Developing a Hazard Detection and Alert System to Prevent Incidents

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16. Abstract

The proposed project creates an economically viable, user-friendly, versatile, precise, and dependable hazard detection and alert system designed for the seamless integration of heavy fleet vehicles and work zone personnel nearby. This endeavor encompasses a comprehensive examination of extant commercial alert systems. The envisioned system is composed of a wearable proximity sensor for personnel, coupled with an in-vehicle, portable detection system, which is intended to promptly notify both workers and vehicle operators when the fleet vehicles are in motion or reversing, thereby mitigating the likelihood of work zone incidents. Furthermore, the project entails the execution of on-site assessments to gauge the effectiveness of the hazard detection and alert system in practical scenarios. A system maintenance strategy for the Missouri Department of Transportation (MoDOT) forms an integral part of this initiative.

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Abstract

The proposed project creates an economically viable, user-friendly, versatile, precise, and dependable hazard detection and alert system designed for the seamless integration of heavy fleet vehicles and work zone personnel nearby. This endeavor encompasses a comprehensive examination of extant commercial alert systems. The envisioned system is composed of a wearable proximity sensor for personnel, coupled with an in-vehicle portable detection system, which is intended to promptly notify both workers and vehicle operators when the fleet vehicles are in motion or reversing, thereby mitigating the likelihood of work zone incidents. Furthermore, the project entails the execution of on-White site assessments to gauge the effectiveness of the hazard detection and alert system in practical scenarios. Additionally, a system maintenance strategy for the Missouri Department of Transportation (MoDOT) forms an integral part of this initiative.

Executive Summary

The project team was dedicated to creating an economically viable, user-friendly, versatile, precise, and dependable hazard detection and alert system designed for seamless integration into environments containing heavy fleet vehicles and construction personnel.

Construction crews are often fully engaged in their tasks and need help maintaining constant vigilance regarding the movement of vehicles within their construction zones. Similarly, the drivers of heavy fleet vehicles may find their awareness compromised due to various physical and cognitive impediments. This is particularly concerning when construction personnel are situated outside drivers’ line of sight, such as within blind spots or behind barriers, increasing the potential for incidents. Even when drivers can visually identify construction personnel 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. Any miscalculation in these situations can have severe and, at times, fatal consequences.

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. Although work zone fatalities declined from their peak of 1,186 in 2002, they began to rise again in 2011. Between 2011 and 2020, work zone fatalities surged by 45.2 percent, rising from 533 to 774, a rate far exceeding the 19.9 percent rise in total traffic fatalities (from 32,367 to 38,824) over the same period. Moreover, the severity of work zone crashes also worsened, with the proportion of fatal crashes within total work zone incidents increasing from 1.8 percent to 2.2 percent between 2011 and 2020.

While work zone crashes are often categorized as a subcategory of traffic incidents, they 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. Nevertheless, 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 passing vehicles and heavy machinery entering and exiting the work zones. Additionally, they are exposed to the hazards associated with equipment operating within the workspace. National work zone safety statistics reveal that workspace incidents are frequently linked to mobile equipment reversing. Therefore, a comprehensive understanding of these backing incidents within the workspace and safeguards for workers on foot are pivotal for enhancing work zone safety.

The core objective of this project is to develop a system that promptly notifies workers and vehicle operators when fleet vehicles are in motion or engaged in reversing maneuvers, thereby effectively reducing the risk of work zone incidents. The project begins with a comprehensive review of existing commercial alert systems. The proposed, novel method comprises a

wearable proximity sensor for personnel, complemented by an in-vehicle, portable detection system.

Furthermore, the project encompasses on-site assessments designed to evaluate the practical effectiveness of the hazard detection and alert system. An essential component of this initiative is formulating a system maintenance strategy tailored for the Missouri Department of Transportation (MoDOT).

In this interdisciplinary research endeavor, the project team develops a cost-effective and reliable bi-directional warning system tailored explicitly for deployment in construction and work zones. This system incorporates a lightweight wearable proximity sensor with a beacon communication handler and auditory and tactile warning capabilities for construction personnel. Simultaneously, an in-vehicle portable detection system featuring a beacon communication handler and an application for visualizing hazard prediction maps is provided for vehicle drivers and operators. Additionally, the design incorporates the deployment of Vehicle Proxy Tags (VPTs) on the rear end of vehicles to address limitations related to direct signal advertising and scanning between construction workers and drivers.

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Chapter 1 Introduction

The project is dedicated to developing a robust, bi-directional proximity detection and warning system that leverages advanced Wi-Fi and Bluetooth-based, device-to-device direct communication technologies. The primary objective of this initiative is to reduce back-over incidents effectively.

Figure 1.1 Proposed Proximity Detection and Warning System

1.1 Hazard Detection and Alert System Architecture

As illustrated in **Figure 1.1**, the system comprises two primary components:

1. **Wearable Proximity Sensor (WPS) Tags:** These lightweight, wearable tag devices are equipped with a beacon communication handler, enabling them to provide sound and vibration warnings. They are designed for workers on foot, serving as a means of enhancing their safety.
2. **In-Vehicle, Portable Detection (iVPD) System:** This component incorporates a beacon communication handler and an application that visualizes a hazard prediction map tailored for drivers. It offers a comprehensive solution to address the safety needs of vehicle operators.

Additionally, the project team integrates Vehicle Proxy Tags (VPTs), which are affixed to the rear end of vehicles. This integration helps overcome challenges associated with direct signal advertising and scanning between construction workers and drivers.

The primary goal of this proposal is to design and develop an affordable, user-friendly, adaptable, accurate, timely, and reliable bi-directional warning system. This system relies on advanced Wi-Fi and Bluetooth-based, device-to-device direct communication technologies, specifically designed for use in construction and work zones. The project creates resilient, non-invasive, cost-effective, situation-aware, and practical safety applications. These applications serve as deliverables, featuring lightweight sensors that harness the capabilities of ubiquitous smart devices and communication technologies. The overarching purpose of these safety applications is to protect both workers on foot and equipment drivers who often face distraction and decreased awareness of traditional safety warnings due to challenging construction and work zone environments.

A key innovation of this project is the incorporation of integrated operational concepts that make use of Vehicle-to-Crew (V2C) data. These concepts serve two primary objectives:

1. **Decreasing Construction Site Incidents:** This is achieved without expensive communication devices and wireless communication technologies.
2. **Enhancing System Accuracy and Reliability:** The project aims to deliver timely warnings of imminent collisions to workers and drivers, particularly those distracted. This enhancement is crucial in ensuring the system's effectiveness in real-world scenarios.

1.2 System Design

The proposed system incorporates operational concepts that leverage Vehicle-to-Crew (V2C) data, aiming to reduce construction site 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 drivers who share the same path. The technical aspects of the system design include the development of a beacon communication handler that utilizes embedded beacon stuffing technologies for Wi-Fi and Bluetooth Low Energy (BLE). The project team also devises an effective collision detection algorithm for embedding into smart devices. Furthermore, the project team creates a visualization software package known as iVPD, which can be deployed on various smart devices, including tablets, laptops, and smartphones (both Android and iPhones). 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.

