GEORGIA DOT RESEARCH PROJECT 11-10

FINAL REPORT

ACTIVE WORK ZONE SAFETY USING EMERGING TECHNOLOGIES

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ACTIVE WORK ZONE SAFETY USING EMERGING TECHNOLOGIES

Final Report

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16. Abstract:
The major objectives of this research were to (1) identify technologies that can be used in real time to detect a hazardous proximity situation between construction equipment and pedestrian workers and provide an appropriate warning; (2) develop a Bluetooth-based proximity alert system; and (3) evaluate the reliability and effectiveness of the technologies through extensive field tests. Some of the pertinent conclusions from this study:

1. Experimental results in controlled environments demonstrate that tested systems provided reliable results with an appropriate alarm with slight performance differences.
2. The Bluetooth proximity system was tested as more effective in terms of cost, small form factor, easy installation, and flexible programming against RFID and magnetic systems.
3. A directional alert display function was positively validated at a real-world construction site.
4. From real-world field tests, the Bluetooth proximity system provided reliable performance results and was positively evaluated by participating equipment operators and pedestrian workers.

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EXECUTIVE SUMMARY

The dynamic nature and limited workspace of Georgia's roadway work zones contribute to the dangerous work environment for construction workers. These characteristics can create hazardous proximity situations because pedestrian workers are required to operate in close proximity to heavy construction equipment. A total of 609 work zone personnel fatalities were experienced in 2012 in the U.S. Previous analysis of work zone fatality data found that of the pedestrian worker and mobile object struck-by fatalities, a majority resulted from pedestrian workers being struck by construction equipment. These statistics indicate that current safety practices for pedestrian workers and equipment operators are inadequate. The primary objective of this research, in three parts, was to 1) identify technologies that can be used in real time to detect a hazardous proximity situation between construction equipment and pedestrian workers and provide an appropriate warning; 2) develop a Bluetooth-based proximity alert system; and 3) evaluate the reliability and effectiveness of the technologies through extensive field tests. Two commercially available technologies, including Radio Frequency Identification (RFID) and magnetic field proximity sensing systems, were identified and tested. A mobile wireless proximity technology developed by the Robotics and Intelligent Construction Automation Lab (RICAL) at Georgia Institute of Technology was evaluated and compared to the RFID and the magnetic sensing systems. Many evaluation metrics were implemented to assess the tested proximity sensing systems including the cost, time and ease of calibration, required hardware, system capabilities, and many others. Various interaction scenarios between pedestrian workers and construction equipment were used in the evaluation of the system. Experimental results demonstrate that all the systems

provided reliable results with an appropriate alarm with slight performance differences. However, the Bluetooth outperformed the others in terms of cost, small form factor, easy installation, and flexible programming. A directional alert display function was developed and added to the Bluetooth proximity system, and its overall performance was validated at a real-world construction site. From the real-world field tests, the Bluetooth proximity system provided reliable performance results and was positively evaluated by the equipment operators and pedestrian workers. Overall, based on the test records and feedback from the workers and operators, it is recommended that Georgia Department of Transportation (GDOT) use the Bluetooth proximity system as an additional layer of hazard avoidance in real time during hazardous proximity situations. Also, it is recommended for GDOT to integrate an intrusion alert system with the Bluetooth proximity system to holistically reducing the risk in the highway work zones in Georgia.

1. Introduction

Roadway work zones often contain multiple construction or maintenance resources in a limited work space. The dynamic nature and limited work space of roadway work zones often require pedestrian workers to work in close proximity to construction equipment which results in hazardous proximity situations. The risk of injuries and fatalities for pedestrian workers increases as contact collisions between pedestrian workers and construction equipment occur.

Previous research efforts of hazardous proximity situations in roadway work zones have focused largely on statistics for worker injuries and fatalities. They have collected and analyzed statistical data for injuries and fatalities from the collision of workers and construction equipment. Despite this fact, there has been a lack of experimental research efforts employing existing safety-related technologies to reveal and demonstrate their potential capabilities in minimizing hazardous being-struck incidents created by proximity situations between workers and construction equipment. In this report, an extensive review of current roadway work zone worker fatality statistics and proximity detection and alert technology was conducted. Experiments were also designed and conducted with two commercially available proximity detection and alert technologies and one wireless technology to emulate typical characteristics and operation scenarios within roadway work zones. The wireless proximity alert technology utilizes the Bluetooth technology that was developed by the Robotic and Intelligent Construction Automation Lab (RICAL) at Georgia Institute of Technology. The experimental results, which encountered limitations and benefits for each of the systems were analyzed and compared. In addition, the research team also conducted performance field tests at a real-world construction site to evaluate the effectiveness and accuracy of the Bluetooth system with various types of equipment and dynamic work conditions. A subsequent discussion of the analyzed field test results and required future research work in proximity detection will follow.

2. Literature Review

Safety is one of the most important components that need to be successfully addressed during construction. The work environment in U.S construction industry has proven to be one of the most dangerous work environments among many other industrial segments (Marks et al. 2012). The Manual on Uniform Traffic Control Devices (MUTCD) defines a work zone as “an area of a highway with construction, maintenance, or utility work activities marked by signs, channelizing devices, barriers, pavement markings, and/or work vehicles” (FHWA 2014). The limited workspace and dynamic environment contribute to the densely populated nature of roadway work zones. A multitude of dynamic interactions between pedestrian workers and construction equipment occur in roadway work zones. The higher the interactions become, the more chances there are for ground workers to get involved with proximity-related accidents. The following discussion reviews roadway work zone personnel fatalities, proximity detection and alert systems, Bluetooth technology, and test methods for the proximity detection and alert systems.

2.1 Work Zone Accident Statistics

Roadway work zones continue to be a dangerous work environment for pedestrian workers. In America, an average of 669 fatalities per year in construction and maintenance occurred from 2007 through 2012 (NIOSH 2014). The Bureau of Labor statistics reported 609 work zone personnel fatalities were experienced in the U.S. (NIOSH 2014). Of the fatalities experienced in 2012, 76% of roadway work zone fatalities were caused by transportation incidents which include struck-by incidents between construction equipment and pedestrian workers (Pegula 2010). The dump truck was most often involved piece of construction equipment during roadway work zone personnel fatalities during contact collisions with pedestrian workers (Pegula 2013). A majority of these fatalities are experienced by construction laborers and typically occur on Wednesday afternoons possibly because workers can become desensitized to hazards associated with working in close proximity to construction equipment by mid-week (Pegula 2013). This historical incident data proves that the current safety practices have not been effective in providing protective, safe working conditions and further improvements are essential for construction safety.

2.2 Georgia Work Zone Accident Statistics

In a preliminary study, the Federal Highway Administration (2010) reported that Georgia experienced 1.9 million total vehicle miles traveled (VMT) in 2010. The VMT gives an estimated value of the number of miles traveled in a state per year and is calculated by multiplying the Average Annual Daily Traffic for a given state by the number of lane miles in that particular state. The VMT value for Georgia was 5th among all states in the 2010 study as well as in 2009 (FHWA 2010).

The state of Georgia experienced 32 fatalities as a result of crashes in work zones in 2009 and ranked 4th highest among the states in fatalities experienced within work zones in 2009 (NWZSIC 2010). The 32 fatalities included vehicle drivers, passengers, construction workers and anyone else involved in a work zone collision. From 2005 to 2009, The National Work Zone Safety Information Clearinghouse (NWZSIC 2010b) records that Georgia experienced 31 fatalities on road construction sites. The 31 fatalities included both private contractors and government employees, and this number ranked 4th among all other states in the United States (NWZSIC 2010b). Between the years 2003 and 2007, Georgia accounted for 5% of the nation's total road construction site fatalities (Pegula 2010).

The Georgia Department of Transportation (GDOT) has experienced 56 employee fatalities from incidents in work zones since 1973 (GDOT 2007). Between 1997 and 2008, eight Georgia Department of Transportation employees died while in work zones.

2.3 Proximity Sensing Technology

Various technologies and system combinations (Kim et al. 2006) are thought to be capable of alerting construction personnel in real time. Initial tests and evaluations have occurred for proximity detection systems in other industries such as underground mining (Ruff 2007), the railroad industry (Begley 2006), and manufacturing (Larsson 2003). Safety technologies can provide workers with a "second chance" by creating an additional layer of protection for ground workers on construction sites (Teizer et al.

2010). Proximity detection and alert systems have been reviewed for their capabilities to function in the mining (Ruff 2004) and construction environment.

Several parameters were used to assess each system including detection area, alert method, precision, size, weight, calibration functionality, power source, ability to identify people from objects, and others. Benefits and limitations of each technology were identified. For example, systems utilizing radio frequency technology can be impacted by direct contact with metallic objects (Goodrum et al. 2006) and experiences multipath or "crosstalk" that limit the system's ability to distinguish individual worker proximity breaches (Lázaro et al. 2009; Castleford et al. 2001). Some of the evaluated systems were incapable of identifying people versus other objects (Hallowell et al. 2010; Ruff 2007; Teizer et al. 2007). These benefits and limitations were used to identify a reliable technology capable of detecting and alerting workers during hazardous proximity situations (Teizer et al. 2007). Results from the review indicate that proximity detection and alert systems utilizing magnetic field technology can be reliable in the construction environment with its own limitations.

2.4 Mobile Wireless Technology

A number of research efforts in recent years attempted to utilize wireless technology for various purposes in many different research areas. Most commonly used technologies in construction area include Global Positioning System (GPS), Wi-fi and Bluetooth technologies. The GPS system is popular for outdoor applications, but its use is limited for indoor applications, such as tunnel construction and building constructions. Wi-fi is another popular technology that has been extensively researched for its potential use. It works on the same principle as the Bluetooth technology. It, however, is a relatively more expensive solution than the Bluetooth technology. Reflecting the various and dynamic characteristics of construction, the Robotics and Intelligent Construction Automation Laboratory (RICAL) at Georgia Institute of Technology has developed a lower-cost Bluetooth proximity safety sensing technology (Park et al. 2015). This system was particularly created to provide a small but inexpensive technology for rapid adoption and wide spread into the industry.

Bluetooth is a term used to describe a wireless technology capable of exchanging data and communicating over short distances (Honey Access 2014). This technology is often found in mobile computing devices, but can also be used by fixed hardware. The data exchange functionality of Bluetooth is accomplished through relatively short-wavelength Ultra-High Frequency (UHF) radio waves around 2.4 GHz (Bhagwat 2001). Bluetooth technology is capable of connecting to several devices in real time simultaneously through an ad-hoc network. Because of this characteristic, Bluetooth technology enables two-way communication between various platforms.

Bluetooth technology has been widely used for point-to-multipoint voice or data transfer because of its rapid connectivity, low-cost hardware, and minimal individual infrastructure requirements (Shorey and Miller 2000). Several researchers have identified these characteristics as benefits for potential construction applications, specifically for construction topology (Salonidis et al. 2005), position tracking of construction vehicles (Lu et al. 2007), and information delivery systems (Behzadan et al. 2008). Furthermore, capabilities of Bluetooth have been used as wireless sensor networks for resource tracking at building construction sites (Shen et al. 2008). The typical maximum range of one Bluetooth enabled device was recorded as 50 meters for location tracking purposes (Behzadan et al. 2008). Because Bluetooth has been successfully evaluated for other construction industry applications, the capabilities of this system could potentially detect and alert workers during hazardous proximity situations. The wireless network and low infrastructure requirements of this technology may overcome barriers of other technologies implemented for this purpose such as: 1) external power requirements; 2) intensifying alerts, depending on the degree of dangerousness; and 3) ability to detect people versus objects.

