	Visual messages	Wanco Mini Message Board Sign and Trailer, Solar and Battery Powered WVT3, Three Line in total $23,854.89
Smart work zone prevention systems	Queue Warning System (QWS)	Radar, traffic condition sensors	Visual messages + WiFi	DMS +
Smart intrusion alert systems (IAS)	Intellicone	Radio	Audio and Visual	$6,600 (PSAs (2 units) and Sensors (20 Units). Also, $11,100 on a Hypothetical Half-Mile Closure
Smart intrusion alert systems (IAS)	SonoBlaster	Kinematic	Audio	$5,670 on a Hypothetical Half-Mile Closure
Smart intrusion alert systems (IAS)	AWARE	Radar	Audio, Visual, Vibration	$31,200, Sensor/Alarm (2 Units) and Worktrax (8 Units)
Smart intrusion alert systems (IAS)	WAS	pneumatic tubes	Audio, Visual, Vibration	$19,278, PAC and Pneumatic Sensor (31 Units) and PSD (8 Units). Also, $4,630 on a Hypothetical Half-Mile Closure

However, most work zone safety approaches require high initial cost, do not give precision warnings, and provide only single-direction warnings. Most importantly, they cannot handle hazardous conditions within work zones (e.g., a construction truck backing toward a worker on foot). In work zones, proximity monitoring technologies, such as video cameras and extra rearview mirrors, are employed on construction vehicles and equipment to help operators detect and alert foot workers near their machinery. These tools complement traditional warning systems, like control personnel and physical signs, and advanced collision avoidance or proximity detection systems, including radar and sonar devices or tag-based systems. However, existing commercial systems have various issues. The rearview video camera-based approach is a one-way (for the operator) monitoring system. Workers on foot cannot sense upcoming hazards with this video system. Operators needs to be vigilant about the environment by monitoring the video screen. Also, those systems cannot detect any objects out of the line of sight or in blind spots. It cannot predict capricious mobilities in speed and direction. Its accuracy can be impacted by weather conditions (e.g., fog or rain) and light conditions (e.g., night or dusk). Also, dirt on the camera lens can impede vision.

Backing sound alerts from the vehicle are unreliable in practical construction environments, which has various noisy distractions. The alarm sound level must be louder and more distinctive than the surrounding noise to be effective. However, as many workers on foot are harnessing noise cancelation headsets, they may not be able to hear the sound alert.

Control personnel and visual warning signs have traditionally been used in the work zone. However, warning signs assume the construction crews' complete understanding and active attention. Furthermore, they are bound by a location that lacks adaptability to the mobile hazards of moving vehicles and construction crews. In addition to their capacity limitation, those traditional approaches are not scalable.

When workers are on foot concentrating on their tasks, looking out for equipment/vehicles moving around the work zone is difficult. Also, heavy fleet vehicle drivers often lose their attention toward the direction of travel due to various physical and cognitive obstructions. When workers on foot are not in the line of sight (e.g., in blind spots or behind obstructions), it escalates potential risks. Even if drivers can spot workers on foot and give alerts through traditional sound or light alarms, it may not adequately warn them due to noise, or the lack of attention. Reducing blind areas is critical when designing a safety alert system for work zones. Incorporating proximity warning technology can help monitoring the presence of workers in blind areas.

Protocol	Range	Mobility	Deployment
DSRC	< 1 Km	> 60 Mph	Not available yet Expensive Hard to retrofit
WiFi	< 100 m	< 5 Mph	Ubiquitous Long association time
Cellular	< 10 Km	> 60 Mph	Ubiquitous Long association time

Figure 2.8 Comparison of Communication Methods

The assessment of current proximity detection and warning systems indicated that real-time, bi-directional communication between workers on foot and operators is critical for work zone safety. The vehicle communication methods (e.g., V2V, V2I, V2X, and V2P) can use LTE, 5G communications, DSRC, and ad hoc WiFi. However, as summarized in **Figure 2.8**, 5G and LTE techniques are not suitable for imminent accident prevention due to the high latency incurred when interactions with third-party servers are used to relay the messages between devices. While DSRC-based techniques satisfy the low latency requirements of incident prevention applications, they require expensive DSRC equipment that manufacturers must fit into their vehicles. Also, wearable devices for construction workers must be equipped with this expensive technology. In addition, it is challenging to equip old vehicles with DSRC units. Ad-hoc Wi-Fi connection techniques use Wi-Fi-Direct features to enable P2P communication. However, setting up the communication channel takes two to three seconds, which is not an acceptable delay for warning applications.

Chapter 3 System Development and Testing

3.1 System Development

The project team developed an alert system comprised of an in-Vehicle Portable Detection (iVPD) system, Vehicle Proxy Tag (VPT), and Wearable Proximity Sensor (WPS) tags. A beacon communication handler was designed and developed using embedded beacon stuffing technologies. A positioning algorithm was also engineered for integration into smart devices.