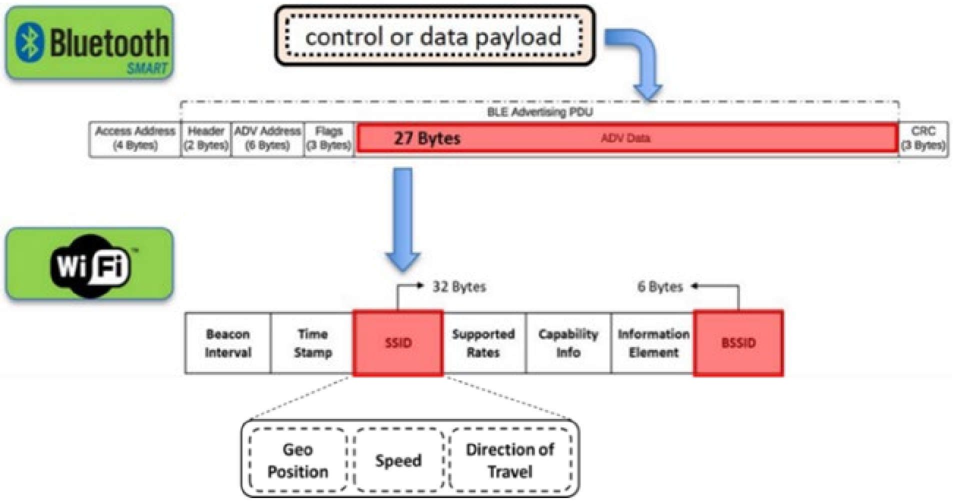


Figure 1.2 Wi-Fi and BLE Beacon Stuffing

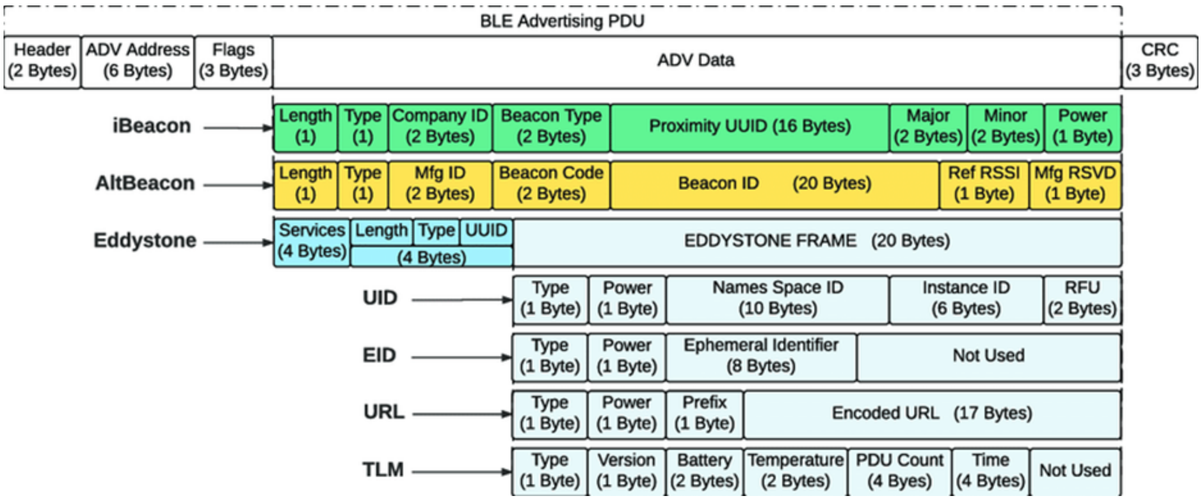


Figure 1.3 Wi-Fi and BLE Beacons' Packet Structures

The proposed initiatives and their significance can be outlined as follows: In pursuing an economically viable and practical safety solution that does not rely on specialized communication devices, the system utilizes Wi-Fi and 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 distracted construction workers and vehicle operators, the proposed approach eliminates the two to three-second Wi-Fi or BLE device connection overhead (e.g., Wi-Fi association) by introducing an innovative concept known as "beacon stuffing."

Figure 1.2 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 the Service Set Identifier (SSID) of a beacon frame. The SSID serves as a human-readable network identifier, with specifications varying (e.g., 32 bytes for Wi-Fi protocol and 27 bytes for Bluetooth protocol (in **Figure 1.3**)). The Wireless Proximity Sensor (WPS) and iVPD components actively seek out periodic beacons to monitor nearby objects.

The system also addresses challenges related to power consumption and potential congestion arising from the periodic broadcast of beacon messages. The project team proposes 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. For instance, Wi-Fi-Direct facilitates the connection of devices without necessitating a wireless access point by employing probe requests and responses when one station searches for another. Rather than configuring tags to transmit beacon frames periodically, the proposed technology enables tags to operate in a listening mode, responding exclusively when prompted by a probe request initiated periodically by Proximity Alerts (PAs).

A second innovative strategy involves 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 collision prediction algorithms to generate timely and accurate warnings is essential to this project. The project team also crafts relative positioning technologies for mobile entities to enhance the accuracy and efficiency of collision alerts. In traditional collision prediction applications, each object derives its absolute location via GPS and maintains a history of location data to compute its speed and direction of movement. By exchanging this information, objects can anticipate potential collisions.

However, the accuracy of collision prediction 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, facilitating the prediction of potential collisions. 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 conducts a meticulous evaluation to reduce the chance of false positive alerts, while ensuring no rise false negatives, i.e., instances where actual collisions go unalerted due to the reduction measures.

Figure 1.4 WPS Harness in Helmet

As for the WPS tags, the project team designs the alert system to be bi-directional, cost-effective (less than sixty dollars per tag with no maintenance costs), flexible in terms of form factors, and power-efficient (lasting over a month without recharging). 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 Wi-Fi and dual-mode Bluetooth 4.2 communication capabilities and antenna switches.

As illustrated in **Figure 1.4**, the WPS tag includes a BLE beacon module, a rechargeable battery, and auditory and sensory alerts, which are incorporated into a helmet enclosure 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 evaluating the movement vectors and visualizing the calculated hazard predictions, including the potential for collisions along projected trajectories.

The WPS incorporates a beacon communication handler and offers auditory and sensory alerts in the form of sound and vibration. At the same time, the iVPD includes a beacon communication handler and a software application for visualization and warnings, specifically a hazard prediction map designed to run on smart mobile devices. 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, geographic location, and details concerning speed and direction of travel. The project team implements reliable information embedding technique 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. The iVPD plays a pivotal role in generating a spatiotemporal understanding of the environment, achieved by evaluating these movement vectors and creating a visual representation of the calculated hazard predictions, indicating any potential collisions on projected trajectories. The system actively alerts drivers and operators through sounds, vibrations, and display screens. Simultaneously, the WPS is designed to detect specific and imminent collision risks posed to the ground crews and alert them via audio and vibrations.

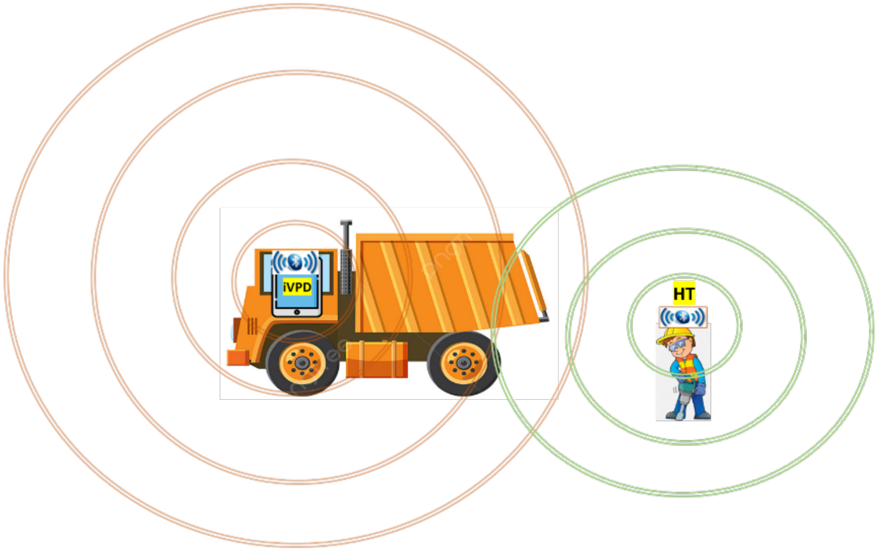


Figure 1.5 Initial Detection Design

One of the key findings from field testing is a design problem that leads to significant variation in distance measurements facing substantial obstacles (i.e., 7 ~ 10 m of fully loaded truck cargo), thereby frequently invalidating the accuracy of practical distance calculations. The project team validates the realistic obstacles' interference significance and pivots to a new VPT design to mitigate the problem. The **initial proposal** incorporates an iVPD app to advertise and scan the BLE signals for detection purposes (in **Figure 1.5**). Nevertheless, as shown in **Figure 1.6**, 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 Human Tags (HT) (i.e., a WPS harnessed by human).

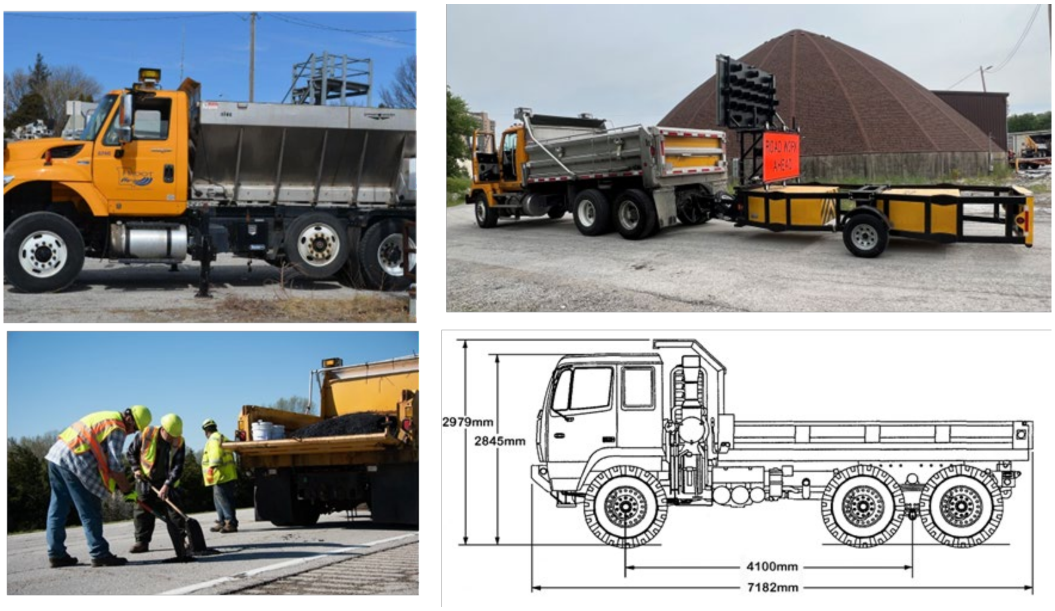


Figure 1.6 Construction Vehicle Form Factors

One of the test scenarios encompasses obstacles such as water, walls, and humans, which possess limited relevance to more significant obstacles such as construction trucks. Consequently, the signals exhibit uncontrollable levels of variation and accuracy. In the field-testing phase, the project team occasionally experiences limited reachability when imposing distance restrictions, whereas allowing unrestricted length results in significant signal variation. To address the design challenge, the project team builds VPT system. This design mitigates the limitations encountered when utilizing the iVPC app for direct signal advertising and scanning. In the proposed approach, a VPT is affixed to the rear end of vehicles, as illustrated in **Figure 1.7**. The iVPC app establishes communication with the VPT, which in turn performs scanning operations. By leveraging this setup, the VPT can advertise beacon signals to the receiving HT, effectively overcoming the issues related to signal variation and accuracy arising from large obstacles.