2.5 Testing Methods for Proximity Detection and Alert Systems

Past research has developed preliminary testing methods to evaluate various proximity detection and alert systems. Ground markings have been placed and manually measured to outline the alert detection area of a system in an outdoor copper mining environment (Ruff 2007). Other testing methods integrated typical surface mining site obstructions to conduct field trials on a radar proximity detection and alert system (Steel et al. 2003). Another proposed testing method integrated various trials of movement from the ground worker and heavy equipment to evaluate the reliability and effectiveness of proximity detection and alert systems (Marks and Teizer 2013). This method measures the alert detection area around a piece of construction equipment as well as the alert distance during construction activity scenarios. Variations of these experiments (including the coverage area and mobile equipment-static worker) were adopted for this research. Based on the results of this review, safety technologies including proximity detection and alert systems can be deployed in roadway work zones to provide an additional safety protection for pedestrian workers. For proper implementation, scientific evaluation data and analysis are required to understand benefits and limitations of these systems.

3. Objective and Scope

The major objective of this research was to identify, develop and evaluate technologies that can be used in real time to detect a hazardous proximity situation between construction equipment and pedestrian workers and provide an appropriate warning. Historical incident data prove that current safety practices have not been effective in providing protective, safe working conditions and further improvements are essential for construction safety. Proactive detection and alert systems should offer the workers enough time and space to escape emergency situations. Three different proximity detection and alert technologies were employed in the research; they are two commercially available technologies, Radio Frequency Identification (RFID) and magnetic field sensing technology, and Bluetooth-based technology developed by the Robotic and Intelligent Construction Automation Lab (RICAL) at Georgia Institute of Technology. Several experimental scenarios were designed and tested to assess the reliability and effectiveness of the proximity detection and alert technologies. In addition to the performance level, there are many other factors that play important roles in practical applicability into practice; these factors include ease of use, calibration, required infrastructure and, most importantly, incurred costs. The mentioned factors were analyzed and presented to show the feasibility and practicality of the technologies. Based on the evaluation results, we chose one proximity sensing system to test it at a real-world construction site. The scope of the performance field test was to identify the proximity issues between construction equipment and pedestrian workers and validate the effectiveness of the proximity sensing system in construction work zones.

4. Experiments and Results

4.1 Field Test in a Controlled Environment

Based on previous research results, three proximity detection and alert systems were selected in this project to evaluate their technical feasibility in providing alerts in real time to pedestrian workers and equipment operators during hazardous proximity situations in roadway work zones. A set of experimental trials were designed at a GDOT district yard to assess the reliability and effectiveness of the created proximity detection and alert system when implemented into simulated roadway work zone operations. The experimental trials simulated operating functions of a roadway work zone including various combinations of static and mobile pedestrian workers and construction equipment. All experimental trials were conducted outdoors with clear weather conditions, low wind speed, and a temperature of approximately 90 degrees Fahrenheit (approximately 32 degrees Celsius). A clear, flat, paved ground surface with no obstructions was used as a testbed for all trials. The created and evaluated proximity detection and alert system details are discussed in this section as well as the experimental methodology and results section.

The three technologies for proximity sensing are composed of Equipment Protection Unit (EPU), Personal Protection Unit (PPU) and additional components (Park 2015). They are expected to:

- Provide alerts in real-time for equipment operators and pedestrian workers during hazardous situations;
- Allow for risk mitigation;
- Operate with an acceptable level of minimal nuisance alerts;
- Create an additional layer of protection for pedestrian workers.

4.1.1 Magnetic Field Proximity Detection and Alert System

This system creates magnetic fields with electronic charges. The strength of the electronic charges diminishes as the distance from the source increases. This concept is used as a range in proximity detection and alert. As a person with a signal receiver, which is essentially a PPU, breaches the proximity hazard zone (coverage area by the magnetic field sensing system), the person is detected to be close to a proximity hazardous situation and an alarm is offered by the system.

The magnetic field sensing system is composed of an antenna (EPU), a power source, and personal protection unit, as shown in FIGURE 1. The system requires a power source for operation, either in the form of a rechargeable battery (shown in left in Figure 1) or direct power connection. If the battery is used in operation, it must be charged every day and must be checked before use. The EPU is mounted on an outer surface of a piece of construction equipment such that objects to be detected should be in line of sight as much as possible for the best EPU and PPU communication. For our field test, an EPU was mounted on top of the cabin for both the simulation with a truck and a wheel loader, as shown in Figure 1. The coverage range for an antenna is determined based on the previous experimental tests. If the range of the previous tested antenna does not provide wide enough coverage, a new antenna with a desired coverage capability needs to be purchased. A PPU is placed anywhere on the pedestrian worker, such as pocket in the safety vest.

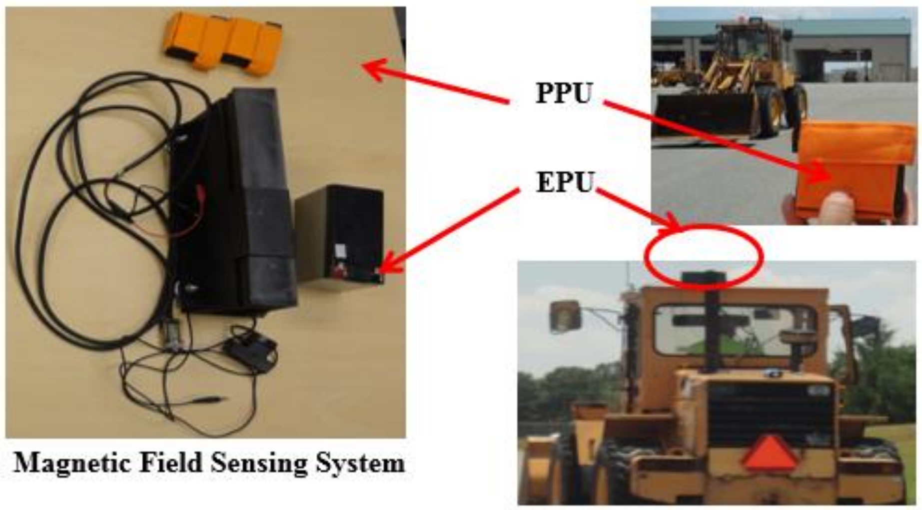


FIGURE 1

Magnetic field proximity detection and alert system (left), EPU mounted on a wheel loader (right bottom), and PPU held by a test person (right top)

4.1.2 Radio Frequency Identification (RFID) Proximity Detection and Alert System

This system uses wireless electromagnetic fields to transmit data over specific sets of devices. Similar to the magnetic system, it detects a nearby object within its specified proximity without making physical contacts. As a person with a PPU enters a proximity hazard zone (coverage area by the RFID system), the person is detected to be in a dangerous situation and an alarm is set off by the system.

The RFID sensing system is composed of EPU (main board and an antenna), a power source, a computer, and personal protection unit, as shown in FIGURE 2. The system requires a power source for operation in direct power connection. The battery on

PPU requires charging every day and must be checked before use. The mechanical connection of mounting the antenna should be made at a specific location on construction equipment. In our testing with the wheel loader, the antenna was mounted on an edge of the door frame. This characteristic inevitably places the antenna asymmetrically on one side of the equipment. This is undesirable as it may impact the coverage area leading to an asymmetrical shape. For our field test, the antenna of the EPU was mounted on the edge of the window of the driver's side. The coverage range for an antenna is determined based on the previous experimental tests. If the range needs to be adjusted, it can be completed by using software installed on a computer. This calibration is accomplished in a relative sense, that is, we calibrate the system through trial. A PPU is placed anywhere on the pedestrian worker, such as pockets.

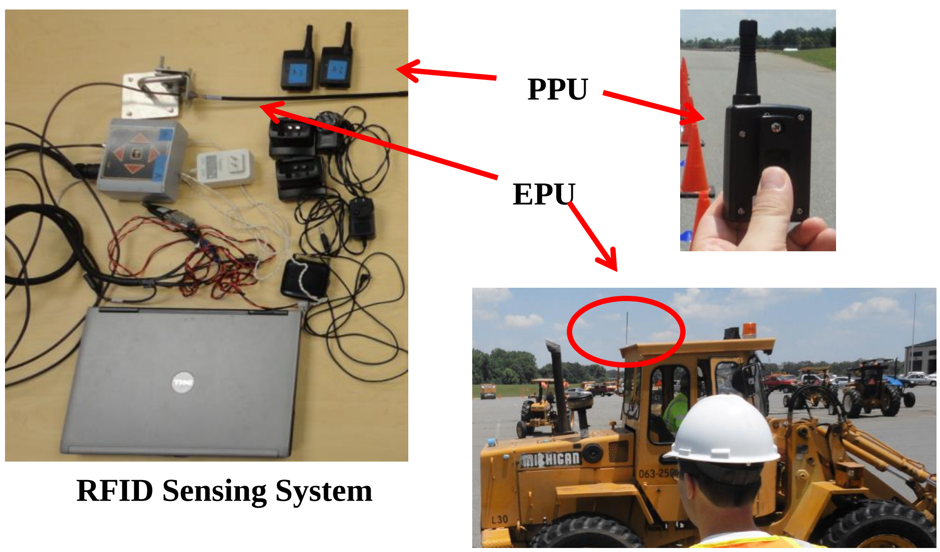


FIGURE 2

RFID proximity detection and alert system (left), EPU antenna mounted on a wheel loader (right bottom), and PPU held by a test person (right top)

4.1.3 Bluetooth Proximity Detection and Alert System

The newly introduced Bluetooth proximity detection and alert system uses a beacon application on a smart phone, tablet or any other "smart" mobile device. Each beacon device hosts a unique identification number for calibration and proximity breach detection. The advertising rate can be set from 2000 up to 100 milliseconds per radio signal. The broadcasting power can be set from 30 Decibel-milliwatts (approximately 1 meter detection range) to 4 Decibel-milliwatts (approximately 70 meter detection range) to configure the physical power of the transmitted signal. The beacon component of the system is equipped with a battery power source with a life span from several months to two years, depending on the user settings.

The system architecture of the developed proximity sensing and alert system using Bluetooth technology is shown in FIGURE 3 (Park et al. 2016).