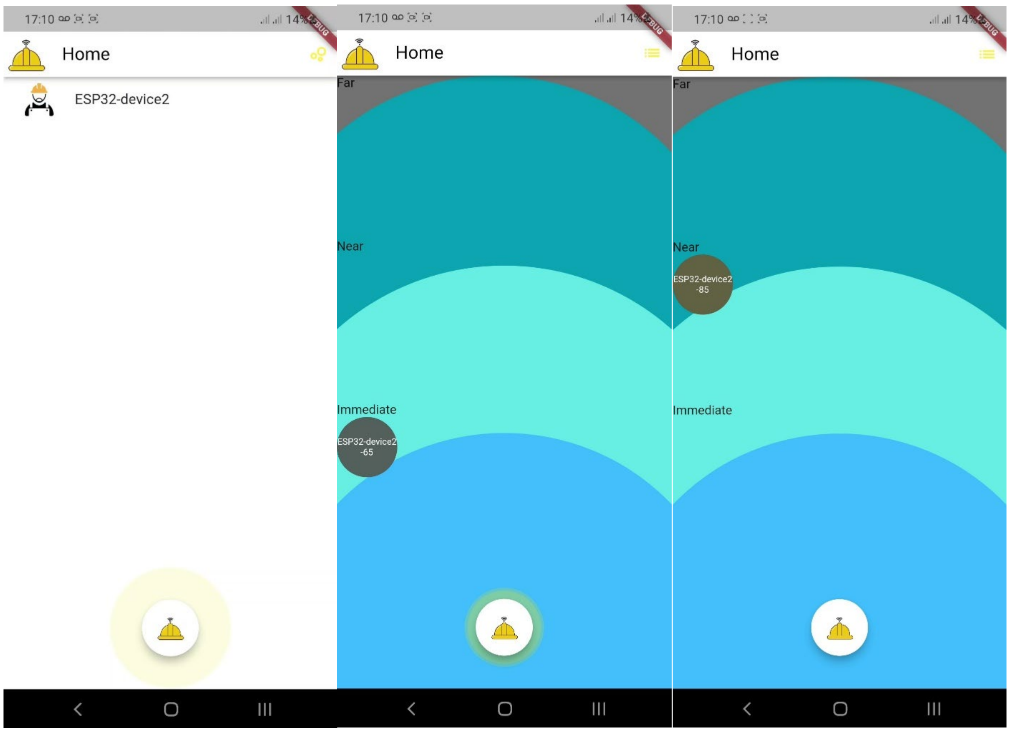


Figure 3.1 iVPD Application Screen Displays

Figure 3.1 shows an example of the iVPD application display developed for the project. The project team developed an application designed to support the visualization of the proximity of workers on foot and warnings of the iVPD system. This application was designed to deploy on Android smart devices for testing. The project team also developed a WPS tag with a target cost of less than $60 per piece. WPS tags were designed to be power-efficient, and the project team built them without using expensive cellular communication. The team used an ESP32 chipset, known for its compact form factor and integration of low-cost, low-power systems-on-a-chip microcontrollers. The chipset featured Bluetooth 4.2 communication capabilities, along with built-in antenna switches. Each WPS tag was packaged with an inertial measurement unit (IMU), a rechargeable battery, and an auditory alert device. The project team designed WPS tags to be attached to a safety helmet. WPS tags were manufactured as the minimum viable prototype products using a 3D printed case.

3.1.1 Mobile Applications and Algorithms

As illustrated in **Figure 3.2**, the application was designed using the following functional structures.

```
START
├─ onCreate()
│  ├─ Initialize BluetoothManager, BluetoothAdapter,
BluetoothLeScanner
│  ├─ Initialize devicesDict and devicesRSSI
│  ├─ Set up the DeviceAdaptor and ListView
│  ├─ Configure scan settings and filters
│  ├─ Start scanning for BLE devices - VH-Tags Only
├─ connectToVHTag()
│  ├─ connect to the vehicle tag
│  ├─ check if worker data service is offered
│  └─ subscribe to the data of the worker tags
├─ notifyOnData
│  └─ addDevice()
│     ├─ Extract device information (UUIDs, name, RSSI)
│     ├─ Check if the device has a valid UUID
│     │  ├─ If yes,
│     │  │  ├─ Add the device to devicesDict if it doesn't exist
│     │  │  ├─ Remove the oldest RSSI value if the list exceeds 15
│     │  │  ├─ Add the new RSSI value to the list
│     │  │  └─ Calculate the average RSSI for the device
│     │  │  └─ Calculate the distance using the Average RSSI
│     │  └─ If no, update the last scanned time
│     └─ Return to notifyOnDataReceived
│
├─ calculateAverage()
│  ├─ Retrieve the RSSI list for the device
│  ├─ If the list is empty, set the average RSSI to 0
│  └─ Calculate the average RSSI and update devicesDict
│
└─ DeviceConnectionLost/Disconnected
   ├─ Restart the Scanning
END
```

Figure 3.2 iVPD Application Structure

- onCreate(): Initialize Bluetooth components and set up necessary configurations.
- Initialization: Initialize necessary variables and data structures.
- Device Setup: Set up the device adapter, device adaptor, and list view.
- Start Scanning for BLE Devices: Begin scanning for BLE devices, specifically VH-Tags.
- connectToVHTag(): Connect to the vehicle tag and check if the worker data service is offered.
- Check Worker Data Service: Determine if the connected device offers the worker data service.
- Subscribe to Worker Tag Data: Subscribe to the data of the worker tags.
- notifyOnData(): Handle notifications received from the worker tags.

- addDevice(): Extract device information, check if the device has a valid UUID, and update the devicesDict and devicesRSSI accordingly.
- calculateAverage(): Calculate the average RSSI for the device based on the RSSI values stored in the devicesDict.
- Update Average RSSI: Update the devicesDict with the calculated average RSSI.
- Device Connection Lost/Disconnected: Handle the scenario where the device connection is lost or disconnected.
- Restart Scanning: Restart the scanning process to continue searching for BLE devices.
- END: Terminate the process.

Flow charts were developed to illustrate the designed workflow of the iVPD mobile app installed on a smart device inside the vehicle (See **Figure 3.3**). iVPD is linked to VPT using an esp32 platform installed on the vehicle's backside. As illustrated in **Figure 3.4**, the workflow of the WPS or HT algorithm was integrated into WPS tags. To illustrate how WPS tags or HT operates, the project team designed a flow chart that outlines the step-by-step process of the algorithm's functionality. VPT's operational workflow was outlined in the accompanying flow chart in **Figure 3.5**.