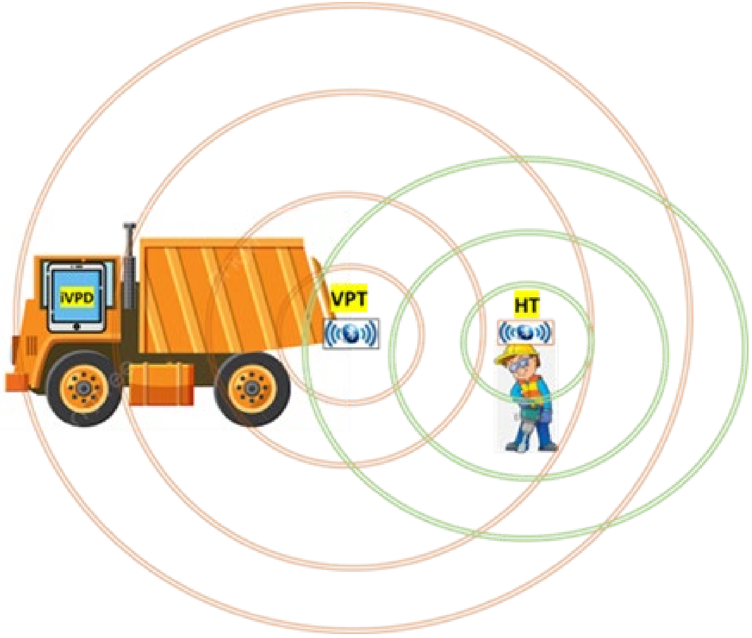


Figure 1.7 Proposed Vehicle Proxy Tag (VPT) Design

Chapter 2 Literature Review

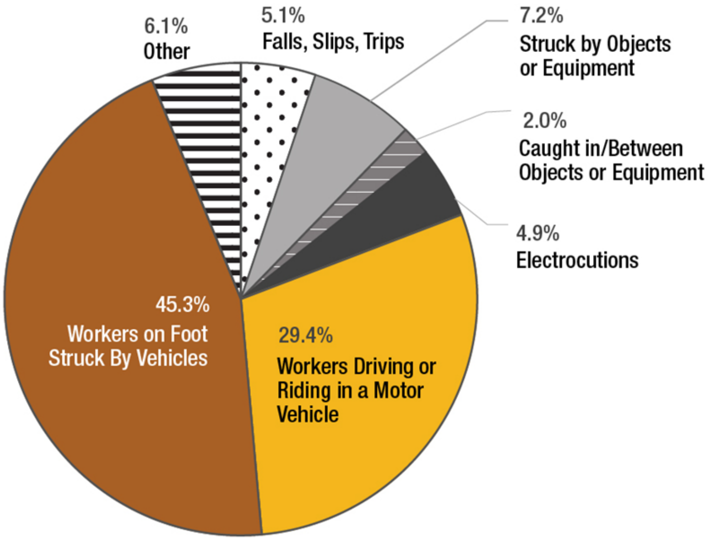
Work zones have been consistently linked to traffic conditions and road environments prone to crashes (Ullman et al., 2018). Despite implementing regulations and various safety measures, work zone crashes have remained a significant highway safety concern. In the United States, from 1982 to 2020, a total 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 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 type of incident within 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 machinery 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 the implementation of measures to safeguard workers on foot are of paramount importance 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 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.

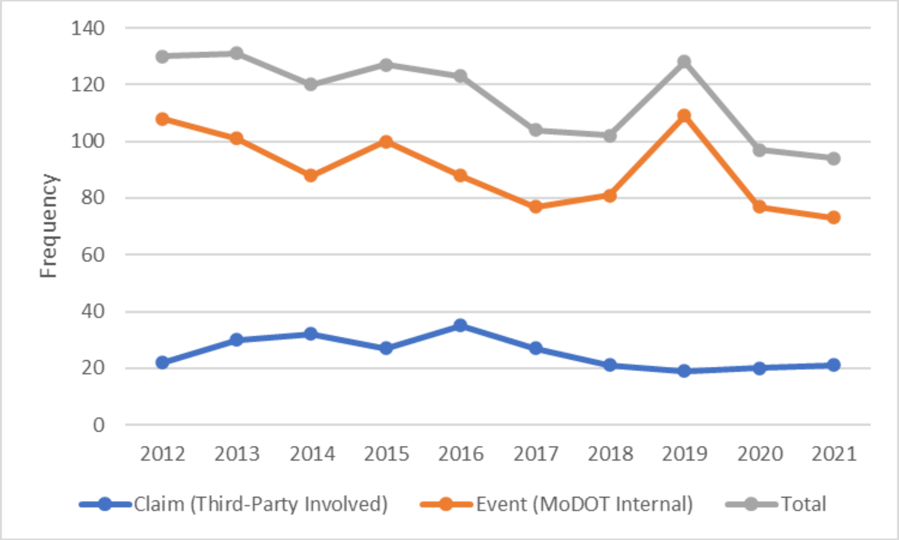


Figure 2.2 Backing Crashes MoDOT's Equipment or Personnel Involved in 2012- 2021

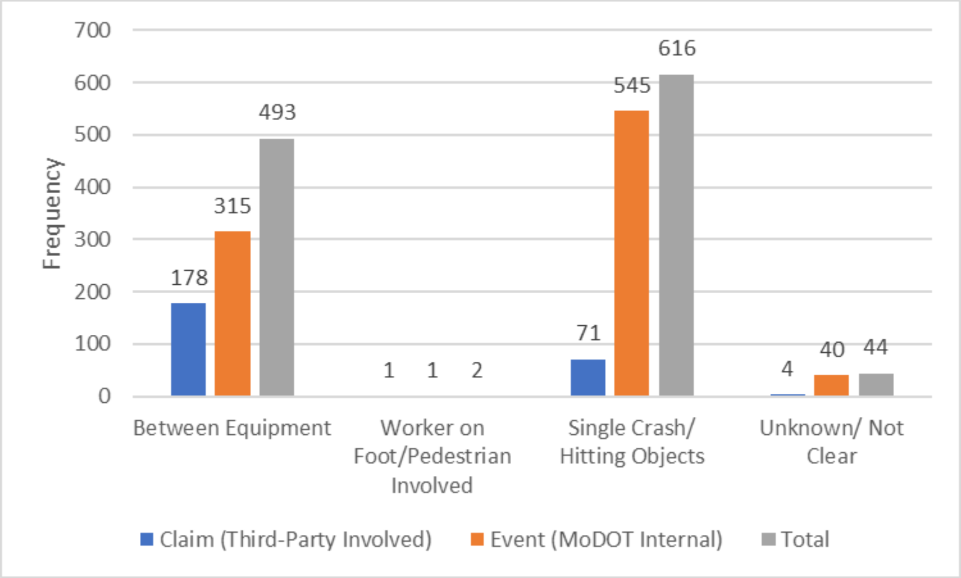
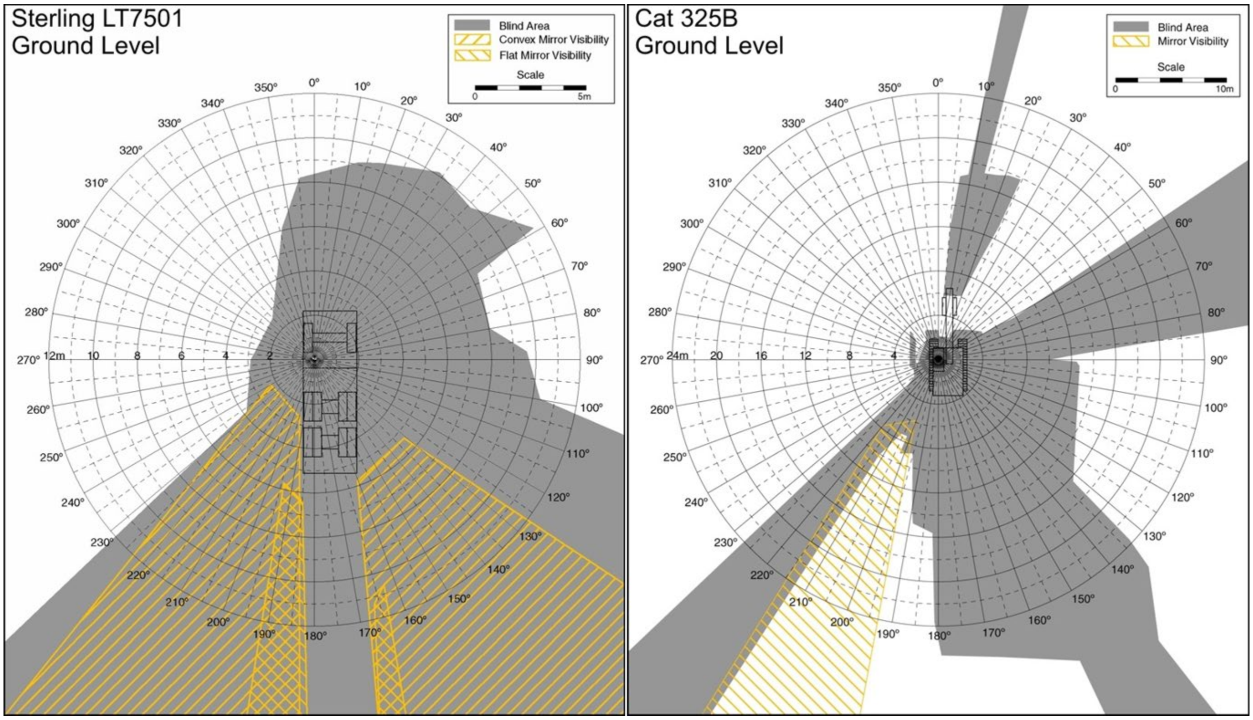


Figure 2.3 Types of Backing Crashes Reported to MoDOT in 2012-2021

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 incident 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



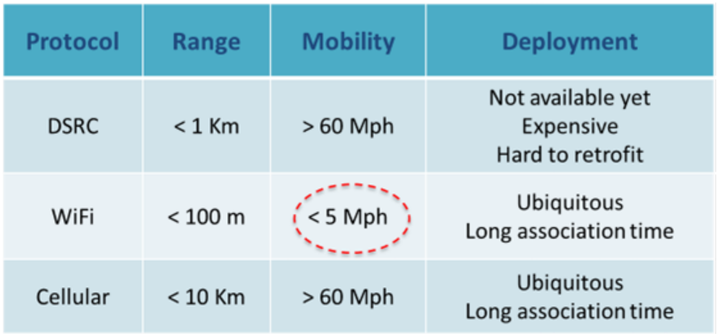
Source: National Institute for Occupational Safety and Health (NIOSH) (n.d.-b.)