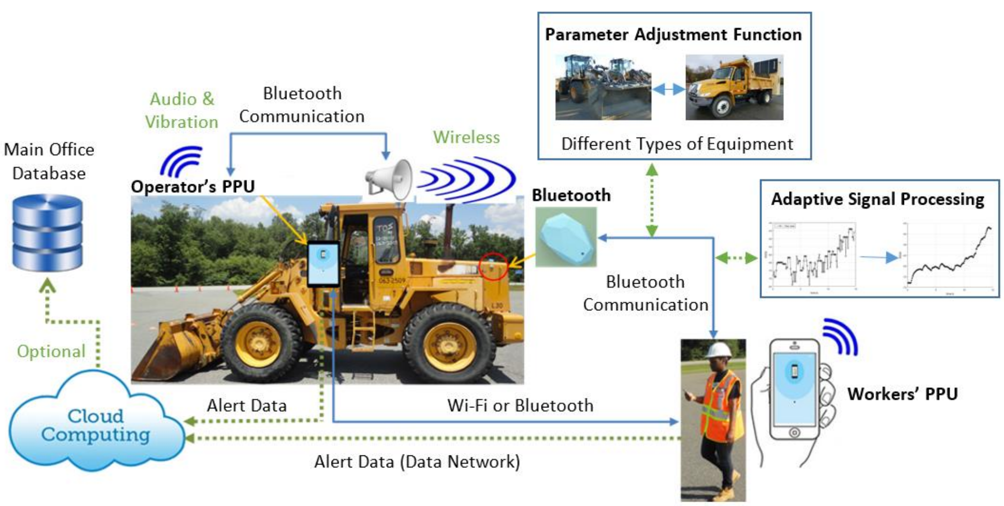


FIGURE 3
Proposed Bluetooth proximity detection and alert system

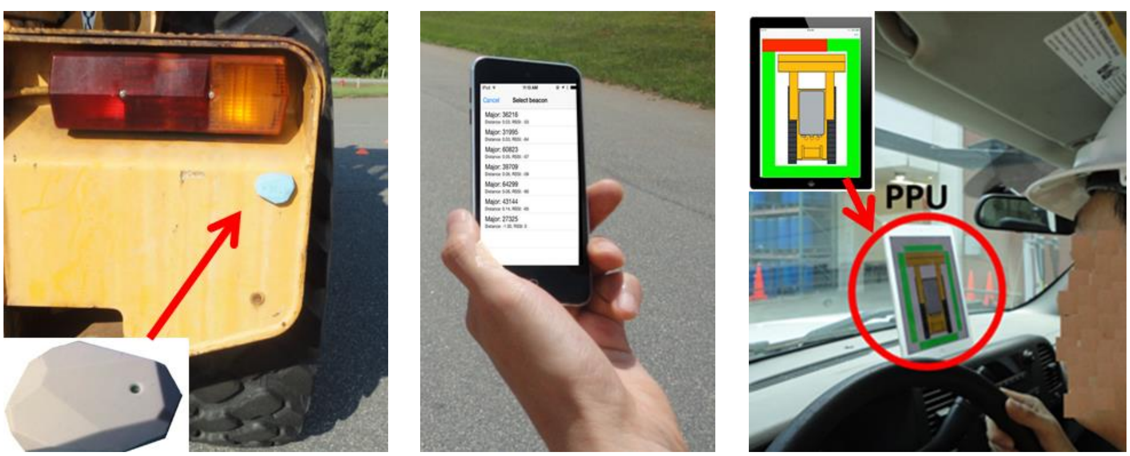
As shown in FIGURE 3, the Bluetooth proximity detection and alert system is comprised of three components that communicate in real time and provide alerts to workers in roadway work zones during hazardous proximity situations. The three system components are:

1) Equipment Protection Unit (EPU) which is several beacons that are mounted at various locations on a piece of construction equipment. The beacons used are radio signal transmitters. They are low cost, which is about $33 for each, as well as small (5cm x 3cm x 2 cm). The Bluetooth system allows the use of multiple sensors around a piece of construction equipment to create more directional coverage areas. For example, eight beacons were mounted on a truck used for the experiments, two beacons an equal distance apart on every side. This allows for Bluetooth technology to be less impacted by surface obstruction compared to other technologies, such as RFID.
2) Pedestrian worker's Personal Protection Unit (PPU) which is an application that functions on any smart phone, tablet, or "smart" device that can be located anywhere on the pedestrian worker. The PPU is able to process the signals for detecting a proximity hazardous situation that is created by interactions of workers and pieces of equipment nearby. This is realized by a software program that was developed by the research team. The smart devices mentioned can turn into a signal transmitter upon the occurrence of a proximity hazardous situation and send related information to equipment operator's PPU through Bluetooth signals. This communication can be achieved through the use of Bluetooth and can provide important hazard information such as direction information that assists the equipment operation.

In addition, it provides the worker with multiple forms of alerts to allow additional time and space to proactively escape from hazardous situations.

3) Equipment operator's Personal Protection Unit (PPU) which is an application that functions on an iPad, iPhone, or "smart" device that can be mounted near the operator in the cabin. It receives a data package from the worker's PPU, which contains the universally unique identifier (UUID) of the Bluetooth transmitter. This data package is used to provide audible alerts and visualization of the detected location of workers around the equipment.

Components of the Bluetooth proximity detection and alert system can be calibrated and mounted before the system can be utilized. EPU and PPU for workers and operators are shown in FIGURE 4.



EPU mounted on a wheel loader	PPU held by a test person	PPU mounted near an operator

FIGURE 4

Bluetooth proximity detection and alert system

The system is capable of providing three separate alert ranges for each beacon. The desired physical horizontal distance between the construction equipment and the pedestrian worker is trisected for the three separate equal alert distances. The alert distances allow for variations in audible alerts and vibrations depending on the location of the pedestrian worker inside the pre-calibrated hazardous proximity zone. As the ground worker nears the piece of construction equipment and penetrates closer to the EPU, the audible alert intensifies in the frequency of beeps and vibrations to the pedestrian worker and equipment operator. These alert distances can be calibrated for specific pieces of construction equipment and site conditions.

The alerts including vibration and beeping sounds are not only via PPUs (e.g., smartphones), but also via additional Bluetooth enabled accessories, including a smart wristwatch and an earpiece (FIGURE 5). In application to construction, one of the most significant concerns raised was impractical warning capabilities of an alert system, especially in a harsh environment. To address this issue, our new development in this research included an addition of optional warning components. The ability of Bluetooth to communicate with other Bluetooth devices was useful in developing the new warning components and overcoming the raised alert limitation. These additional alerting devices can reinforce communicability of alerts in a harsh environment.

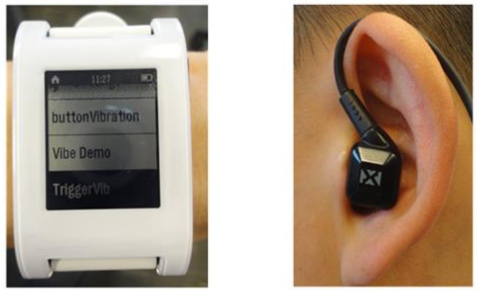


FIGURE 5

Multiple forms of alerts enabled by Bluetooth

To sync settings of parameters and information for hazardous proximity cases, a database was built to facilitate information communications between various PPUs for operators, which is shown in FIGURE 6. Though the database, various PPUs for workers are able to sync calibrated parameters for each piece of equipment. In addition, for each alert case, detailed information such as worker ID, alert time, equipment ID are saved through both mobile platform and database.

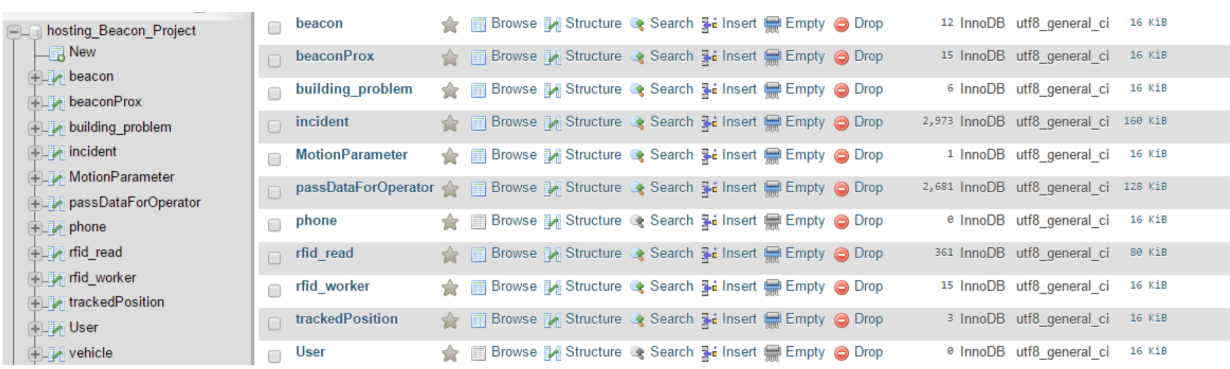


FIGURE 6

Database for the Bluetooth proximity detection and alert system

4.1.4 Coverage Area

The coverage area for experimental trials was designed to simulate the interactions between a stationary piece of construction equipment and a mobile pedestrian worker. These trials assessed the reliability and effectiveness of the three technology sensing systems to detect and provide alerts when the mobile pedestrian worker crossed into the pre-calibrated hazardous proximity zone. Two pieces of construction equipment were used for the coverage area experiments: 1) a wheel loader and 2) a small dump truck, where system setup plans for each piece of the equipment are shown in FIGURE 7 and FIGURE 8. For all trials, the PPUs were placed in the pedestrian worker's right pocket.

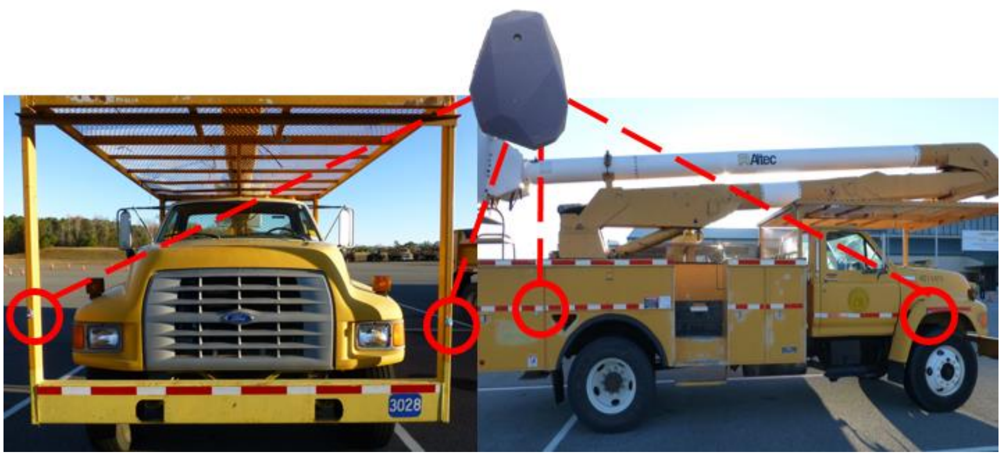


FIGURE 7

System setup with Bluetooth sensors for the tested truck

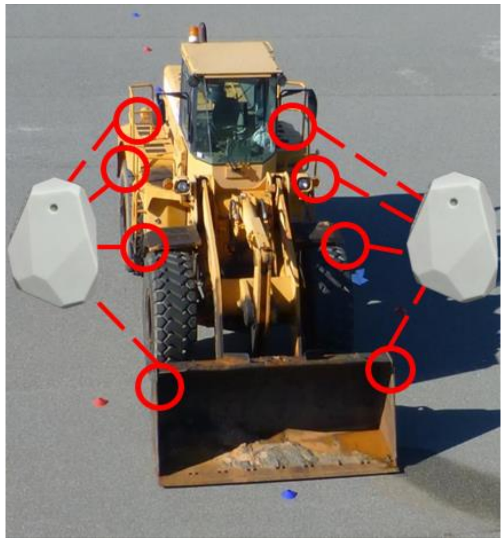


FIGURE 8

System setup with Bluetooth sensors for the tested wheel loader

The experimental testbed was outlined by placing ground markers at eight equal distance locations (45-degree offsets) on an unobstructed, flat surface. FIGURE 9 shows the test bed for the coverage area experiments on the small dump truck. Ground markers were placed at 5ft (1.5m) intervals along the approach angles. The centroid of the piece of construction equipment (wheel loader and small dump truck) was placed in the middle of the test bed.

The pedestrian worker equipped with the PPU approached the wheel loader and small dump truck at a constant walking pace (approximately 2 m/s) from eight different equal distant approach angles. When the proximity sensing system detected the worker's breach into the pre-calibrated hazardous proximity area, the alert was active, and the test person stopped walking, and the researchers measured the horizontal alert distance. The alert distance was measured from the pedestrian worker's stopped position to the centroid of the construction equipment. Each approach angle was tested 20 times for each 45-

degree section (0°, 45°, 60°, …, 270°, 315°). This procedure was completed for all three proximity detection and alert systems. For the Bluetooth proximity detection and alert system, each trial also recorded three different ranges, as the system can uniquely provide intensifying alerting sounds at three different distances.