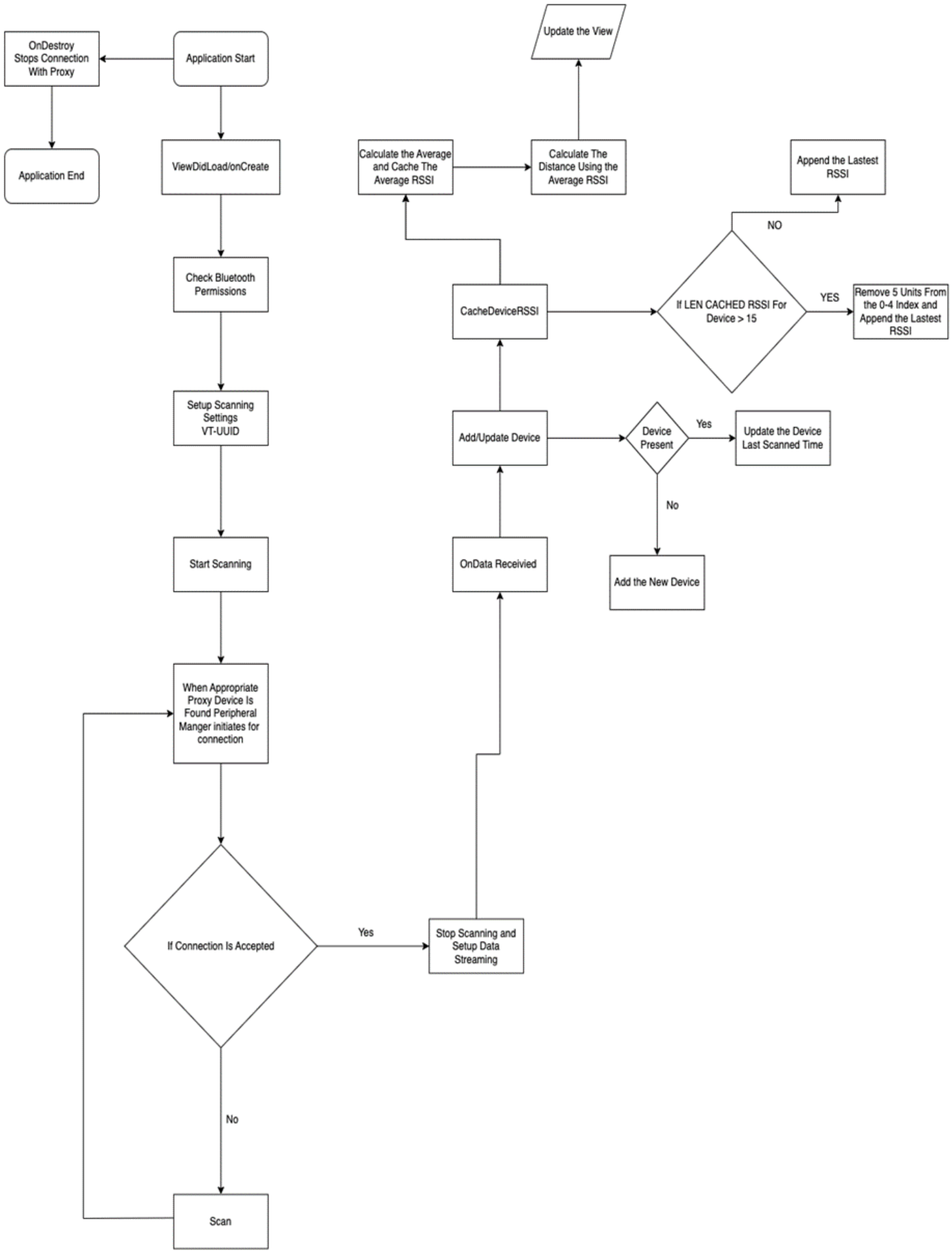


Figure 3.3 In-vehicle Portable Detection (iVPD) Algorithm

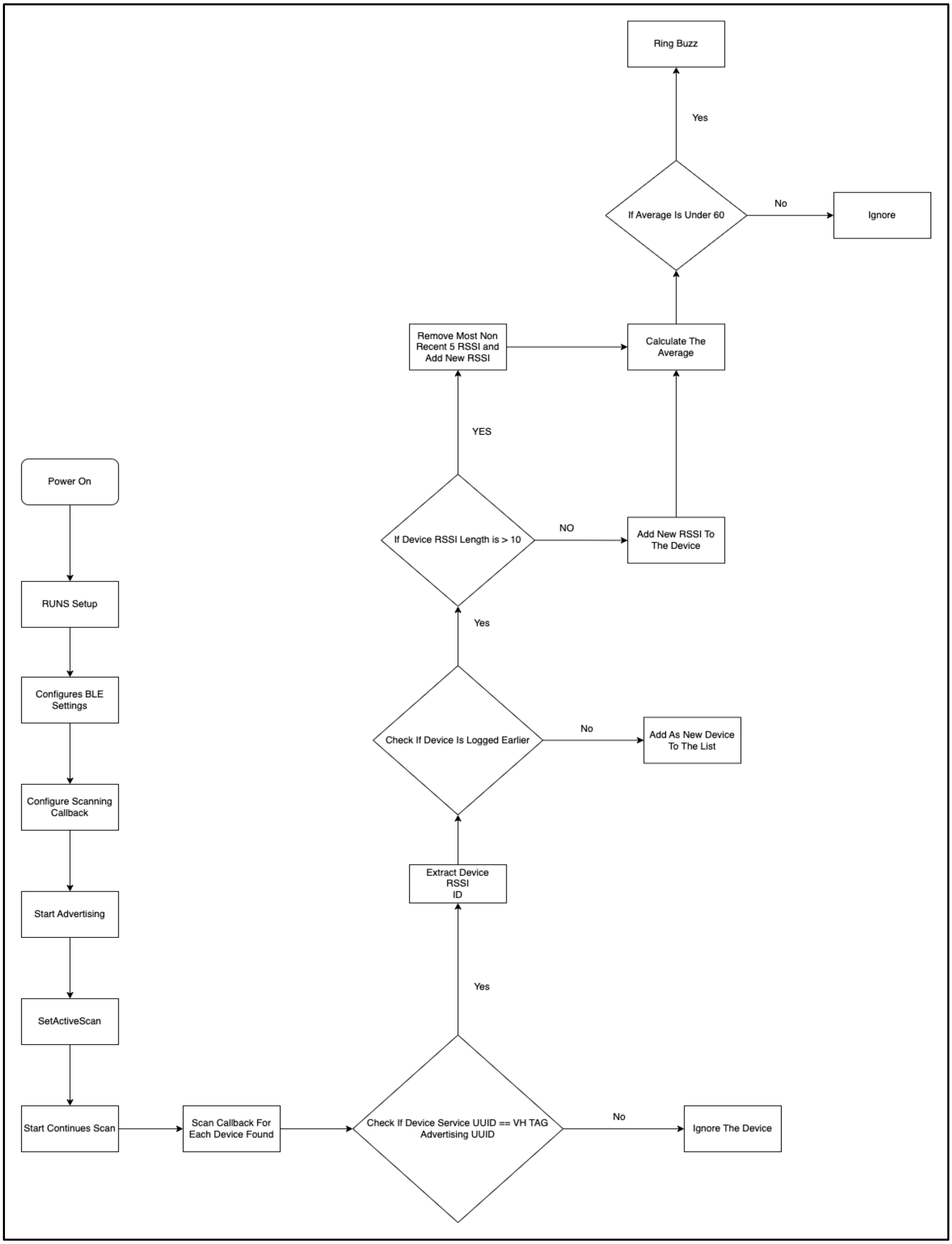


Figure 3.4 Wearable Proximity Sensor (WPS) Tag or Human Tag (HT) Algorithm

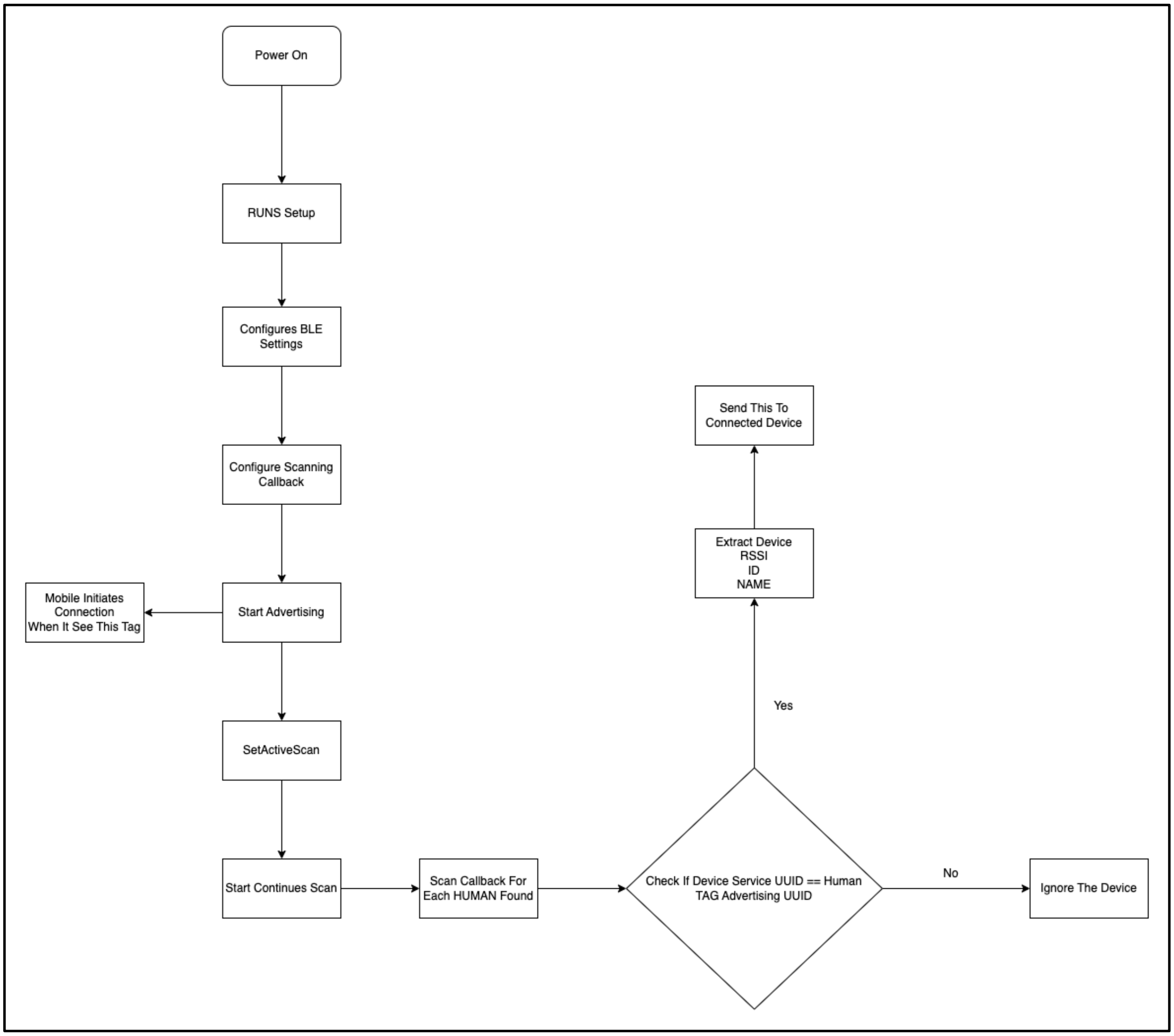


Figure 3.5 Vehicle Proxy Tag (VPT) Algorithm

3.2 Testing Results

3.2.1 Preliminary Testing

As presented in **Table 3.1**, the project team conducted various system tests comprising four categories, including functional test (FT), interference test (IT), accuracy test (AT), and power duration test (PT). The objective of the testing was to validate the simulated environment test results in practice. The project team used helmets, WPS tags attached, an iVPD, and a VPT. VPT is attached to the backside of the vehicle used for testing. The project team calibrated the system for testing.

- FT assessed tracking app function given different tag locations, tracking app function for moving tags, tag buzzer volume change, tracker app warning types, short tag and tracker distance warning, and filtering tags from a tag (only tracking multiple trackers).

- **IT** assessed multiple tag interference and obstacles (water, wall, human, etc.) between tags and tacker (smartphone) and scalability on the tags.
- **AT** assessed distance accuracy and tag tracking accuracy on the app.
- **PT** assessed beacon frequency and the number of tags.

Table 3.1 Testing Check List

	Explanation	Note
FT.1	The correctness of the tracking app function given different tag locations (multiple stationary tags for a moving tracker)	Identifying tags on the moving trajectory
FT.2	Tracking app function for moving tags (a stationary tracker app for moving tags)	Identify the tag locations (no exact direction)
FT.3	Tag buzzer volume change	Find audible volume levels for different distance and environment noise
FT.4	Tracker app warning types	Check if the app shows exact level of warning in color, sound, and frequency