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

Figure 2.5 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)



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

Workers on foot in the workspace are vulnerable since they often work close to heavy construction machinery and vehicles that usually have 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. **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

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 alarm’s set-up procedures are often complicated (Krupa, 2010). The NJDOT study concluded that, given the quality control and reliability issues, combined with the cost of the alarm, the use of the alarm system was not effective.

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. Additionally, 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.

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.

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*.

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 Among 10 State DOTs

		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.

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.

Table 2.4 Mitigation Plan and Vulnerability Assessment for Backing Incidents Among 10 State DOTs

		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.

2.4 Assessment of Existing Proximity Detection and Warning Systems

Existing work zone safety approaches can be described as a geo-fenced work zone 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. 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.

Workers on foot concentrate on their tasks and are difficult to look out for cars and trucks moving around the work zone. 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.

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 vehicle manufacturers must fit into their vehicles. Also, wearable devices for construction workers must equip 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 Implementation and Experimentation

3.1 System Implementation and Deliverables

The project team successfully developed a cost-effective, user-friendly, accurate, adaptable, timely, and reliable alert system that predominantly relies on software-based solutions, except for a simple wearable WPS tag. The key system components comprised an iVPD application and WPS tags, which have been crafted to meet specific safety requirements. First and foremost, a beacon communication handler was designed and developed using embedded beacon stuffing technologies for Wi-Fi and BLE. Additionally, an effective collision detection algorithm has been engineered for seamless integration into smart devices.

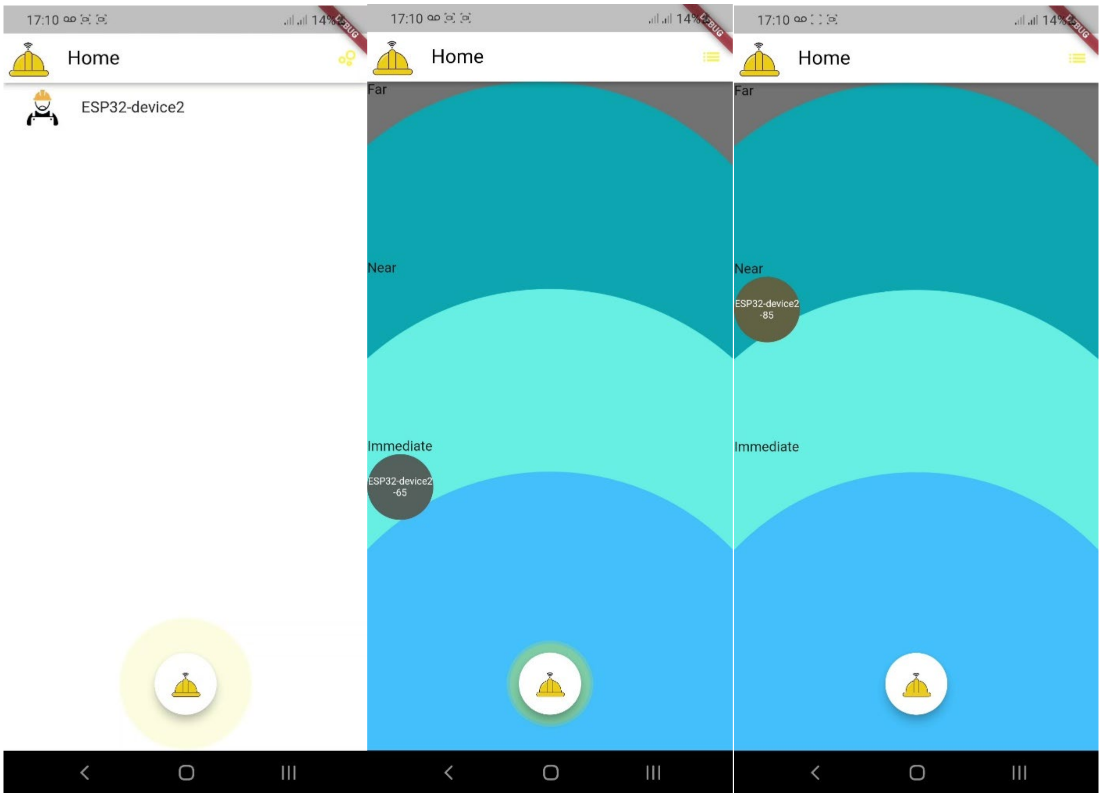


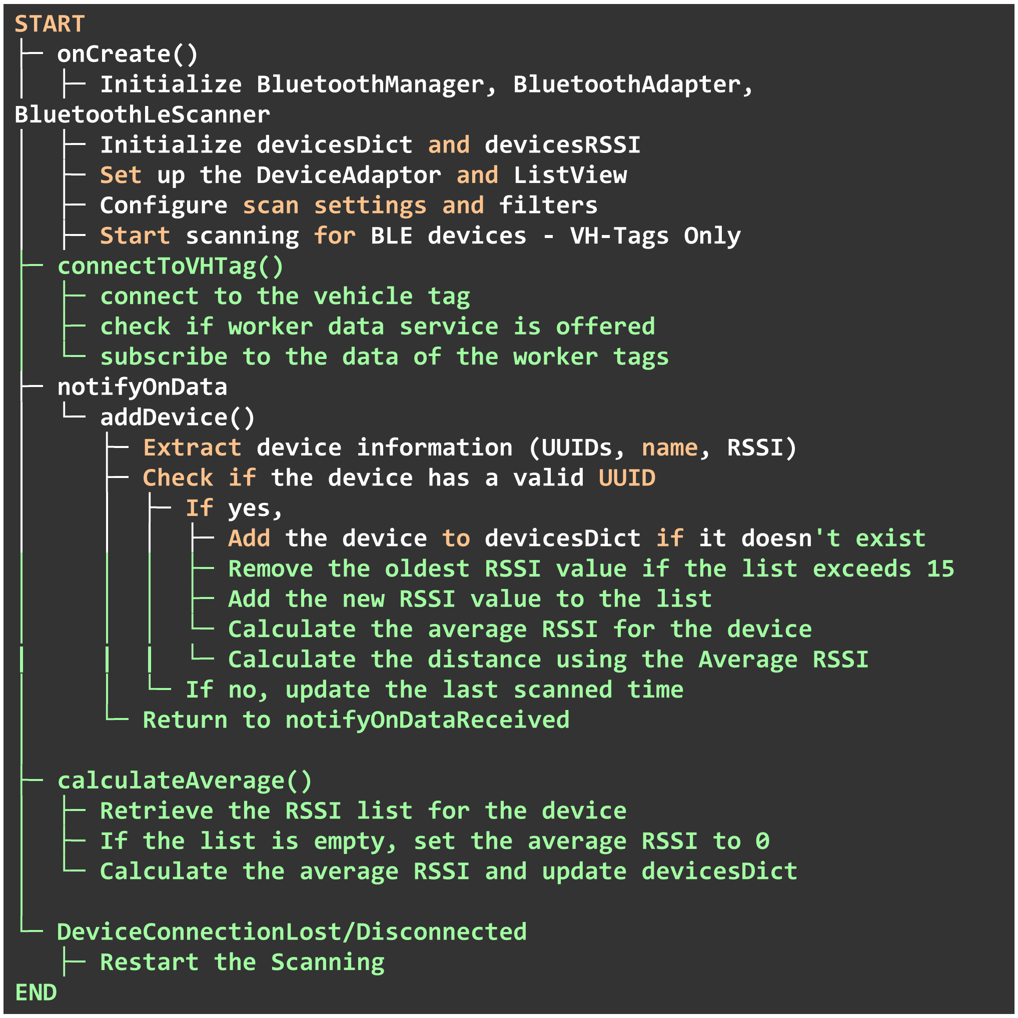
Figure 3.1 iVPD Application Screen Displays

As shown in **Figure 3.1**, a visualization software package known as the iVPD application was developed. This application was designed to deploy on various smart devices, such as tablets, laptops, and smartphones, encompassing Android and iOS platforms. The iVPD application is not a fragmented software solution; instead, it offers the flexibility to be configured with various functions. The project team developed a cross-platform application that works on both Android and Apple devices, designed to support the visualization and warnings of the intelligent Vehicle-Pedestrian Detection (iVPD) system. This app includes customizable features such as frequency, color, and alert types. Remote control of the iVPD application was facilitated through Google Cloud Messaging (GCM). The third facet of the project created a cost-effective

WPS tag with a target cost of less than $60 per tag and no maintenance costs. This WPS tag was highly adaptable regarding form factors, with multiple options available. The project team designed the WPS tag to be power-efficient; it can last over a month without requiring recharging. The tag can monitor beacons from neighboring objects, including construction crews and drivers, to provide critical proximity information. To achieve these objectives, the project team built the WPS tag without using expensive cellular communication. Instead, 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 integrated Wi-Fi and dual-mode, Bluetooth 4.2 communication capabilities, along with built-in antenna switches. The WPS tag was packaged with an inertial measurement unit (IMU), a rechargeable battery, and various auditory and sensory alerts, including sounds, vibrations, and LED lights. The project team diversified form factors for the WPS tag by offering options such as headphone attachment, helmet enclosure, goggle attachment, shoestring, clip, and sticker. Five WPS tags were manufactured as the minimum viable prototype products using a 3D printed case.