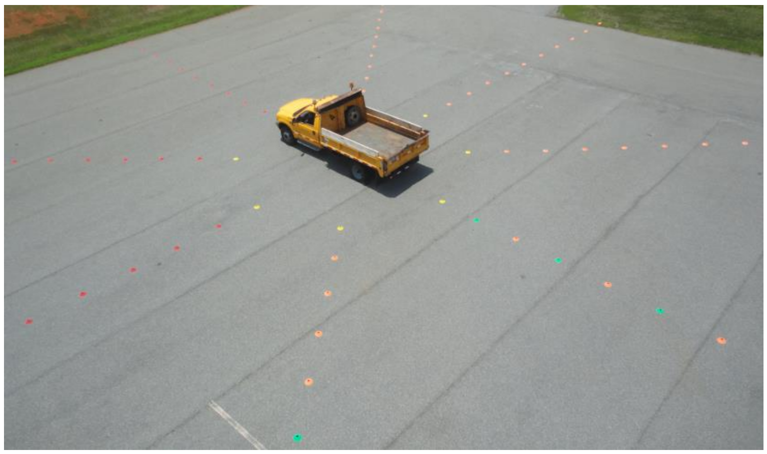


FIGURE 9

A test bed for coverage area experiments with the tested small dump truck

Statistical analysis was performed on each approach angle of the test person. The data was also analyzed for true positive readings, false negative readings, nuisance alerts, and overall recall. The following circumstances were used for each of the following:

- True positive alert: Instances in which an alert is activated when the test person is in the range of defined danger.
- False negative alert: Instances in which an alert is not activated when the test person is in the range of defined danger.
- Nuisance alert: Alert distances that measure three times larger than the upper quartile value for each specific approach angle for that sample size. These

alerts occur when a safety condition is present (i.e., the pedestrian worker is a safe distance from the construction equipment)

- Recall: Alerts that were deemed to be accurate with regards to the distance of the pedestrian worker to the tested equipment at the time of the alert. This value was calculated by using the number of success alerts (true positive) as a ratio compared to the total number of trials.

No nuisance alerts were recorded for all the three systems during the experimental trials. Of the 320 trials, one false negative alert was recorded for the Bluetooth technology proximity detection and alert system for the approach angle 270° with the wheel loader simulation, and a total of 11 false negative alerts were recorded for the RFID proximity detection and alert system for the approach angle 180° with the wheel loader simulation, and no false negative alert was found for the magnetic field proximity detection and alert system. The rates of the false negative alerts were less than 1% and 4% for both Bluetooth and RFID systems, respectively. The recall value for both systems was 1.0 for all approach angle trials except 0.95 for the Bluetooth system at the approach angle 270° with the wheel loader simulation and 0.45 for the RFID system at the approach angle 180° with the wheel loader simulation.

Table 1 shows the statistical average and standard deviation data of the 45-degree intervals for the PPU alert distance measurements. The statistical analysis was performed individually on each 20 trial sample size provided by each approach angle, excluding one failed simulation. Values in the bold text represent the lowest average distance in each column. The values in italic text are the highest average distance. Analyzing the average alert distance distribution for each system indicates that the magnetic was the most reliable in providing alerts and the RFID was the least reliable. The benefit of the Bluetooth system was shown in this table that it can provide intensifying alerts based on the degree of proximity to the hazardous situation (Figure 6). The Bluetooth system experienced an unexpected decrease of the mean alert distance at the 225 degrees approach angle which indicates the received signal strength at this location was weaker than other approach angles tested. Potential reasons for this decrease of mean alert distance could be any of the following: 1) A potential low battery level of the device could have negatively impacted the performance; 2) signal transmitters on the individual beacon could have malfunctioned; 3) signals transmitted by the beacon may have been impacted by the environmental settings such as a component of the construction equipment or the test person; or 4) the ambient condition, the angle between EPU and PPU, existence of direct or indirect obstruction, and many others may contribute to the variation.

TABLE 1

Statistical Analysis of Alert Distance Measurements Averaged at each Angle with Wheel Loader Simulation (in meters)

Angle	Magnetic	RFID	Bluetooth		
			Zone1	Zone2	Zone3
0°	9.1	19.9	15.2	11.9	7.4
45°	10.1	15.7	17.3	11.8	5.6
90°	9.3	13.0	15.3	9.1	4.6
135°	7.5	7.5	12.2	7.1	4.2
180°	6.9	2.7	12.4	7.5	3.8
225°	8.3	10.0	5.3	0.3	0
270°	9.7	6.9	12.4	6.9	2.1
315°	9.1	18.8	13.0	5.7	2.4
Ave.	8.7	11.8	12.9	7.6	3.8
Std.	1.0	5.7	3.3	3.5	2.1

Another statistical analysis was completed to compare the reliability of the three systems when deployed in the same simulated experimental environment. Table 2 presents the results of the data analysis with respect to the range and standard deviation for each approach angle. Because the alert zones varied based on the calibration capabilities of each respective system, only the range and standard deviation were compared for each approach angle between the different evaluated systems. As before, values in the bold text represent the lowest range and lowest standard deviation among the three different proximity alert systems evaluated. Also, the values in italic text denote the highest range and highest standard deviation among proximity sensing systems tested.

TABLE 2

Statistical Analysis of Alert Range and Standard Deviation Measurements at each Angle for Wheel Loader Simulation (in meters)

	Magnetic		RFID		Bluetooth	
Angle	Range	Std. Dev.	Range	Std. Dev.	Range	Std. Dev.
0°	0.9	0.26	14.6	3.29	4.6	1.00
45°	1.2	0.33	7.92	2.21	3.0	0.87
90°	0.6	0.21	3.35	0.89	7.0	2.67
135°	0.9	0.23	4.88	1.73	11.6	2.97
180°	0.9	0.24	6.7	3.07	12.1	3.56
225°	0.9	0.31	1.5	0.40	8.2	1.81
270°	0.9	0.28	5.5	1.53	14.6	3.88
315°	0.6	0.23	15.2	4.39	12.1	3.58

A coverage area graph was also created to visually compare the three evaluated proximity detection and alert systems. Because the calibration zones were different, one should focus on the consistency and reliability of each of the proximity sensing systems separately and then compare the change per approach angle. FIGURE 10 presents the average coverage area graph for the RFID, magnetic field, and Bluetooth (zone 1) proximity detection and alert systems. Recorded alert distance measurements for each of the three pre-calibrated hazard zones experimental trials on the Bluetooth technology proximity detection and alert system were displayed on coverage area graphs in FIGURE 11. More results from these experiments can be viewed in Appendix A of this report. The results presented in Appendix A, are presented in the form of graphs and include the following plots: 1) the average coverage area for the Magnetic, RFID and Bluetooth systems; 2) the average coverage area for the three zones of the Bluetooth system; 3) the average and plus and minus standard deviation coverage area for each system; and 4) the average, minimum and maximum coverage area for each system.

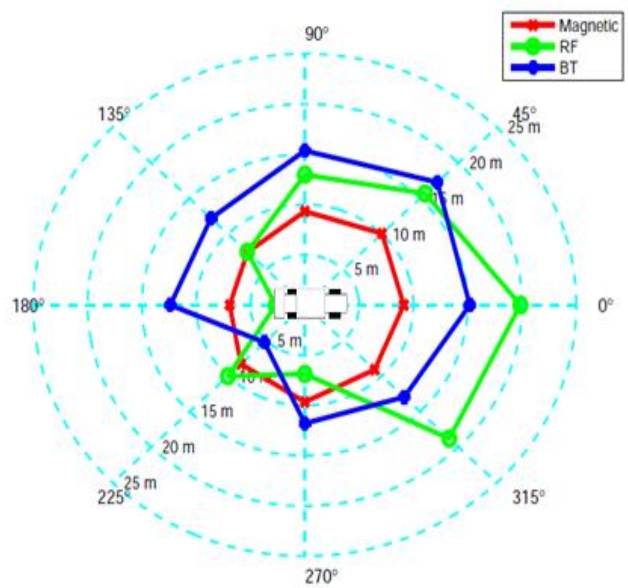


FIGURE 10

Average coverage area for three proximity sensing systems deployed on a wheel loader (in meters)

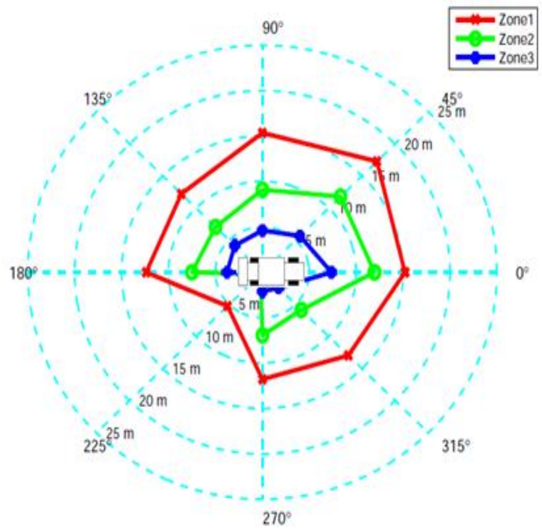


FIGURE 11

Average coverage area for the Bluetooth technology proximity detection and alert system deployed on a wheel loader (in meters)

In order to increase consistency and accuracy of the Bluetooth system for various types of equipment under several test conditions, a parameter adjustment function was developed to calibrate the system. Table 3 summarizes the numerical results of Bluetooth system for two types of equipment in aspects of the average, standard deviation, deviation to the desired distance setting with and without the parameter adjustment function. Equation 1 shows the formula to compute the deviation to the desired distance setting. For the test cases, the results indicate an improvement in consistency by showing the deviation, on average, to the desired setting from 5.54 m to 0.03 m for the 160 trials with the truck, and from 0.88 m to 0.37 m for the 160 trials with the wheel loader. Furthermore, the standard deviations for both cases are found to have a minor improvement: from 2.7 m to 2.6 m with the truck and from 3.35 m to 2.84 m with the wheel loader. As a note, no false negative instances were observed among all trials.

Deviation to the desired distance = abs (average – desired distance) (1)

TABLE 3

Test Results of Bluetooth System with Parameter Adjustment Function

Equipment		Average (m)	Deviation to setting (m)	Standard deviation (m)
Truck	Without calibration	15.54	5.54	2.70
	With calibration	9.97	0.03	2.60
Wheel loader	Without calibration	10.88	0.88	3.35
	With calibration	9.63	0.37	2.84

Another static test was conducted to evaluate the reliability of the Bluetooth system in various carrying locations. The pedestrian worker equipped with the PPU approached the tested dump truck at a constant walking pace (approximately 2 m/s) with the PPU mounted in various locations, which are shown in Figure 12. Because holding in hand has minimum impacts to the signal strength, we chose it as the ground truth to evaluate other two carrying locations.