FT.5	Short tag and tracker distance warning	Check if tag and tracker app detect and warn of any imminent risks (tag and truck, but not tag and tag)
FT.6	Filtering tag signals for a tag (only receives signals from the tracker)	No warning is given when a tag is getting closer to a tag
IT.1	Multiple tag interference	When there are more tags, check how much those tag signals impact each other
IT.2	Obstacles (water, wall, human, etc.) between tags and tacker (smartphone)	When there are obstacles (wall and human), check how they impact on the tag signal reception
IT.3	Scalability on trackable tags	Theoretical limitations and practical degradation
AT.1	Distance measurement accuracy	Accurately measured distance for a given distance
AT.2	Tag tracking accuracy on the App	Accurate tag locations for a given tag distances
PT.1	Power duration for beacon frequency	Measured power usage for a tag with a given test duration
PT.2	Power duration for the number of tags	Measured power usage on a tag for different numbers of tags and trackers

The project team performed multiple tests at various locations at the University of Missouri – Kansas City.

- **Warning sound** with 85dB buzzer worked well regardless of the harnessing position (front, near ear, overhead, etc.). The warning was evident against any loud outside sound.
- **Battery life** with 350mA (small form factor) lasted long enough. The project team tested in the lab with a 350mA battery by sending beacons every 100 ms. It lasted 4.5 hrs.
- **Tag placement**. The tag comprised in-case components (350mA battery and ESP32) and an out-case buzzer. The project team harnessed it to the helmet with double-sided tape.
- **Correctness** of safety detection. Real-time BLE distance fluctuated. So, the project team relied on averages and applied the zone concept instead of using the BLE distance. Both tag and cell phone iVPD buzzed when they were within certain distances. The project team tested one-to-one and many-to-many cases. The project team found no scalability or delay issue. However, physical obstacles impacted zone-based accuracy.