3.1.1 Mobile Applications and Algorithms

Flow charts were crafted that represent the working flow of the mobile app which was installed inside of the vehicle (iVPD in **Figure 3.3**) and connected to the VPT using an esp32 platform installed on the backside of the vehicle. 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.

As illustrated in **Figure 3.4**, the workflow of the HT algorithm was integrated into the WPS (Worker Positioning System) tag, which was attached to workers' helmets. To illustrate how HT operates, the project team designed a flow chart that outlines the step-by-step process of the algorithm's functionality. The VPT’s operational workflow was outlined in the accompanying flow chart in **Figure 3.5**.

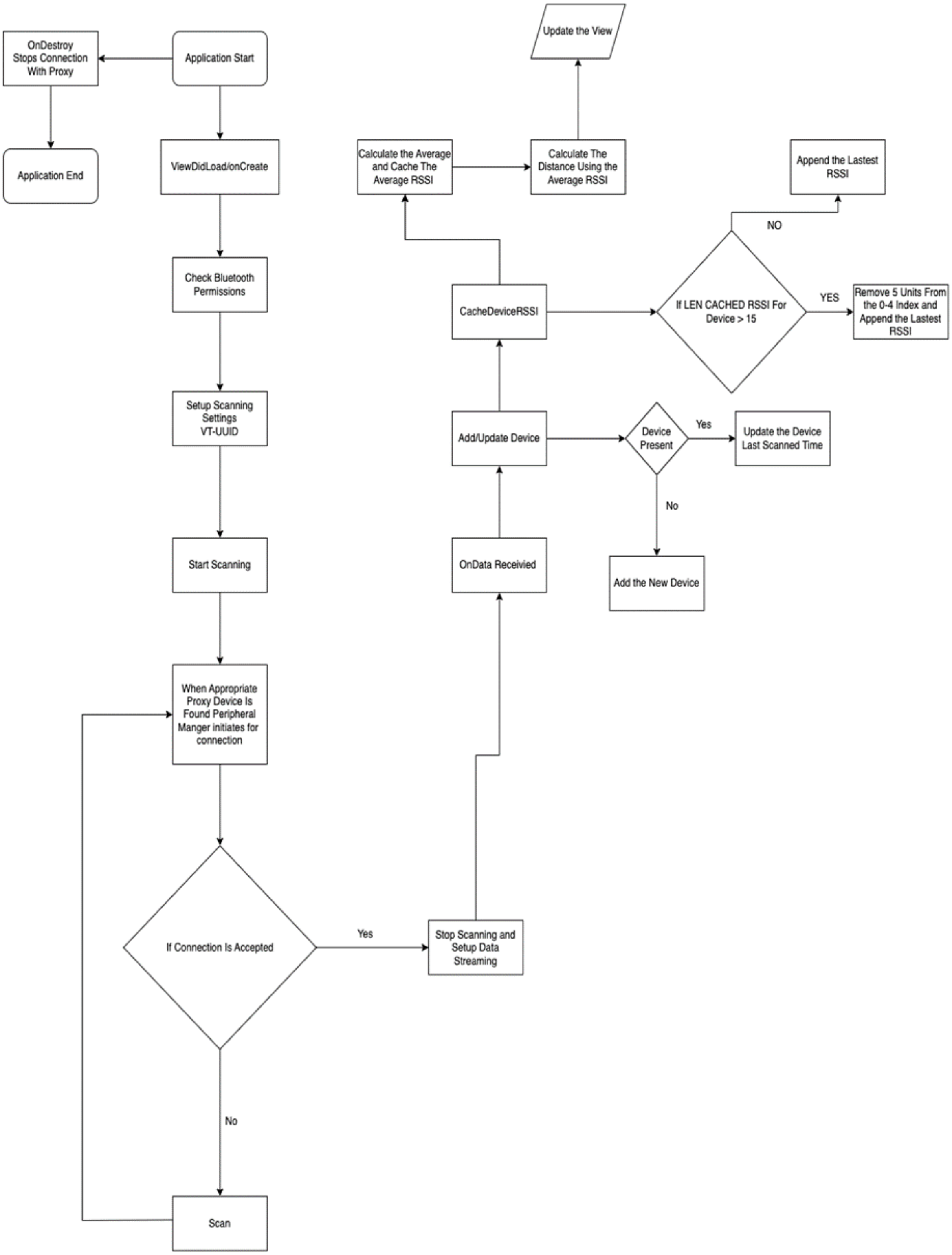


Figure 3.3 In Vehicle Algorithm

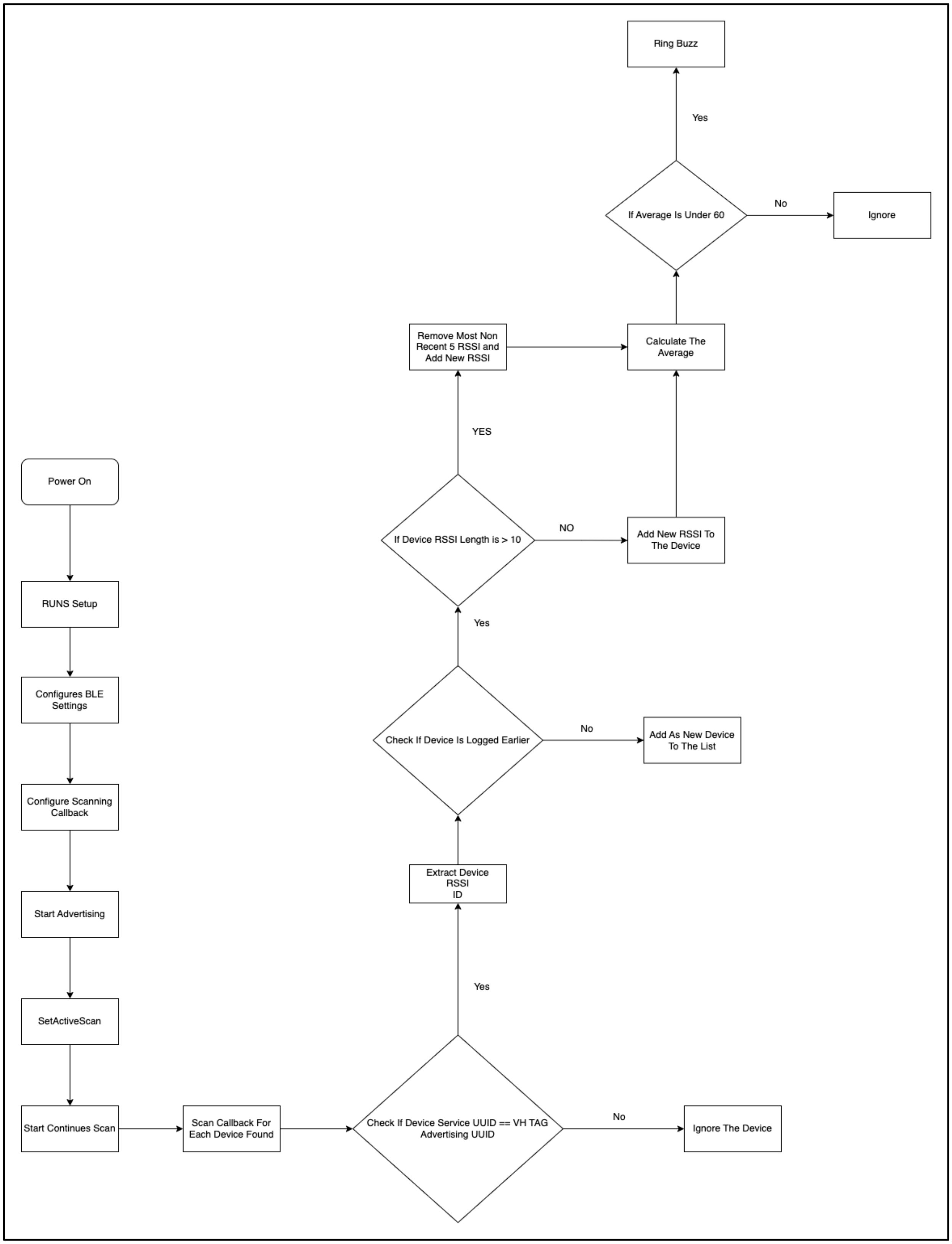


Figure 3.4 Human Tag (HT) Algorithm

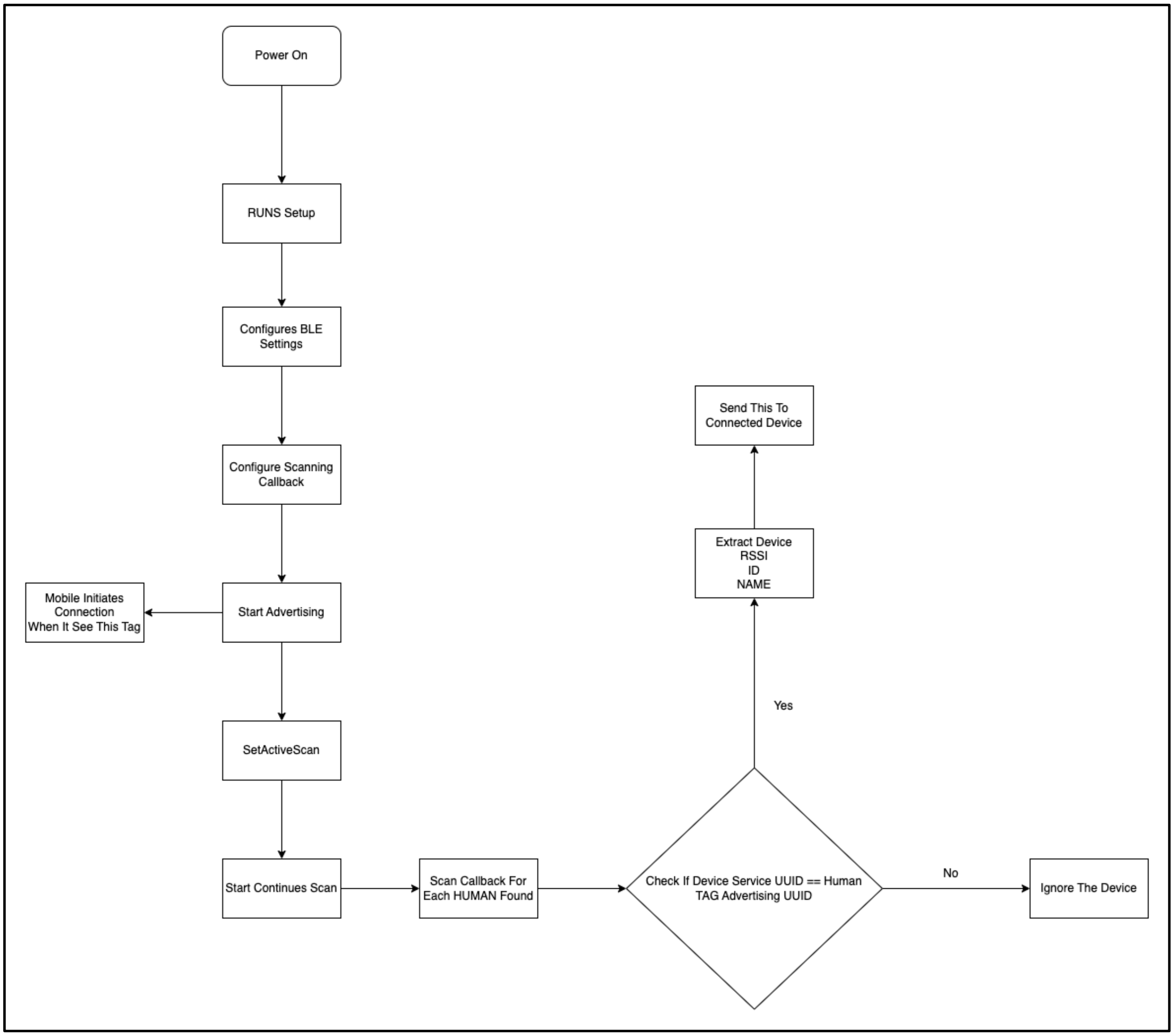


Figure 3.5 Vehicle Proxy Tag (VPT) Algorithm

3.2 Experimental Results

3.2.1 The Field Test

As presented in **Table 3.1**, the testing scenarios comprised five categories including functional test (FT), interference test (IT), accuracy test (AT), power duration test (PT), and resilience test (RT). The objective of the field test was to validate the simulated environment test results in practice. During the test, the project team complied with all safety rules and did not distract any construction workers. The tracking app test for back-up trucks can be tested in simulation with moving people (no need to schedule any trucks). During the field test, the project team (four people) brought three helmets with attachable beacon tags and three construction jackets with three harnessing beacon tags. Two smartphones with tracking apps were used.

- The **FT** included assessment of tracking app function given different tag locations (multiple tags for a moving tracker), 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).
- The **IT** included assessment of multiple tag interference and obstacles (water, wall, human, etc.) between tags and tacker (smartphone) and scalability on the tags.
- The **AT** included assessment of distance accuracy and tag tracking accuracy on the app.
- The **PT** included assessment of beacon frequency and the number of tags.
- The **RT** included assessment of heat resistance, wet resistance, concussion resistance, and harness resistance for different mobility and tag locations.

Table 3.1 Test Scenarios

Test Scenarios	Explanation	Results	Notes
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	**Pass**
FT.2	Tracking app function for moving tags (a stationary tracker app for moving tags)	Identify the tag locations (no exact direction)	**Pass**
FT.3	Tag buzzer volume change	Find audible volume levels for different distance and environment noise	**Pass**
FT.4	Tracker app warning types	Check if the app shows exact level of warning in color, sound, and frequency	**Pass**
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)	**Pass**
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	**Pass**
IT.1	Multiple tag interference	When there are more tags, check how much those tag signals impact each other	**Pass**

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	**Pass**