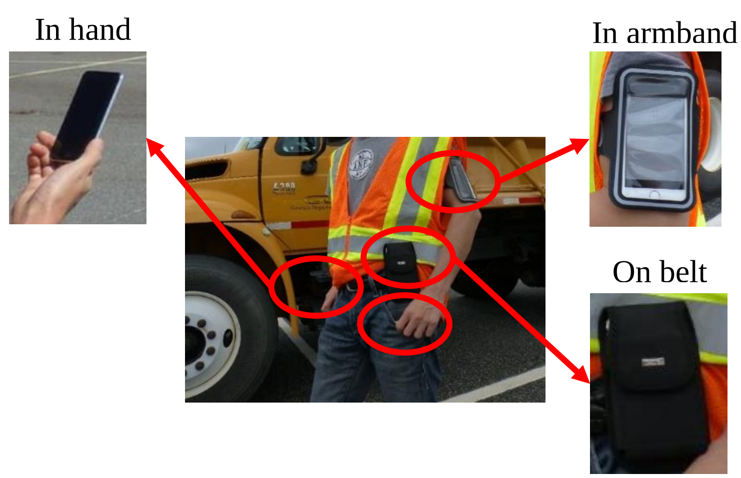


FIGURE 12

Various PPU carrying locations for workers

Statistical analysis of the test results was completed and a box plot is shown in Figure 13. For the test cases, the results indicate that the carrying locations of PPU have limited influences on the median value of alert distances. However, compared to holding in hand, the receiver gave larger deviations when it was mounted to belts or in armbands.

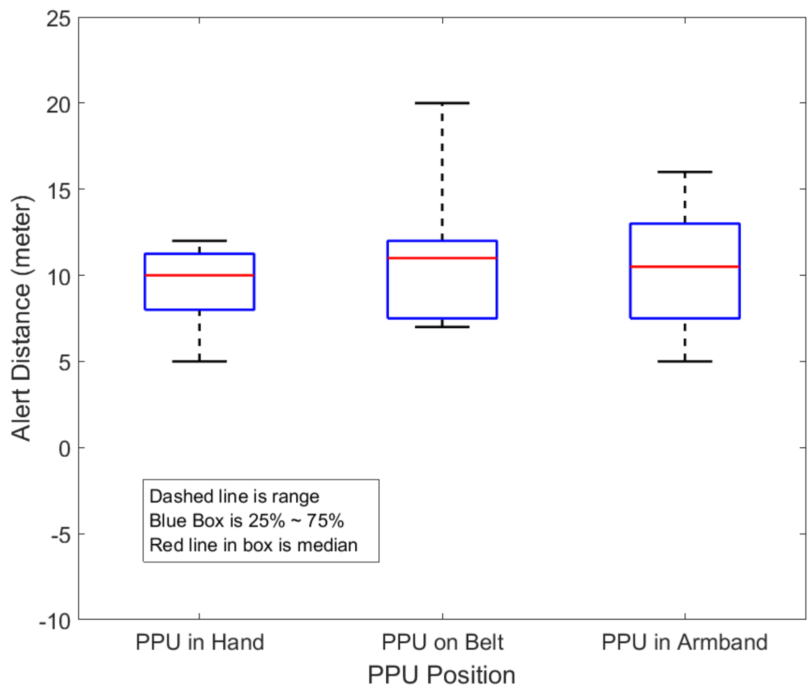


FIGURE 13

Box plots of proximity sensing systems for various carrying locations

4.1.5 Mobile Equipment and Static Pedestrian Worker

This set of experimental trials tested the effectiveness of the proximity detection systems on a static test person and mobile wheel loader. The same flat, unobstructed surface was used to conduct these trials. 20 ground makers were positioned at 1.5-meter intervals along the straight-line parallel to the wheel loader's travel path (FIGURE 14). The wheel loader approached the simulated pedestrian worker (traffic cone) in a forward travel direction at a constant speed of 8 kilometers per hour and stopped once the EPU alert was activated for 20 trials. For comparison purposes, a RFID system and a magnetic field system were subjected to the same experimental trials. All three PPU's (RFID, magnetic field, and Bluetooth) were positioned at the static location on top of a traffic cone approximately at one-meter vertical distance from the ground surface.

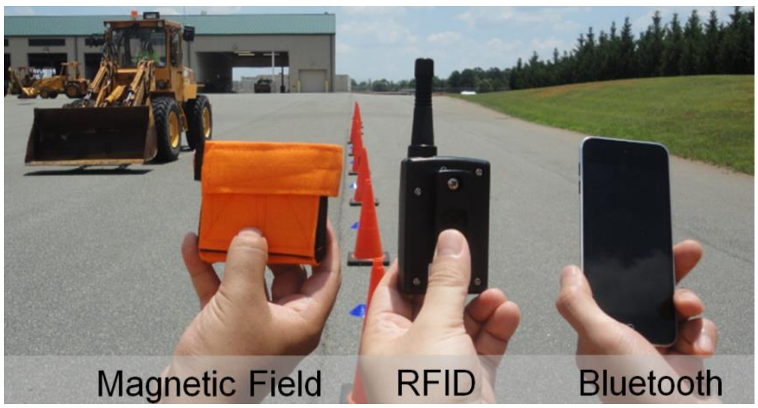


FIGURE 14

Mobile equipment and static pedestrian worker experimental testbed

Data obtained from these trials were analyzed using the same statistical criteria discussed in the previous experiment. None of the proximity sensing systems assessed (RFID, magnetic, and Bluetooth) experienced any nuisance alerts; however, the Bluetooth system recorded two false negative alerts, and the RFID system recorded four false negative alerts. Although the magnetic field system successfully provided alerts for all the 20 trials, the alert distances of the magnetic system were much smaller than the other two systems, which may not be a sufficient distance to take a proper action for the avoidance of collision. FIGURE 15 presents a box plot of the results from the mobile equipment static pedestrian worker experiments.

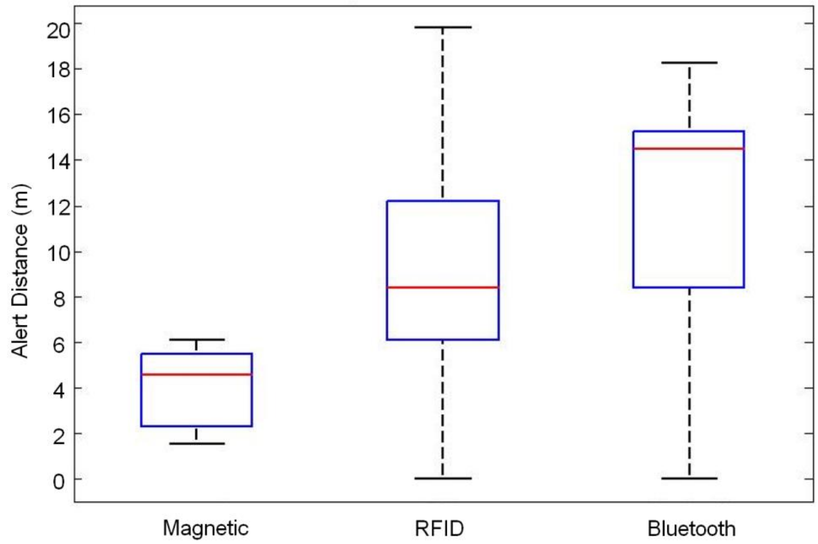


FIGURE 15

Box plots of proximity sensing systems for mobile wheel loader and static pedestrian worker trials

TABLE 4 shows the statistical range, standard deviation, and interquartile range for each of the evaluated proximity sensing systems (RFID, magnetic, and Bluetooth) for the mobile wheel loader and static pedestrian worker. The highest statistical range value (19.8 meters) was experienced by the RFID proximity sensing system. The lowest statistical range value (4.6 meters) occurred when testing the magnetic proximity sensing system as shown in TABLE 4.

TABLE 4

Statistical Analysis of Mobile Wheel Loader with Static Pedestrian Worker Alert Distances

	Magnetic	RFID	Bluetooth
False Negatives	0	4	2
Nuisance Alerts	0	0	0
Recall	1	0.95	0.9
Range	4.6 m	19.8 m	18.3 m
Standard Deviation	1.7 m	4.7 m	5.9 m
Interquartile Range	3.1 m	6.1 m	6.5 m

During the experimental trials, the research team also logged metrics outside of experimental data including set-up time, calibration time, and required infrastructure. The set-up duration and infrastructure required (including exterior power access and antenna mounting) for the magnetic field and RFID proximity detection and alert systems were drastically increased when compared to the Bluetooth system, mainly because the Bluetooth system does not require an antenna mounting or access to an external power source. The research team also found that the time required to calibrate the proximity alert zone for the RFID and magnetic field system was much longer than that required for the Bluetooth proximity sensing system. This is because a simplified set-up and calibration mobile application was developed for the Bluetooth system.

4.1.6 Communication Test between PPUs

To assess the reliability and responsiveness of the warning system for the operator's PPU, a set of 30 trials were performed. To measure the signal communication and its warning responsiveness between the worker and the equipment operator, hazard detection tests were conducted in one direction. The worker on-foot subject approached a stationary pickup truck in a forward moving direction, and signaled, by raising a hand, at the initiation of an alert to indicate the initiation to the operator (FIGURE 16). The time gap between the initiations of an alert from the ground worker's PPU and the equipment operator's PPU was measured as a start delay. When the worker moved out of the hazardous zone (when the alert terminates), the worker lowered the hand to indicate it to the operator, and the alert time gap (end delay) was measured again. FIGURE 17 shows the measured time delay data for operator's PPU alerts.

In achieving reliable and responsive alert communication, signal communication time delay measurements were taken. Based on the results of the 30 trials, the system was found to consistently provide almost immediate alerts to the equipment operator upon the detection of proximity hazards. It demonstrates the capability of reliable and timely signal communication between the involved worker's PPU and the operator's PPU. The end delay had an average time delay of 8.03 seconds. This delay was found because a portion of Bluetooth signals hovers before it completely disappears. Although it showed a delay, this delay can offer a positive effect as it provides an additional time for confirmation of safety.

FIGURE 16

Operator's PPU responsiveness test

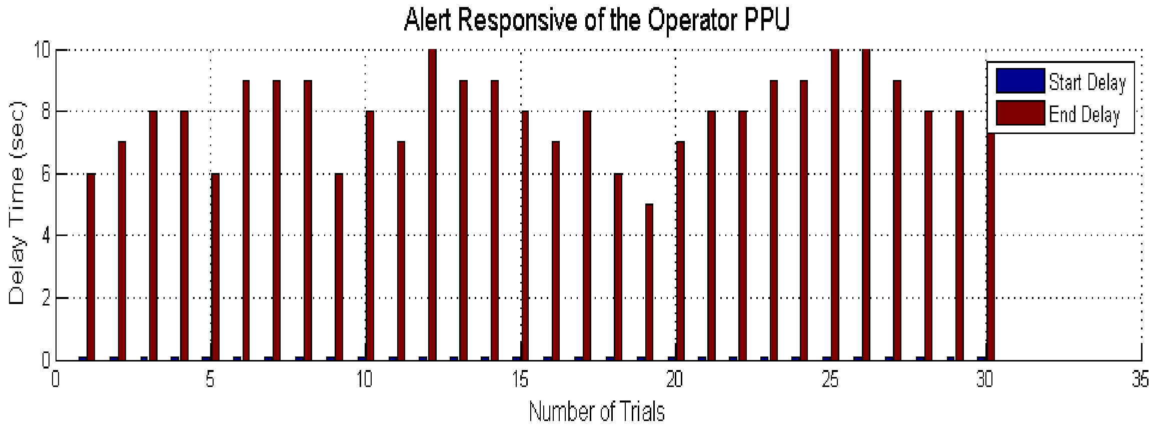


FIGURE 17

Operator's PPU responsiveness test results

4.2 Real-World Field Tests

Another goal of the field test was to evaluate the functional reliability of the Bluetooth proximity sensing system and obtain feedback from working crews through real-world construction projects. From the real-world field tests, the effectiveness, barriers, and benefits of the Bluetooth proximity detection and alert system were measured and analyzed. In addition, interviews with a regional panel of experts were conducted to decide types of equipment and settings for safety distance should be used for the field test.