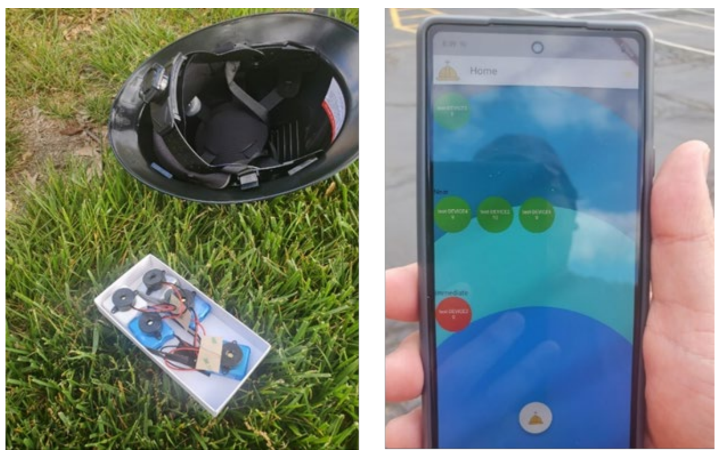


Figure 3.6 Warning Sound Tags and App

Figure 3.7 Wearable Proximity Sensor (WPS) Tags Attached to Safety Helmets

The project team tested to quantify the beacon accuracy variations. The technology was distinctive because of its ability to estimate distances between two BLE devices without relying on GPS or anchor-based triangulation methods. RSSI-based localization, which hinged on measuring the received signal strength and estimating the distance between nodes, required improved accuracy, primarily due to factors such as non-line-of-sight (NLOS) conditions, signal fading, noisy data, and other challenges. A predominant issue affecting RSSI accuracy was obstructions that can hinder signal propagation. Additionally, the distance between iVPD and VPT played a crucial role; connectivity became problematic if they were too far apart. To address these challenges and enhance the accuracy of BLE RSSI measurements, the project team employed a Kalman filter for noise reduction and the integration of distance and variation measures.

Figure 3.8 RSSI Accuracy Testing

As shown in **Figure 3.8**, the approach to estimating distance from RSSI involved the following steps:

1. **Distance Estimation from RSSI:** The project team developed a methodology to estimate distances based on RSSI values, laying the foundation for accurate distance calculations.
2. **Fluctuation Reduction:** The project team integrated a Simple Kalman filter to effectively mitigate fluctuations in RSSI measurements, further enhancing the precision of the

distance estimations. Additionally, the project team introduced a sliding window algorithm, denoted as AVG_RSSI, on mobile devices to stabilize the RSSI data.

3. **System Components and Code:** The project's components and the codebase used for RSSI distance estimation were carefully presented, offering insights into the technical aspects of the system.
4. **Communication Flow:** The project team described the flow of communication between the various components and devices involved in the distance estimation process, providing a comprehensive overview of how data is exchanged and processed.
5. **Testing in Various Conditions:** The project team conducted thorough testing in various conditions, encompassing the following scenarios:
    - **Over Set Distances:** Testing at predetermined distances to evaluate the accuracy of the distance estimations.
    - **No Obstacles Testing:** Assessment of the system's indoor performance when physical obstacles are minimized.
    - **Outdoor Testing:** Evaluation of system performance in outdoor environments.
    - **Human Obstacles Testing:** Testing conducted under conditions involving human obstructions to gauge the system's response.

3.2.2 Preliminary Field Test Data Analysis

The project team examined the testing outcomes. Firstly, the project team conducted a comparative analysis between the estimated distances generated by the system and the corresponding ground-truth measurements. This comparison was a pivotal metric for evaluating the system's accuracy. Subsequently, the project team systematically examined variations in distance estimations under diverse conditions to assess the system's reliability across varying circumstances. Lastly, the findings were communicated through comprehensive graphical representations and detailed data analysis. This approach aimed to enhance the clarity and interpretability of the results.

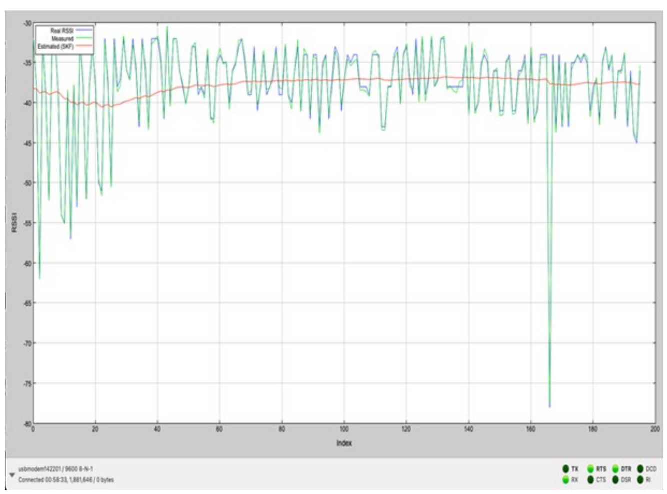


Figure 3.9 Measured Power Result

The project team employed the formula in equation (3.1) to calculate the distance from the RSSI. This formula served as the basis for the distance estimation methodology, enabling us to translate RSSI measurements into accurate distance calculations.

$$Distance = 10\hat{}((Measured\ Power - Instant\ RSSI) / (10 * N)) \tag{3.1}$$

- **Measured Power** represents the Received Signal Strength at a reference distance of 1 meter. As shown in **Figure 3.10**, the project team measured the power strength of the RSSI in 1 meter distance, which is -43 dB.
- **Instant RSSI** corresponds to the currently measured RSSI value.
- **N** stands for the Path Loss Exponent, typically taking on a value within the range of two to four. A value of two is commonly used for free space scenarios, while higher values are applied when obstacles are present. The project team chose to use a value of 2.4 for the outdoor testing.

The project incorporated vital system components for testing in diverse scenarios. The client device (WPS or HT) was designed to scan nearby BLE devices, read their RSSI values, and process them using a Kalman filter. Its primary function was to check for nearby devices, read their data, and act as a data receiver and processing unit crucial in data acquisition and processing. The server device (VPT) advertised itself over BLE, scanned for nearby BLE devices, read their RSSI values, processed the data using a Kalman filter, and transmitted the processed data to connected client devices. It served as a data source, processing unit, and transmitter, facilitating essential data communication with other system components. The mobile app operated as a BLE central and peripheral device. It scanned for nearby BLE devices, established connections, read advertised data, and calculated distance based on RSSI values. The app presented this information, incorporating a timer mechanism to remove devices that are not updating their data. It functioned as a data receiver processor and provided a user interface for presenting distance estimations and visualizing data.

Using a Kalman filter plays a crucial role in the program by reducing the noise in RSSI values. Various environmental factors can affect these RSSI values, leading to fluctuations and undesired noise. The Kalman filter estimates the signal strength by mitigating the noise and providing a more stable and accurate representation of the RSSI values. In the code implementation, the project team initially measured the RSSI value, which is anticipated to contain some degree of noise due to factors like physical obstacles and interference. To assess the effectiveness of the Kalman filter, the project team intentionally introduced random noise, as shown in equation (3.2), to the RSSI value for testing purposes. Subsequently, the project team employed a Kalman filter to estimate the genuine RSSI value from this noisy data.

$$float\ measured\_value = rssi + random\,(-100{,}100)/100.0 \tag{3.2}$$

Using the Kalman filter to estimate the real RSSI value from the noisy data, the resulting estimated value in equation (3.3) was expected to provide a cleaner and smoother representation of the signal strength, reducing the impact of noise, and enhancing the accuracy of the RSSI measurements. This process enhanced the system when estimating distances based on RSSI values.

$$float\ estimated\_value\ =\ simpleKalmanFilter.updateEstimate(measured\_value) \tag{3.3}$$

The experimental protocol encompassed several sequential stages of communication. In the “discovery” phase, both devices concurrently operated in advertising and scanning modes, fostering mutual discoverability and the identification of proximate devices. Subsequently, the “data logging and filtering” phase involved the maintenance of logs detailing RSSI values derived from identified devices advertising a specific service. To assess the system performance, a controlled introduction of intentional noise and a Kalman filter were applied to the recorded RSSI values to estimate the genuine RSSI, thereby mitigating the impact of introduced noise.