IT.3	Scalability on trackable tags	Theoretical limitations and practical degradation	**Pass**
AT.1	Distance measurement accuracy	Accurate measured distance for a given distance	**Pass**
AT.2	Tag tracking accuracy on App	Accurate tag locations for a given tag distances	**Pass**
PT.1	Power duration for beacon frequency	Measured power usage for a tag with a given test duration	**Pass**
PT.2	Power duration for the number of tags	Measured power usage on a tag for different number of tags and trackers	**Pass**
RT.1	Heat resistance	The range of the functional temperature	**N/A**
RT.2	Wet resistance	Tags are functional despite rain or sweat	**N/A**
RT.3	Concussion resistance	Tags are functional despite different concussion scenarios	**Pass**
RT.4	Harness resistance for different mobility and tag locations	Check how long those harnesses last (dusty, hot, and cold environment)	**Pass**

The project team (four students and two PIs) performed multiple tests of safety tags at various locations (in **Figure 3.6** The Project Team in Field Testing). The project team built five tags and an Android app.

Figure 3.6 The Project Team in Field Testing

- **Warning sound** with 85dB buzzer worked well. Regardless of the harnessing position (front, near ear, overhead, etc.), if the buzzer was harnessed within the helmet, the sound was loud enough to warn construction workers. 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. However, when the project team changed the algorithm to have tags send beacons only if any moving truck was identified near the tag, it lasted several days. There was no power outage or degradation during the field-testing process of 4 hrs. (3 hrs. before the test and 1-hr. testing). Simultaneously, the project team harvested power with a mini solar panel.
- **Tag placement**. The tag comprised in-case components (350mA battery and ESP32) and an out-case buzzer. The project team harnessed it inside the helmet with double-sided tape. There was no deformation, even after the helmet dropped to the ground.
- **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 buzzed when they were within 2 m. The app warned in time in different zones. The project team tested one-to-one and many-to-many cases. The project team found no scalability or delay issue. Obstacles impacted zone-based accuracy little.

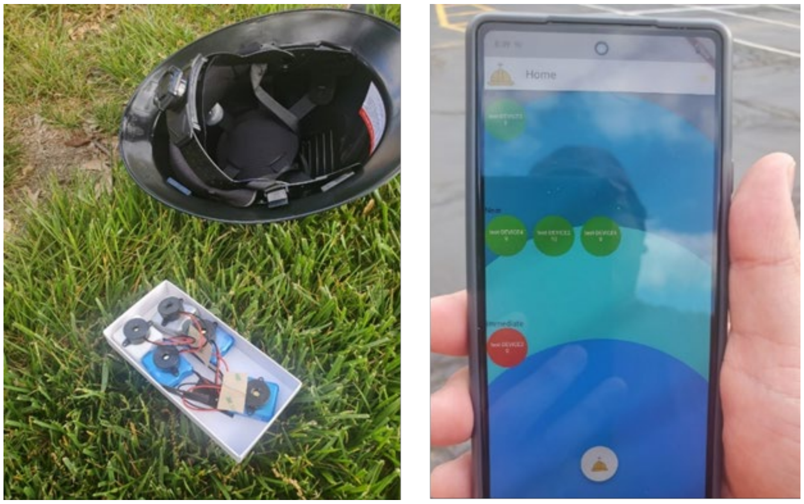


Figure 3.7 Warning Sound Tags and App

The project team tested to quantify the beacon accuracy variations. The technology was distinctive for the 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, such as walls, doors, or furniture, which can hinder signal propagation. Additionally, the distance between the router and the device played a crucial role; if they were too far apart, connectivity became problematic.

To address these challenges and enhance the accuracy of BLE RSSI measurements, the project team employed several key strategies, including the implementation of a Kalman filter and the integration of distance and variation measures. The Kalman filter was a powerful tool for noise reduction in inherently noisy signals. Its computational efficiency, owing to easily computable update functions, resulted in a high-performing system.