To determine appropriate alert distance settings for various types of equipment under both static and dynamic circumstances, interviews with a regional panel of experts were conducted regarding these questions: (1) if a certain type of equipment is in a static status, but has a potential to move, what is the preferred safety distance? (2) If the equipment is moving toward a worker at a normal speed, what is the preferred safety distance? Answers for the interview are summarized in TABLE 5 and TABLE 6.

TABLE 5

Preferred Safety Distance for Static Equipment

Type of equipment	Preferred safety distance settings /m
Dozer	More than 1.5
Skid Steer	More than 1.5
Truck	More than 1.5

TABLE 6

Preferred Safety Distance for Moving Equipment

Type of equipment	Preferred safety distance settings /m	
	Moving backward	Moving forward
Dozer	More than 3	More than 3
Skid Steer	More than 3	More than 3
Truck	More than 3	More than 3

Two pieces of construction equipment were used for the field test: 1) a dozer and 2) a skid steer, where the system setup plans for each piece of the equipment is shown in FIGURE 18 and FIGURE 19. For each equipment, eight beacons were mounted in various directions, where two beacons were placed an equal distance apart on every side. This allows the system to be less impacted by surface obstruction. The beacons are represented by FR: Front Right; RF: Right Front; RB: Right Back; BR: Back Right; BL: Back Left; LB: Left Back; LF: Left Front; FR: Front Right. We used 3m as the alert distance setting for both dozer and skid steer loader according to the preferred safety distance in Table 6.

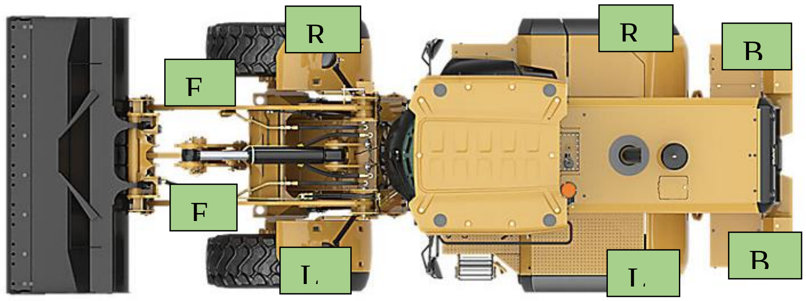


FIGURE 18

System setup with Bluetooth sensors for the tested dozer

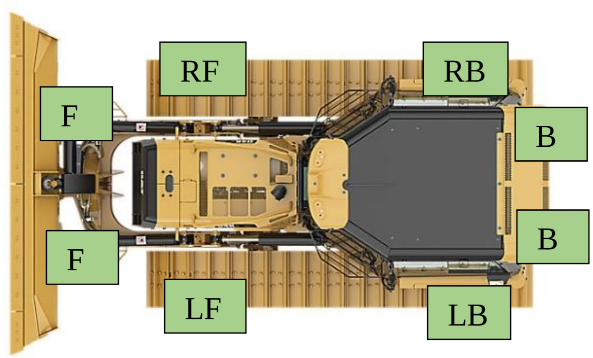


FIGURE 19

System setup with Bluetooth sensors for the tested skid steer loader

Five subjects among crew members participated in the field test. The subjects wore the PPUs (smartphones) either to arm or waist. During the 10-hours test, the researchers observed 28 hazardous proximity cases, where the distance between the subjects and tested equipment was less than or equal to 3m. Among all of the recorded cases, the Bluetooth system provided 27 alerts in total, where 12 alerts were triggered by the dozer and 15 alerts were triggered by the skid steer loaders. Alert frequencies for mounted beacons are summarized in TABLE 7 and TABLE 8. The results indicate that types of equipment have a great influence on the total number of alerts and the alert frequency for each direction of a certain type of equipment. Compared to dozers, skid steer loaders tend to cause more hazardous proximity situations.

TABLE 7

Number of Proximity Alerts for Tested Dozer in Each Direction

Beacon location	Frequency
Front Right	2
Right Front	2
Right Back	1
Back Right	1
Back Left	1
Left Back	1
Left Front	2
Front Right	2

TABLE 8

Number of Proximity Alerts for Tested Skid Steer Loader in Each Direction

Beacon location	Frequency
Front Right	2
Right Front	1
Right Back	1
Back Right	1
Back Left	1
Left Back	4
Left Front	2
Front Right	3

The result of statistical analysis of the alerts triggered by each worker is summarized in TABLE 9 and FIGURE 20. The results indicate that the number of proximity cases depends on both work types and locations. Compared to the main gate, working zones gave a large number of proximity alerts. The low counts of alerts for worker 5 is because his job duty was to clean trucks rather than the tested equipment. As mentioned before, trucks were not equipped with sensors because of their long cycle time.

TABLE 9

Number of Proximity Alerts for Subjects

Worker ID	Number of proximity alerts	Work type	Work location
worker1	9	Survey and map	Main site
worker2	3	Traffic control	Gate
worker3	2	Survey and map	Gate
worker4	11	Traffic control	Main site
worker5	2	Truck clean	Main site

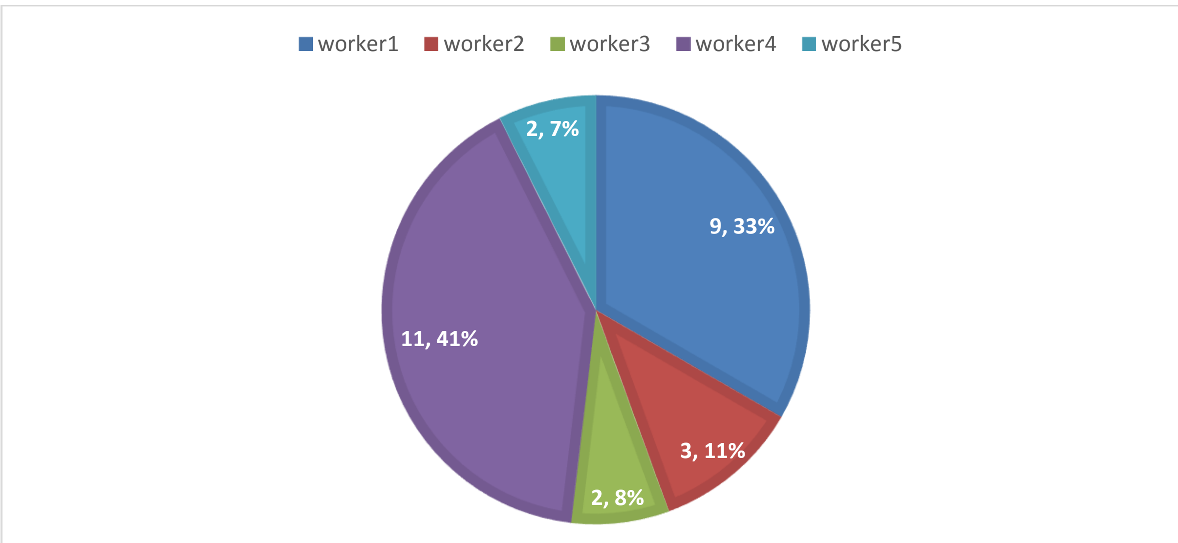


FIGURE 20

Alerts frequencies for workers

To find preferred carrying positions, a survey was conducted with the workers participating in the field test. First, the workers worked with PPU on three carrying positions, armband, belt clip, and pocket. Then they chose the one that had minimum impacts to their regular work. Four workers among five chose a belt clip as their preferred carrying positions; the answers for the survey are summarized in TABLE 7.

TABLE 7

Answers for Preferred Carrying Location of PPU for Pedestrian Workers

Worker ID	Arm Band	Belt Clip	Pocket
1		√	
2		√	
3		√	
4			√
5		√	

To find effective alert types of the PPUs for both workers and operators, another survey with the workers and operators was conducted. The workers worked with the PPU with three alert modes: audio, vibration, and audio plus vibration. Then they chose the alert mode that gave most effective notification during their regular work. Four workers among five chose audio plus vibration as the most effective alert mode. The answers are summarized in TABLE 8. A similar survey regarding effective alert modes of the PPU mounted in the cab was also conducted among the operators; the answers are summarized in TABLE 9.

TABLE 8

Answers for Preferred Alert Modes of Pedestrian Workers' PPU

Worker ID	Audio	Vibration	Sound & Vibration
1			√
2			√
3		√	
4			√
5			√

TABLE 9

Answers For Preferred Alert Modes of Operators' PPU

Operator ID	Audio	Vibration	Visualization	Combined
1				√
2		√		

In addition, both the workers and operators participating in the test were asked to give an overall evaluation of the Bluetooth system based on whether the system provided reliable alerts during the test period. The answers are summarized in TABLE 10. Over half of the workers thought that the system provided reliable alerts when the tested equipment was too close to them. Half of the operators commented that the system was able to provide reliable alerts and useful hazard direction information to them when pedestrian workers were too close to the equipment.

TABLE 10

Overall Evaluation of Bluetooth System

Worker ID	Low	Medium	High
1			√
2		√	
3		√	
4			√
5			√
Operator 1			√
Operator 2		√	

5. Economic Analysis

In Section 4, Experiments and Results, the performance of each of the proximity detection and alert systems was statistically analyzed and discussed. This section is to perform economic analyses to demonstrate the feasibility of each of the systems. Projects are budgeted under limited resources, and a number of proposed systems, despite their excellence in performance, have not been adopted into practice mainly due to economical infeasibility. Economic feasibility is a major factor that plays a key role in the adoption of any technology in practice. Thus, it is required to conduct and present an economic analysis for a technology that is proposed for potential adoption into construction practice. Economic analysis performed in this section does not take into account for any qualitative measures, including the performance, settings, required infrastructure, and ease of use, but only focuses on quantitative monetary measures.

5.1 Collection of Data and Assumptions

To perform an economic analysis, the cost information required for each of the technologies must be acuired. Each of the technologies is composed of equipment protection units (EPU) and personal protection units (PPU). Depending on the system, additional items may be needed, which also need to be included in the cost information. An important note for the additional items for each of the systems is as follows; 1) the magnetic sensing system used in this project includes one additional EPU as a change of range requires a change of an antenna. 2) the RFID system used in this project includes a laptop which is used to change the range of the system. 3) a smart wristwatch and a Bluetooth earpiece may be added to the Bluetooth system. Although the additional devices for the developed Bluetooth detection and alert system are optional , they are included in the economic analysis for more reliable detection and communircation. The EPU and PPU's cost of the magnetic sensing system and the RFID system were obtained from the manufacturers of the test systems. For the PPU of the Bluetooth sensing system, an iPhone 6 was selected and its cost was estimated based on its market value (estimated on 07/19/2017) from https://glyde.com/buy/used-Apple-iPhone-6S-16GB-Gold-Verizon/12078867. An additional component of the RFID system was not available directly from the manufacturer, so its cost was approximated as follows; a computer that is used to calibrate the RFID was estimated at $500. These data are tabulated in TABLE 11.

TABLE 11

Unit Cost Data for Proximity Sensing and Alarm Technologies

	Magnetic	RFID	Bluetooth
EPU ($/EA)	$1295	$500	$300
PPU ($/EA)	$495	$100	$144
Additional item 1 ($/EA)	$1295 (antenna)	$500 (laptop)	NA
Expected service life (year)	10	10	5

Note that the 1) magnetic and 2) RFID systems include 1) an antenna and 2) a computer, respectively as their additional items.