The subsequent “data sharing” stage involved the proxy device disseminating the filtered RSSI data to connected clients (HT or WPS) upon recognizing a device advertising the expected service. In the “mobile device” phase, the smart device operated as a client, connecting to the proxy (VPT), and subscribing to data. Employing a sliding window technique, the mobile device or iVPD systematically processed RSSI values to derive estimates. The final stage, called “output,” involved the client device printing the RSSI data onto the serial monitor, facilitating real-time monitoring and visualization during the system's operation. This communication flow ensured that both data logging and sharing were efficiently managed, noise was reduced through filtering, and real-time monitoring was available for assessing system performance and results.

The data flow and processing sequence within the experiment also involved several distinct stages. During the “data collection and processing” phase, the server device actively searched BLE signals by collecting RSSI data. Subsequently, the gathered data undergo processing by a Kalman filter algorithm to diminish noise and improve accuracy. Simultaneously, the client device, another active participant, discovered RSSI data, subjecting it to a parallel processing workflow. Following the data processing stages, the “data transmission” phase was orchestrated by the server device, responsible for centralized data management. It transmitted the filtered RSSI data to connected BLE clients, encompassing relevant information such as RSSI value, device name, and address. The subsequent "mobile app interaction” phase involved the mobile app functioning as a user interface and control point. It conducted BLE scanning to identify nearby devices, established connections with them, and retrieved the advertised data, including processed RSSI values.

The “distance calculation” phase was then executed by the mobile app, wherein estimated distances for each detected device were calculated based on the RSSI value. Each device's information and related data were maintained in the app's memory. The “user interface update” phase involved the app presenting the list of detected BLE devices and their calculated distances to the user. Users can switch between list and grid-view formats for customized data presentation. Additionally, the app incorporated a timer mechanism to automatically remove devices that have not updated their data recently, ensuring that the displayed information remained current and relevant. Finally, the “real-time data display” phase provided users immediate access to a list of nearby BLE devices, complete with their respective distances, presented on the mobile app's interface.

Figure 3.10 shows the measured distances at 1, 2, 5, 10, 15, and 20 m. over 22,000 sec. These measurements were conducted without interference between the BLE tags, and data was transmitted every 10 seconds.

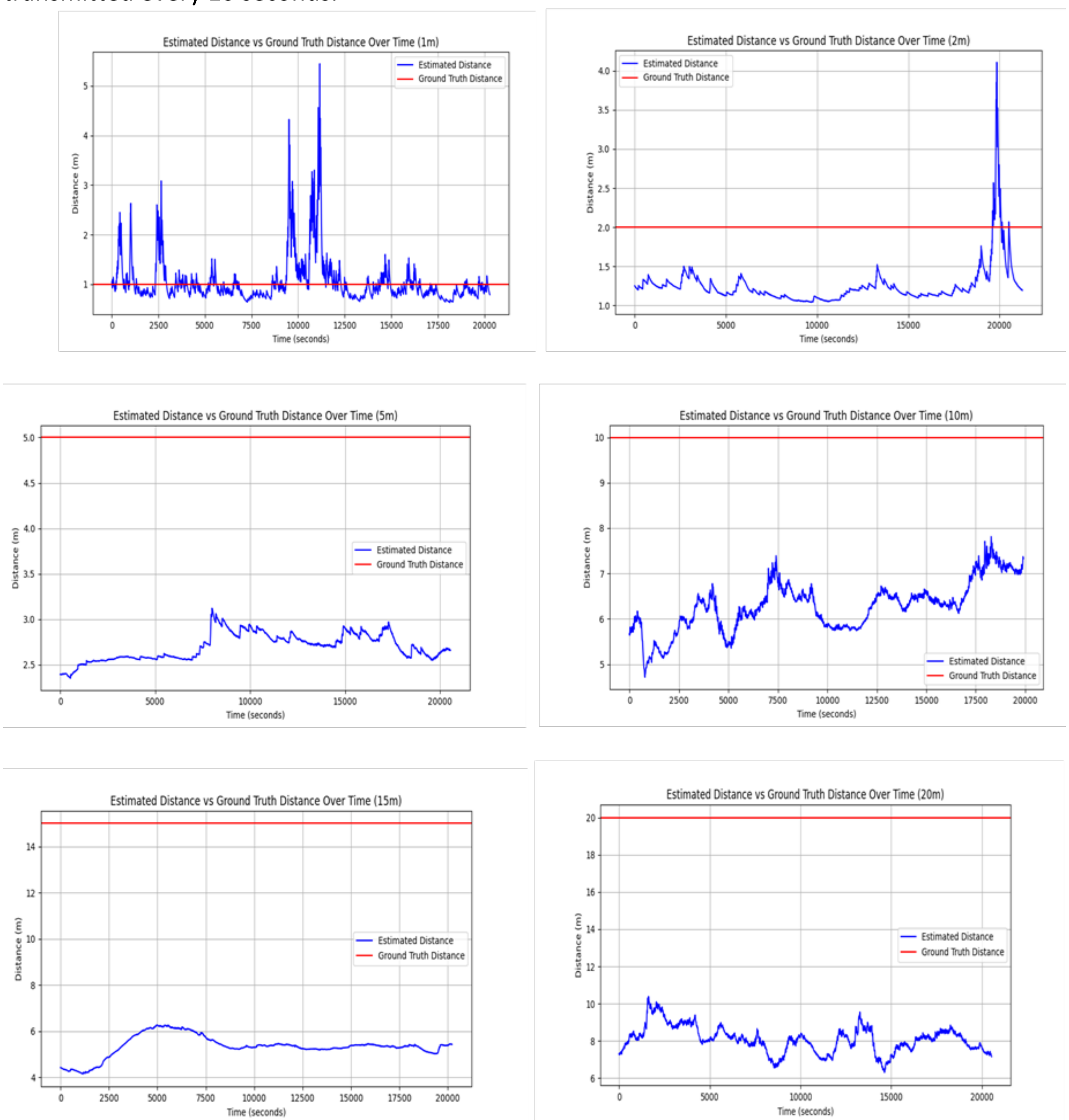


Figure 3.60 RSSI Tests without Interference

Figure 3.11 shows the measured distances at 1, 2, 5, 10, 15, and 20 m. over 22,000 sec. These measurements were conducted with heavy human interference between the WPS tags, and data was transmitted every 10 sec.