Figure 3.8 RSSI Accuracy Testing

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

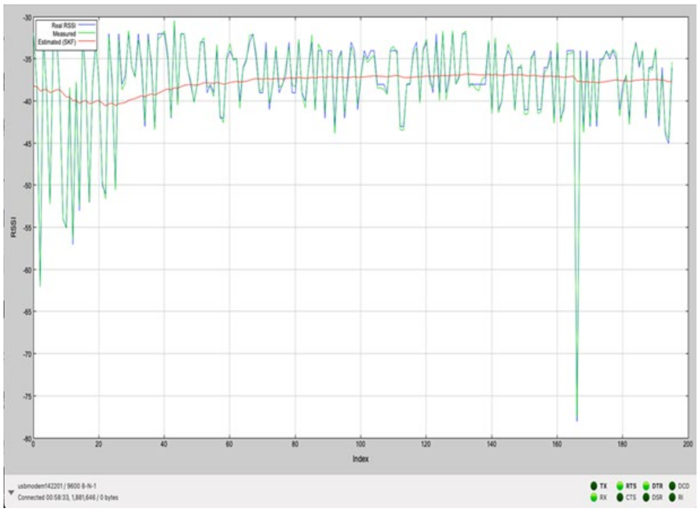
1. **Distance Estimation from RSSI:** The project team developed a methodology to estimate distances based on RSSI values, laying the foundation for accurate distance calculations.
2. **Fluctuation Reduction:** The project team integrated a Simple Kalman filter to effectively mitigate fluctuations in 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 diverse conditions, encompassing the following scenarios:
    - **Over Set Distances:** Rigorous testing at predetermined distances to evaluate the accuracy of the distance estimations.
    - **Outdoor Testing:** Evaluation of system performance in outdoor environments, which often present unique challenges.
    - **No Obstacles Testing:** Assessment of the system's performance when physical obstacles are absent.
    - **Human Obstacles Testing:** Testing conducted under conditions involving human obstructions to gauge the system's response in real-world situations.

3.2.2 Test Result Analysis

The project team thoroughly examined the testing outcomes, which involved several vital components. Firstly, the project team engaged in 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 scrutinized variations in distance estimations under diverse conditions, offering valuable insights into 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, facilitating a more nuanced visualization, and understanding of the outcomes.



usbmodem142201 / 9600 8-N-1
Connected 00:58:33, 1,881,646 / 0 bytes

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.

$$Distance = 10\text{^}((Measured\ Power - Instant\ RSSI) / (10 * N)) \qquad (3.1)$$

In equation (3.1):

- **Measured Power** represents the Received Signal Strength at a reference distance of 1 meter. As shown in **Figure 3.9**, 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 like walls 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 (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 in a user-friendly manner, incorporating a timer mechanism to remove devices not updating their data. It functioned as a data receiver processor and provided a user interface for presenting distance estimations and visualizing data.

These system components collectively contributed to the comprehensive testing and data processing in various scenarios, enabling the project's objectives to be achieved effectively. The simple Kalman filter plays a crucial role in this program by effectively reducing the noise in RSSI values. These RSSI values can be influenced by various environmental factors, 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 the Kalman filter to estimate the genuine RSSI value from this noisy data.

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

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 robustness of 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 system performance, a controlled introduction of intentional noise was applied to the recorded RSSI values. A Kalman filter was systematically applied 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 upon recognizing a device advertising the expected service. In the “mobile device” phase, the mobile device operated as a client, establishing a connection to the proxy (VPT) and subscribing to data. Employing a sliding window technique, the mobile device systematically processed RSSI values to derive more accurate 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 operation of the system. 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 involved several distinct stages, as well. Initially, 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 it calculated estimated distances for each detected device based on the RSSI value. This information and related data for each device 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 haven't 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. As illustrated in **Figure 3.10**, this comprehensive data flow and user interface design ensured efficient data processing, accurate distance calculations, and real-time monitoring for the users, enhancing their understanding of the proximity of nearby BLE devices.

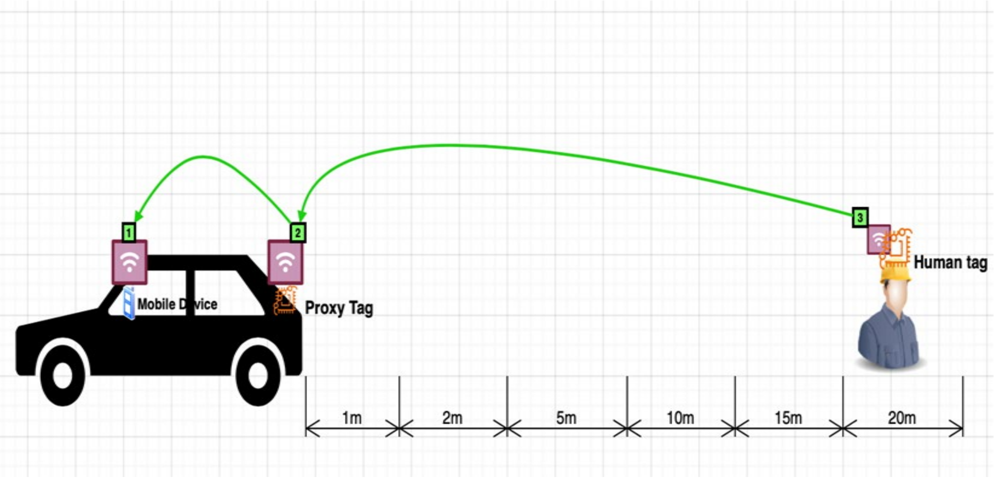


Figure 3.10 Test Settings

Figure 3.11 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.

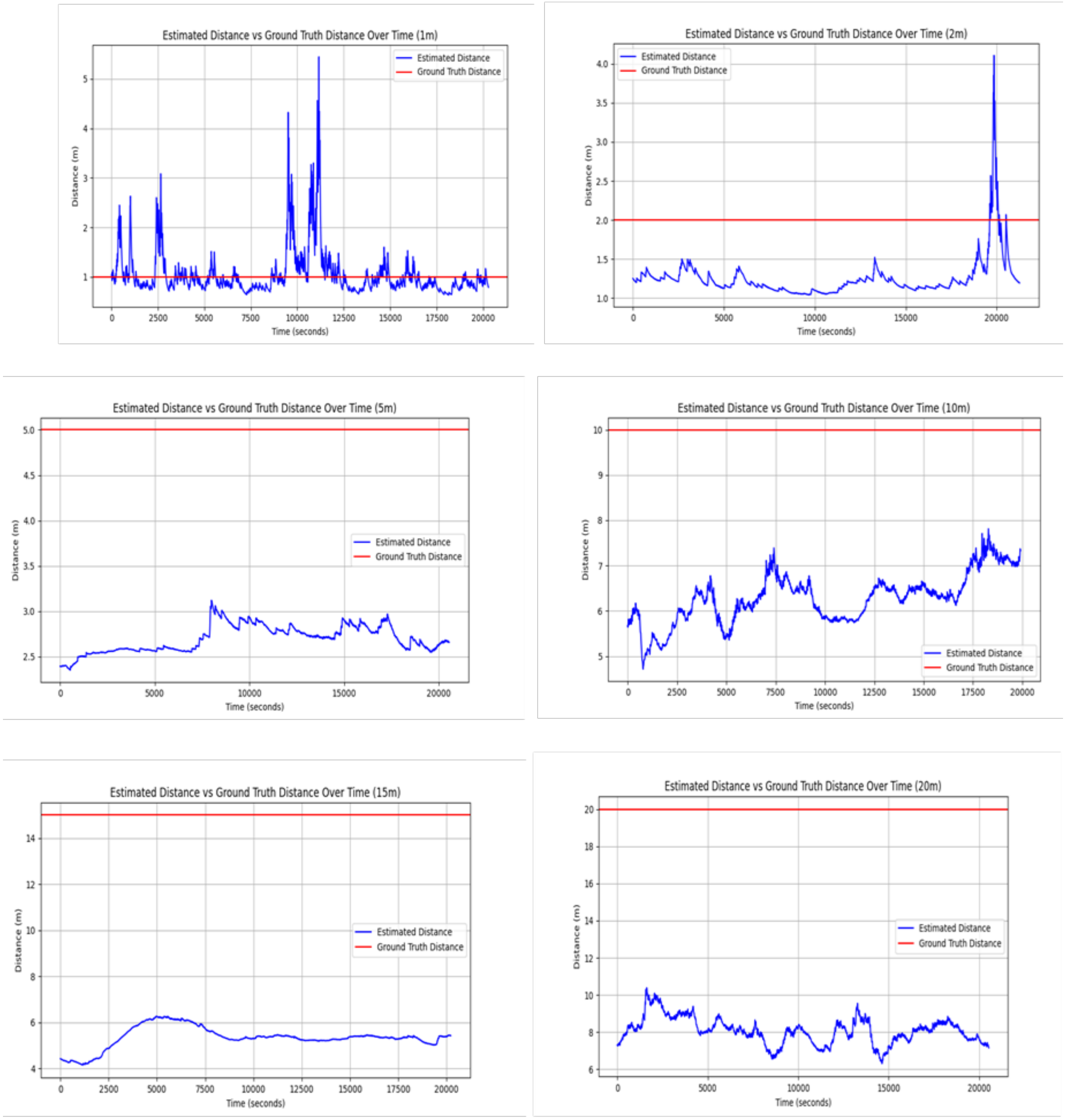


Figure 3.11 RSSI Tests without Interference

Figure 3.12 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 BLE tags, and data was transmitted every 10 sec.