5.2 Cost Comparison

The data presented in Table 11 is based on the unit price of each item. One EPU is to be installed on each piece of equipment, and one PPU (Pedestrian) is to be possessed by each of the workers in the work zone or who may potentially enter the work zone. Cost comparison that is made herein is based on the assumption of one piece of equipment. In consideration of economic analysis for more pieces of equipment, one needs to multiply the number of pieces of equipment by the results of our analysis to get an approximate estimation. The first comparison made in FIGURE 21 is to visualize the effect of the number of involved workers. The number of workers is directly related to the number of required PPU. For the Bluetooth system, two cases were considered; 1) pedestrian PPUs' are available and require no additional cost, and 2) pedestrian PPUs are not available and require a purchase of an iPhone 5 per each pedestrian worker. FIGURE 21 clearly shows that an addition of PPU for the Magnetic system increases the total cost at a faster rate than the other two systems. The Bluetooth case 1 is comparable to, but more economical than the RFID system case up to the ratio of nine workers per equipment. For the Bluetooth case 2, it is shown that additional workers have no impact on the cost of the PPUs.

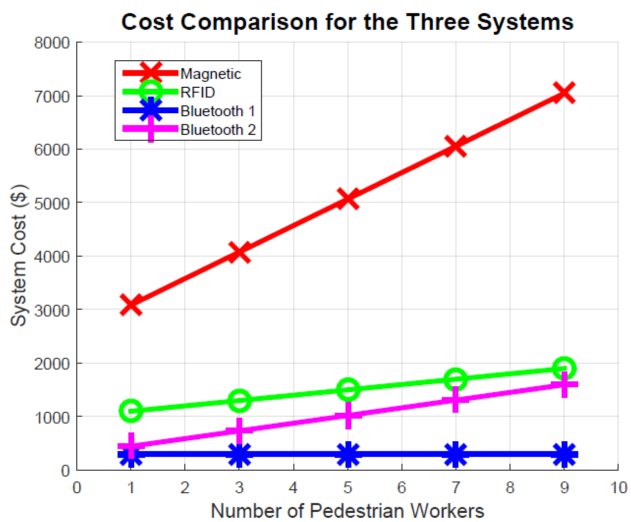


FIGURE 21

Cost comparison of the three sensing and alerting systems for protection of one piece of equipment

An equivalent uniform annual cost (EUAC) was calculated for a situation where five pedestrian workers are involved. To reflect various, but realistic interest rates in the economic analyses, three rates were studied; they are 5%, 10%, and 15%. The total equipment cost was converted to EUAC based on the assumed internal rate of return (IRR). FIGURE 22 displays a two-dimensional bar plot to compare the EUAC results.

Higher values on the ordinate indicate higher annual payments that are anticipated from using the corresponding device. Regardless of the interest rates, 1) the magnetic system is expected to cost more than the other two devices by a significant margin, and 2) the Bluetooth and RFID systems are not significantly affected by the interest rates.

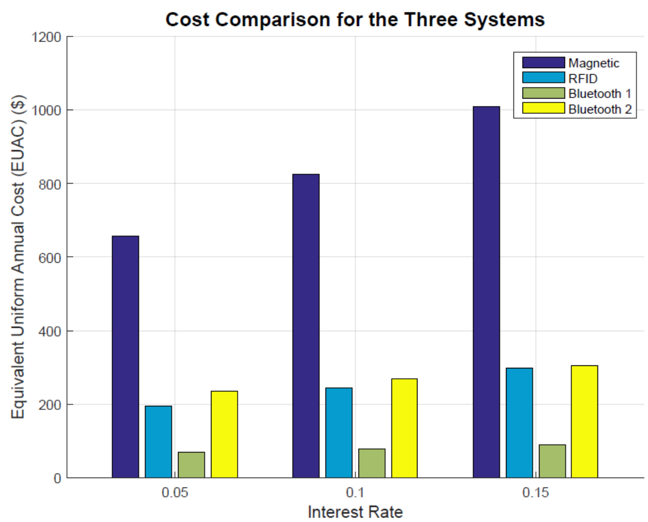


FIGURE 22

EUAC for the compared systems

6. Conclusions and Recommendations

Current safety practices exercised by roadway work zone personnel are inadequate to prevent contact collisions between pedestrian workers and construction equipment. This is evident from the injuries and fatalities still experienced by roadway work zone personnel (Teizer et al. 2008, NIOSH 2014, Pegula 2010). The main objective of this research was to 1) identify technologies that can be used in real time to detect a hazardous proximity situation between construction equipment and pedestrian workers and provide an appropriate warning and 2) evaluate the reliability and effectiveness of the technologies when deployed in a roadway work zone environment. Experiments were designed to specifically test and reveal the three technology proximity detection and alert systems' abilities to provide alerts in real time for pedestrian workers during hazardous proximity situations. Two experiments simulating various human and construction equipment interactions were completed to test the technology proximity detection and alert systems.

Experimental results demonstrate that 1) the most reliable detection and alert was provided by the magnetic field proximity sensing system with the smallest standard deviation for both mobile worker and static equipment scenario and the mobile equipment and static worker scenario. However, for the second scenario, the results of the magnetic system showed a major drop in the alert distance to about five meters, which may not offer sufficient time and space for a worker to escape from the hazardous scene. 2) Overall, the results revealed that the RFID system was the least accurate and least reliable. 3) The performance of the Bluetooth proximity technology was the second best reliable and effective for the first scenario but the most effective and the second best reliable for the second scenario. Overall, all the systems provided a recall rate of higher than 90%, which we interpret to be able to provide, with an appropriate alarm, additional layers of hazard avoidance in real time during hazardous proximity situations in roadway work zones.

When compared to the RFID and magnetic field proximity detection and alert systems, the developed Bluetooth proximity sensing system required the least amount of infrastructure and time for calibration. The magnetic field proximity sensing system recorded the highest reliability and accuracy values when compared to the RFID and

Bluetooth technology proximity sensing system. Economic analyses were performed to demonstrate the feasibility of the tested systems. The Bluetooth and RFID systems offered the most economical solution to proximity sensing and detection technology while the Magnetic field system turned out to be much more costly than the other two systems.

Field tests were designed and conducted at a real-world construction site with the Bluetooth proximity sensing and alert system. Test results demonstrate that the Bluetooth system provided reliable and accurate alerts when there were hazardous proximity situations between pedestrian workers and construction equipment. Also, analyzed results show that the frequency of hazardous proximity situations depended on work types, equipment types, and work locations.

Overall, based on the test records and feedback from the workers and operators, it is recommended that Georgia DOT use the Bluetooth proximity system as an additional layer of hazard avoidance in real time during hazardous proximity situations. Also, it is recommended to integrate an intrusion alert system with the Bluetooth proximity system to detect proximity situations between workers and construction equipment and intrusions made by passing vehicles; thus, holistically reducing the risk in the highway work zones in Georgia.

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APPENDIX A: COVERAGE AREA EXPERIMENTAL RESULTS

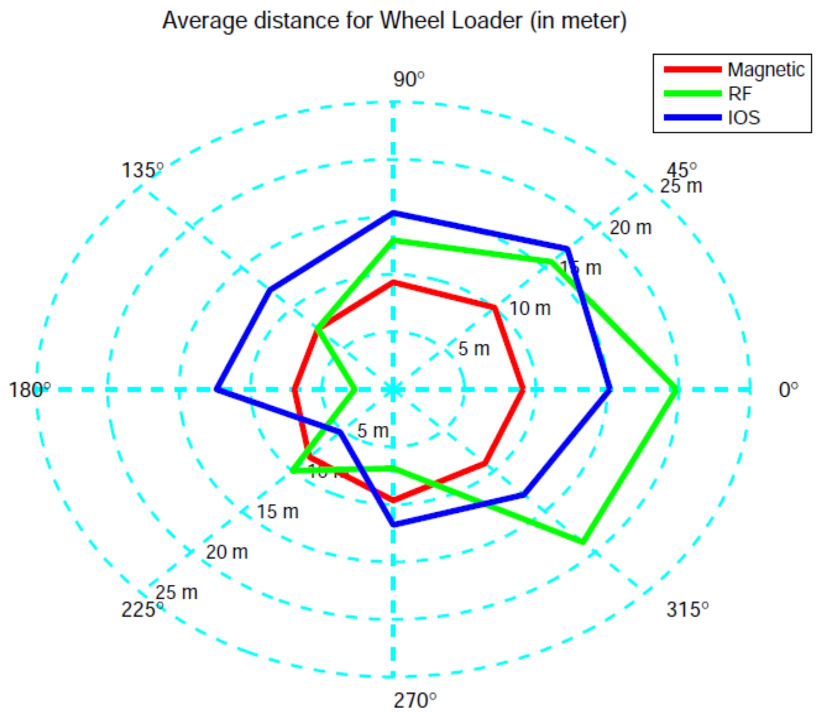

Figure 23: Average coverage area for three proximity sensing systems deployed on a wheel loader

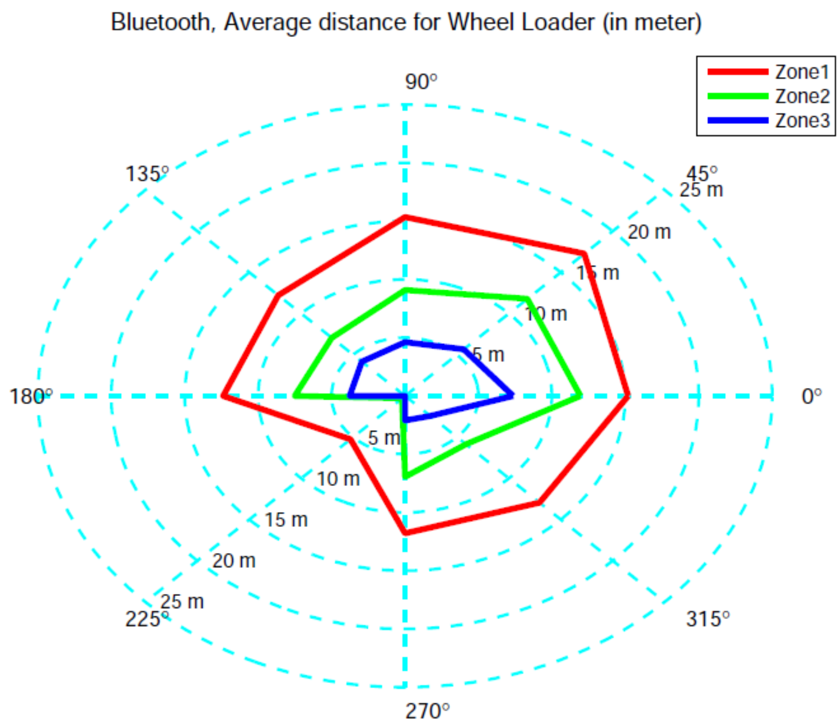

Figure 24: Average coverage area for Bluetooth technology proximity detection and alert system deployed on a wheel loader