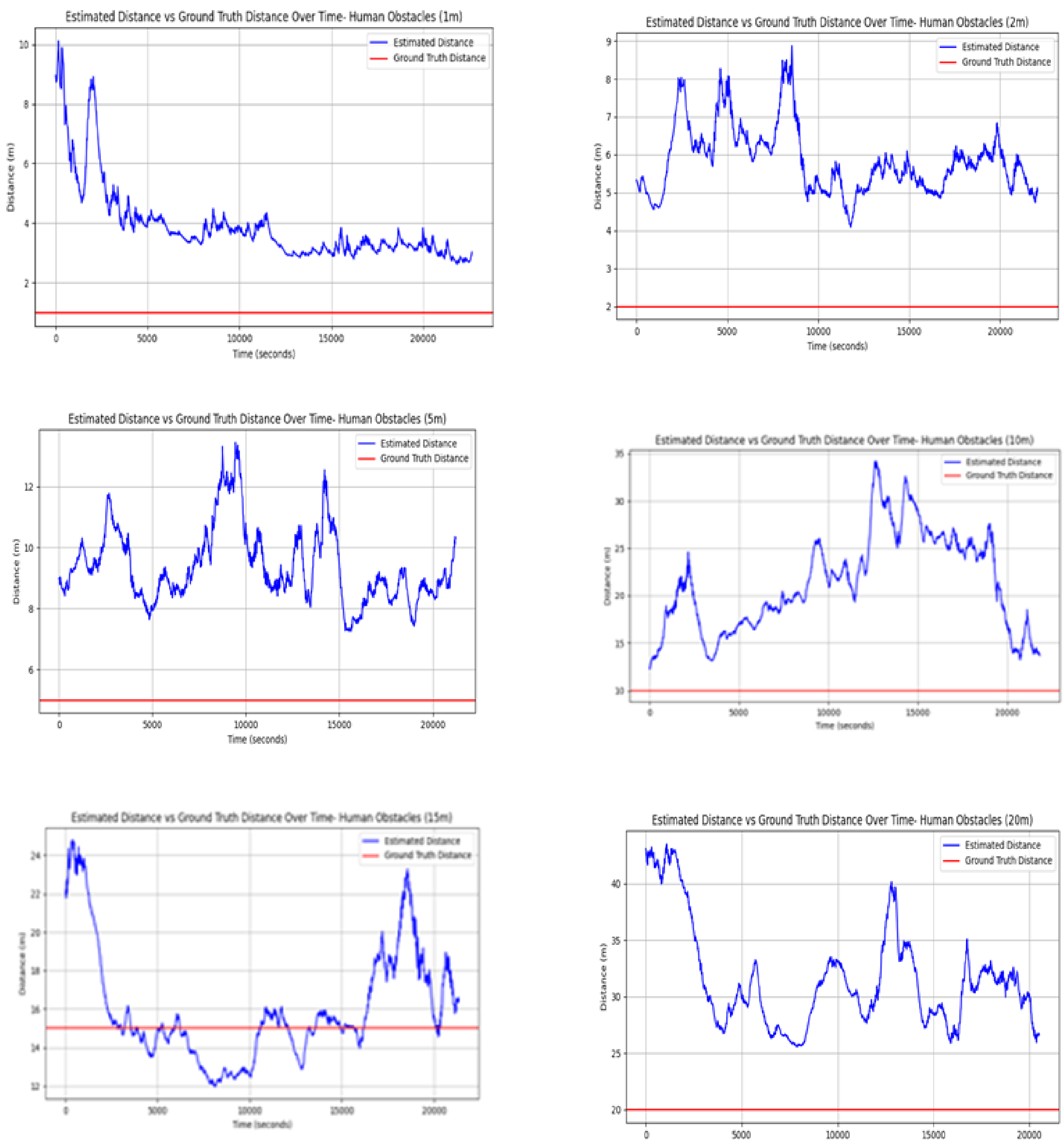


Figure 3.71 RSSI Tests with Interference

In summary, the VPT and client devices (HT or WPS) were continuously scanning for BLE signals, during which they processed RSSI data. In the case of the server (VPT), this data was transmitted to connected clients, ensuring that relevant information was distributed effectively. The Android app operated as a BLE central device, taking on the duties of scanning for BLE signals, establishing connections with devices, and receiving data from the VPT. The processed data was then presented on the app's user interface, providing users with real-time information about nearby devices and their estimated distances. Based on the analysis of the RSSI data, its correlation with distance, and variation with and without the interference of human obstacles, the project team observed several vital implications.

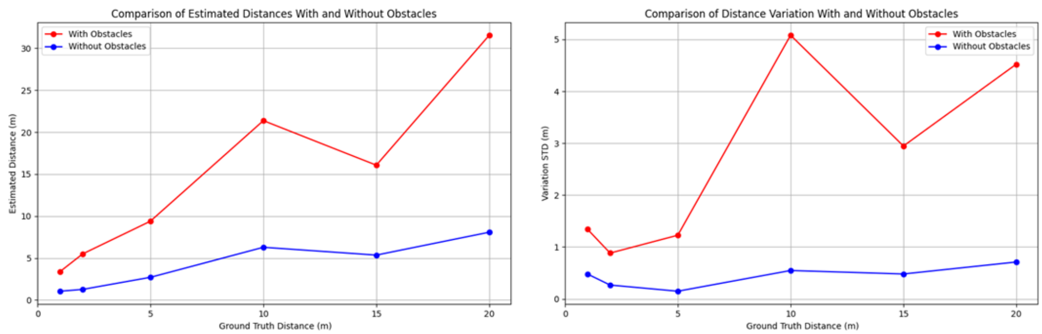


Figure 3.82 Distance and Variation Results with and without Obstacles

Figure 3.12 presents distance and variation results with and without obstacles for various distances. RSSI values served as a viable method for estimating distances in wireless networks, yet the accuracy of these estimations was subject to notable fluctuations contingent on environmental conditions and obstacles. Human obstacles significantly impacted RSSI readings, particularly at shorter distances, resulting in increased variability. Human obstacles introduced additional interference into the wireless signal, leading to fluctuations in RSSI values. In scenarios devoid of human obstacles, RSSI values exhibited more stability.
However, variability may persist due to other environmental factors, contributing to fluctuations in the RSSI readings. Notably, this variation was more pronounced at shorter distances. The accuracy of distance estimation using RSSI was inversely related to the distance between devices. As the distance increased, the accuracy of distance estimations tended to degrade. The discernible manifestation of this phenomenon became apparent through the heightened variability observed in RSSI values. Furthermore, negative variations were noted in certain instances, signifying a pronounced level of uncertainty in distance estimations, particularly over extended distances.