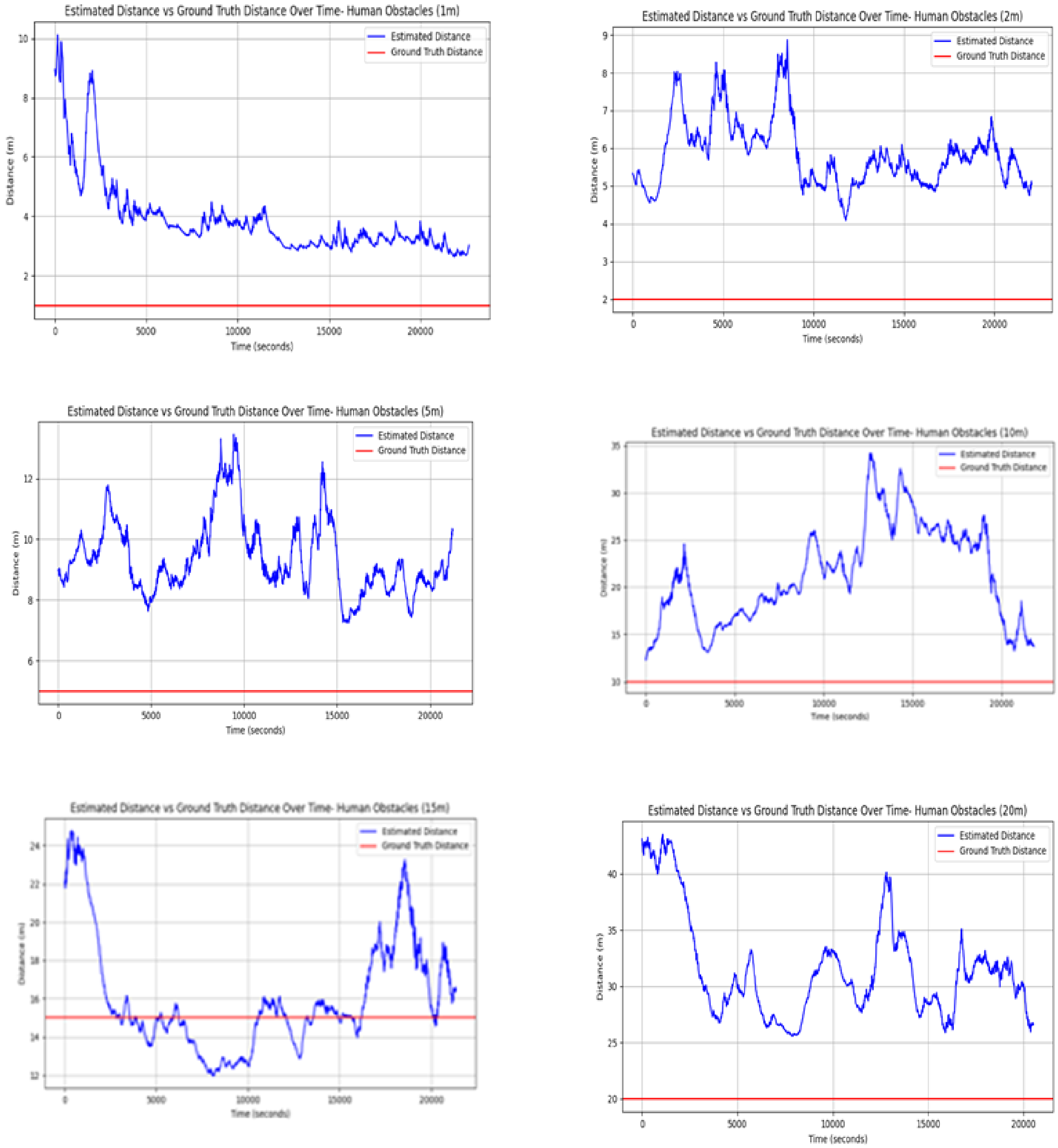


Figure 3.12 RSSI Tests with Interference

In summary, the VPT and client devices (HT or WPS) were in a continuous scanning mode 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 iOS and Android apps operated as a BLE central device, taking on the duties of scanning for BLE signals, establishing connections with devices, and receiving data from the Arduino server (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. This user-friendly interface enhanced the user's experience and facilitated a better understanding of the environment through accurate and updated information. 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.

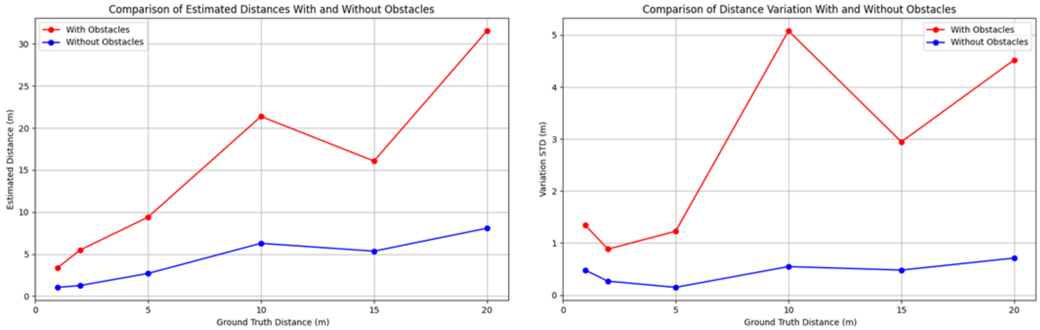


Figure 3.13 Distance and Variation Results with and without Obstacles

Figure 3.13 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 valuable insights into the practical utility and 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.

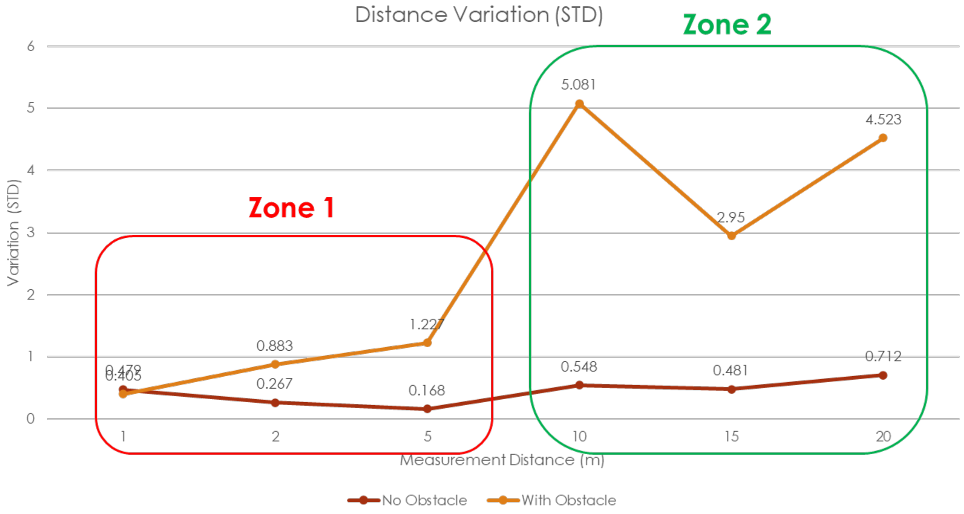


Figure 3.14 Safe and Risk Zones

As illustrated in **Figure 3.14**, 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. Devices exhibiting a variation in RSSI values exceeding a predetermined threshold of two were 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 were categorized into Zone 1, signifying a higher potential risk of collision. This zoning and risk classification system was implemented to strengthen safety measures and diminish the likelihood of collisions within the monitored environment, ultimately contributing to a safer and more efficient operational context.

Chapter 4 Conclusion and Recommendation

The present undertaking involved the development of an economically feasible, user-friendly, versatile, precise, and reliable hazard detection and alert system specifically tailored to integrate seamlessly with heavy fleet vehicles and adjacent construction personnel. The critical findings are summarized as follows.

- This project undertook a comprehensive review of existing commercial alert systems.
- The research initiative systematically examined existing commercial alert systems, culminating in constructing a wearable proximity sensor for personnel.
- Complemented by an in-vehicle, portable detection system, the primary objective was to expeditiously notify workers and vehicle operators of fleet vehicle movement or reversing maneuvers, thereby effectively mitigating the potential risks associated with work zone incidents.
- Conducting on-site assessments to evaluate the practical efficacy of the hazard detection and alert system was an integral aspect of the project.
- A pivotal component of this endeavor involved formulating a system maintenance strategy tailored to meet the Missouri Department of Transportation (MoDOT) requirements.
- The project team successfully designed and developed a cost-effective, user-friendly, adaptable, accurate, timely, and reliable bi-directional warning system. This system leveraged advanced Bluetooth-based device-to-device direct communication (beacon) technologies, meticulously tailored for deployment in construction and work zones. Components of the system included:
    - A lightweight wearable proximity sensor.
    - A beacon communication handler.
    - Auditory and tactile warning capabilities for construction personnel.
- An in-vehicle portable detection system featuring a beacon communication handler and an application for visualizing hazard prediction maps was provided for vehicle drivers and operators.
- The project incorporated the deployment of VPTs on the rear end of vehicles to address challenges related to direct signal advertising and scanning between construction workers and drivers. This augmentation enhanced communication efficacy and overcame limitations inherent in the interaction between construction personnel and drivers.

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