These conclusions offer insights into the inherent limitations of using RSSI as a distance estimator in wireless networks. They underscore the pivotal role of environmental conditions and human obstacles in shaping the accuracy and reliability of such distance estimations. In response to these findings, the project team has taken concrete steps to enhance safety by implementing distinct zones based on the estimated distance and variation.

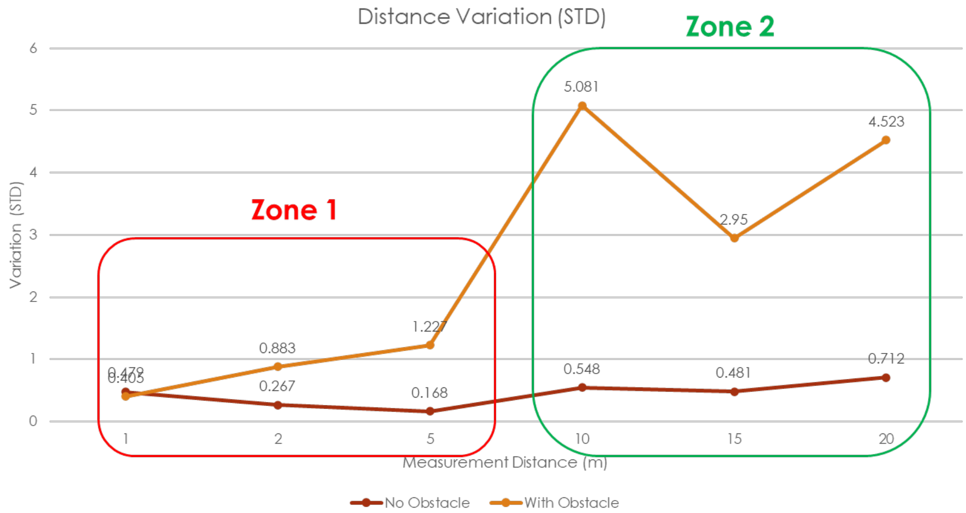


Figure 3.93 Safe and Risk Zones

As illustrated in **Figure 3.13**, implementing distinct zones allowed the project team to proactively detect potential collision risks and classify devices into specific zones:

- **Zone 1:** Devices falling within this zone are at a potential risk of collision. Consequently, the project team implemented alert mechanisms to mitigate these risks. If a tag is classified within Zone 1, it triggers alerts to ensure the safety of individuals and assets.
- **Zone 2:** Devices in this zone were not deemed to be at risk of collision. The variation in these devices' data did not exceed a predefined threshold, indicating a lower likelihood of potential collisions.

Specific criteria determined the classification of devices into distinct zones. For example, devices exhibiting variations in RSSI values exceeding a predetermined threshold of two can be assigned to Zone 2, indicating a lower risk level. In contrast, devices within a measured distance of less than seven meters and a variation in RSSI values below two can be categorized into Zone 1, signifying a higher potential risk of collision.

3.2.3 Final Field Testing

The project team conducted a field test with MoDOT on April 4th, 2024, at MoDOT's Motor Carrier Services complex in Jefferson City. The testing used an iVPD on an Android phone, a VPT, and five WPS tags. VPT was attached to a MoDOT's dump truck bed panel behind the operator's cabin. The system was calibrated to trigger an alarm (beeping sound) when WPS is detected within 15 feet of VPT. The testing revealed several issues associated with BLE beacon technologies. The issues observed are discussed below.

First, there were many false positives. The sound alarm was triggered when a WPS was outside the calibrated detection range. The recalibration did not improve the false positive issue.

Second, beeping sounds were intermittent. The sound stopped and started irregularly. A WPS tag made a beeping sound, while the other did not when the two tags were side by side.

Third, beeping sounds went off when WPS tags did not face VPT.

Fourth, A worker in front interferes with the function of the WPS tag behind. This issue was observed in the project team's preliminary testing.

Fifth, the locations of WPSs shown on the iVPD were not reliable.

BLE has been promising for indoor positioning systems with a multi-antenna array receiver system (Litum, 2021). The issues found during the final field testing are potentially linked to BLE's limitations in outdoor environments that can impact its performance and reliability. BLE is interfered with by vehicles, heavy machinery, electronic equipment, and building structures in outdoor environments. Natural obstacles, such as trees and hills, can also block or attenuate BLE signals, thus affecting effective range and reliability. BLE performance is affected by a clear line of sight. However, maintaining a clear line of sight can be challenging in outdoor environments with obstacles and variable terrain. Lastly, weather conditions, even wind and humidity, can directly and indirectly affect the transmission of BLE signals. The final testing site has various interference obstacle elements.

WPS tags developed for the project used a rechargeable battery (350mA) that contributed to a relatively bulky tag to be attached to the safety helmet. Even though BLE is designed to be of very low power consumption, the actual battery life of BLE devices can be significantly affected by environmental conditions and the need for higher transmission power to overcome interference and maintain communication over longer distances.

BLE's susceptibility to interference might have contributed to the performance of the BLE system developed for the project. Despite the calibration of the system, controlling various interference elements was challenging. Existing BLE may not be suitable for deployment as an alert system that requires high accuracy and reliability in work zones.

Chapter 4 Conclusions

The project aimed to develop a cost-effective, user-friendly, and reliable hazard detection and alert system specifically tailored to work zone incidents between heavy equipment/vehicles and workers on foot. The findings and outcomes are summarized below.

- Backing crashes are a substantial work zone safety issue that needs to be addressed nationwide. Missouri is not an exception. Over 100 backing crashes involving MoDOT equipment/vehicles occurred per year on average in a recent decade.
- There are various commercial alert systems utilizing sonar and radar sensors and electronic magnetic and radio tags. However, the project team's survey study on 10 state DOTs found that state highway agencies have not used those systems. Back-up video cameras and back-up alarms are popular for preventing backing crashes. State DOTs consider cost, ease of use, and maintenance were included in their criteria for choosing their prevention measures. However, proven safety benefits and effectiveness were the most significant considerations for state DOTs. This finding indicates that safety effectiveness should be critical in developing a safety system to prevent backing crashes in work zones.
- A bidirectional alert and warning system between equipment/vehicle operators and workers on foot has merit compared to a unidirectional system (e.g., sonar and radar systems), which may have higher potential safety effectiveness.
- The project developed a bidirectional BLE-based safety alert and warning system for construction equipment/vehicle operators and workers on foot. The BLE beacon technology has become a popular positioning system, particularly for indoor.
- The project explored the potential application of the BLE beacon technology to work zone environments. However, the system developed for the project revealed several operational accuracy and reliability issues caused by outdoor environmental and locational factors that block or interfere with BLE beacon signals. The calibration of the model algorithm had a limited effect on the system performance.
- The project concluded that the existing BLE beacon technology is unsuitable for developing a safety alert system for work zones that require high accuracy and reliability.

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