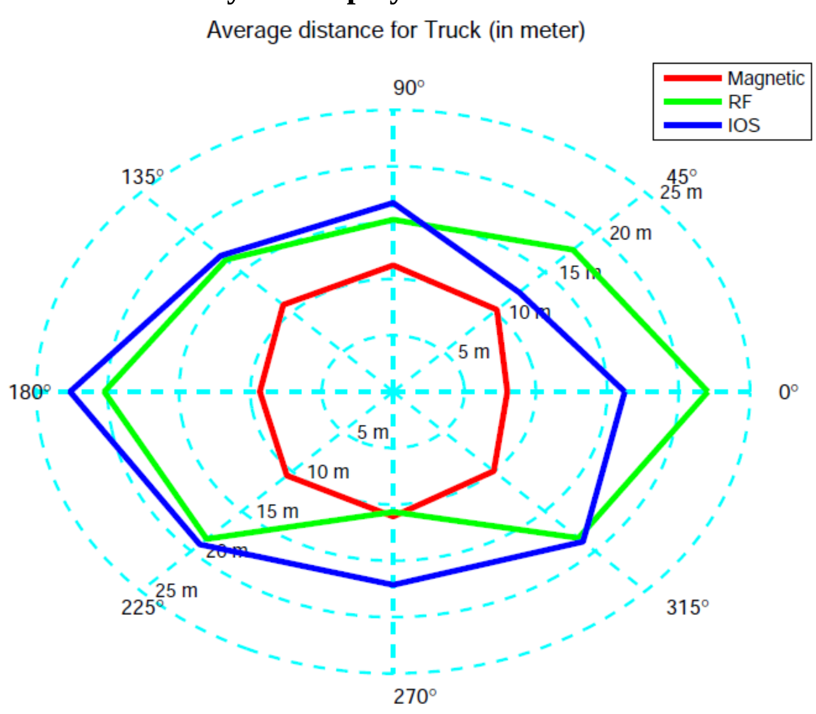

Figure 25: Average coverage area for three proximity sensing systems deployed on a truck

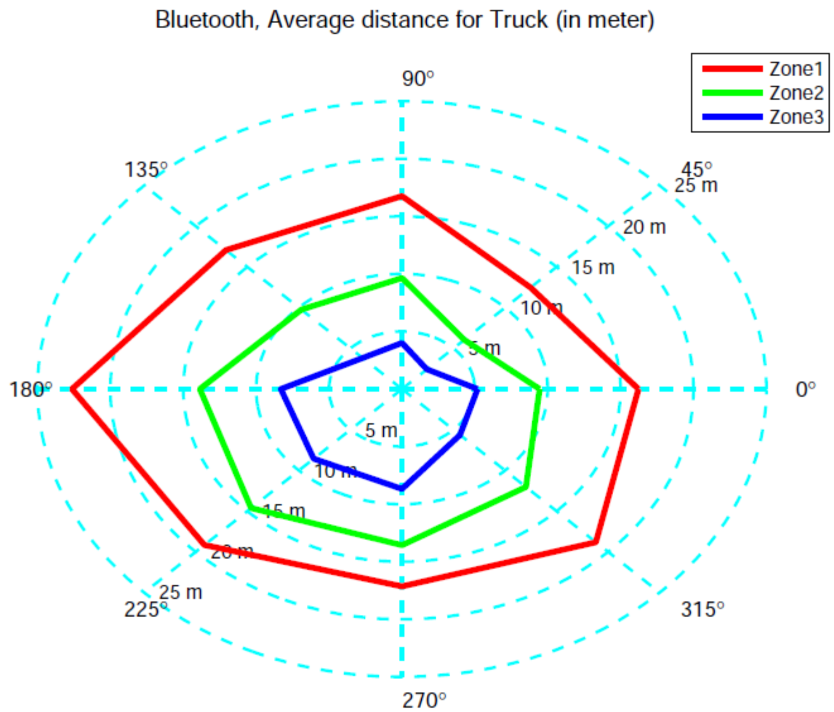

Figure 26: Average coverage area for Bluetooth technology proximity detection and alert system deployed on a truck

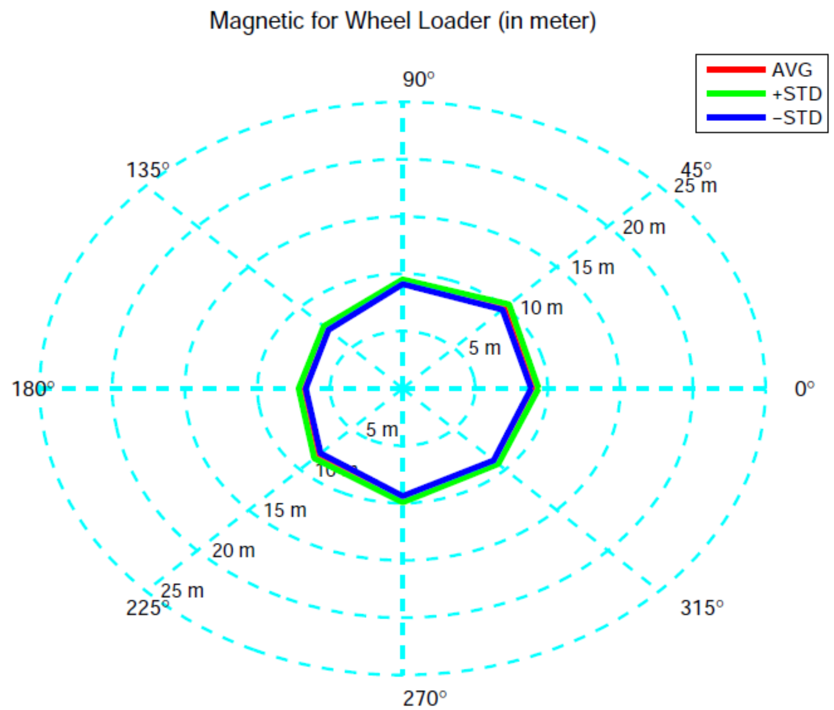

Figure 27: Average and standard deviation coverage area for Magnetic proximity sensing systems deployed on a wheel loader

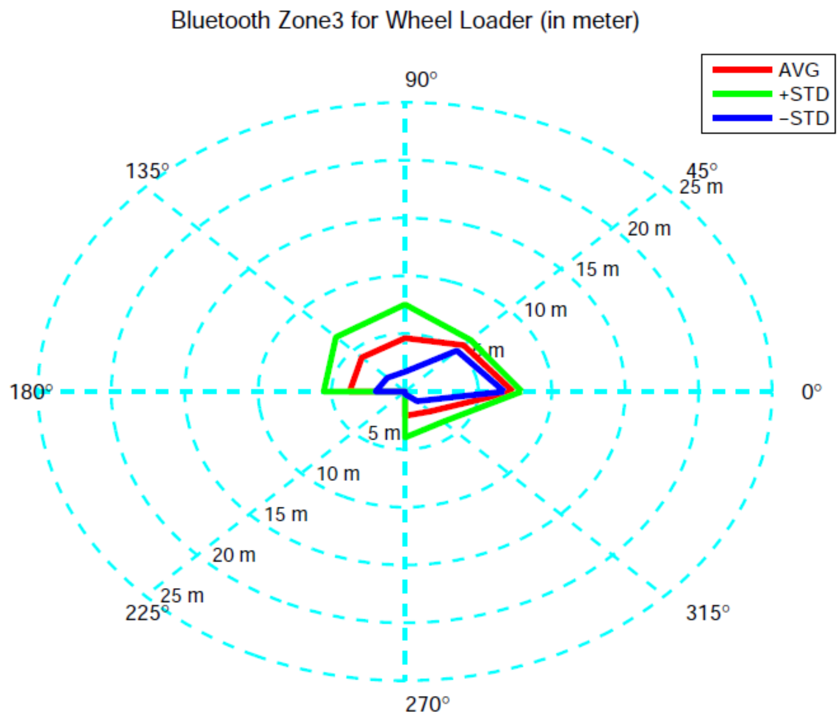

Figure 28: Average and standard deviation coverage area for Bluetooth proximity sensing systems deployed on a wheel loader (zone 3)

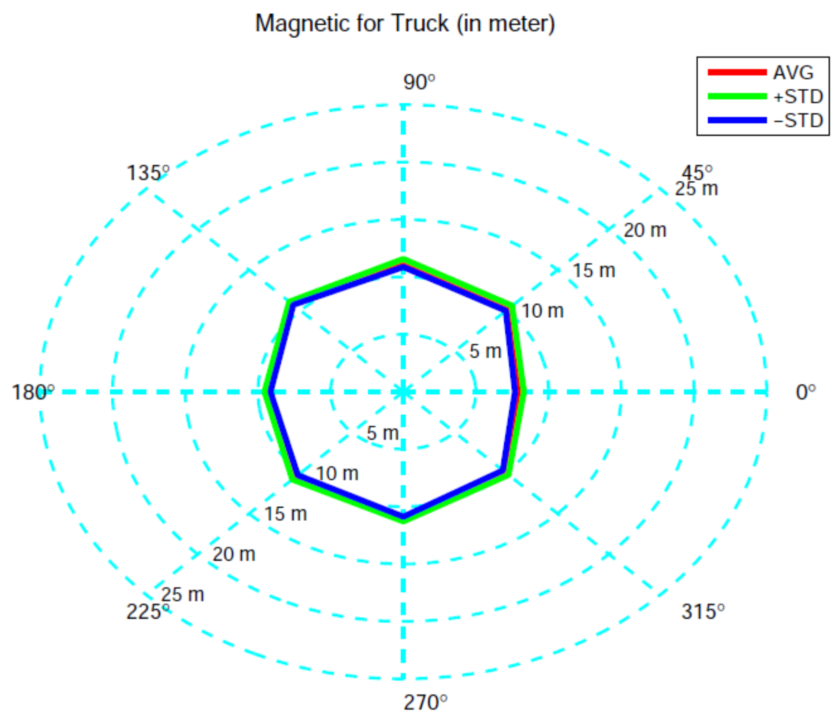

Figure 29: Average and standard deviation coverage area for Magnetic proximity sensing systems deployed on a truck

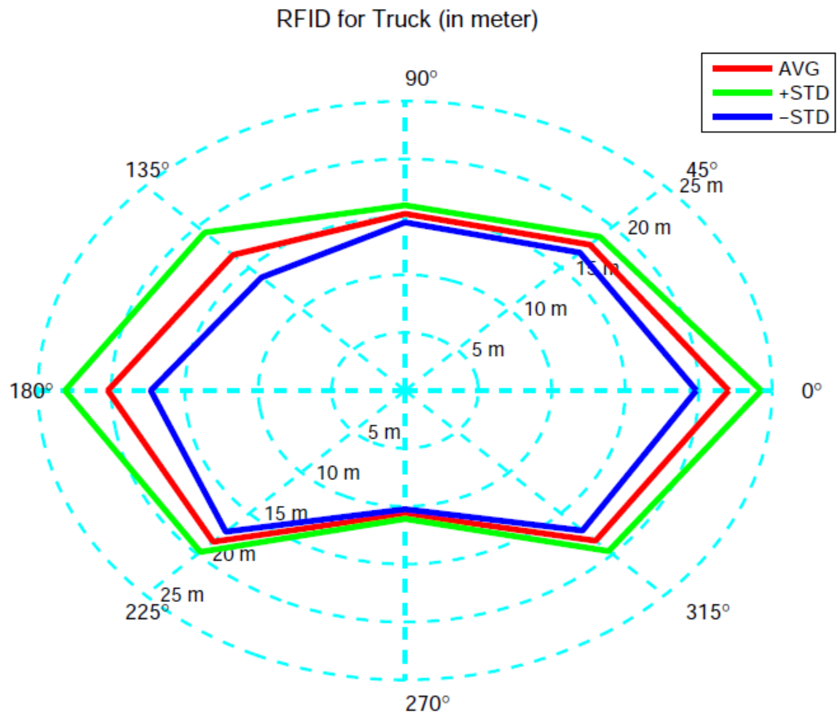

Figure 30: Average and standard deviation coverage area for RFID proximity sensing systems deployed on a truck

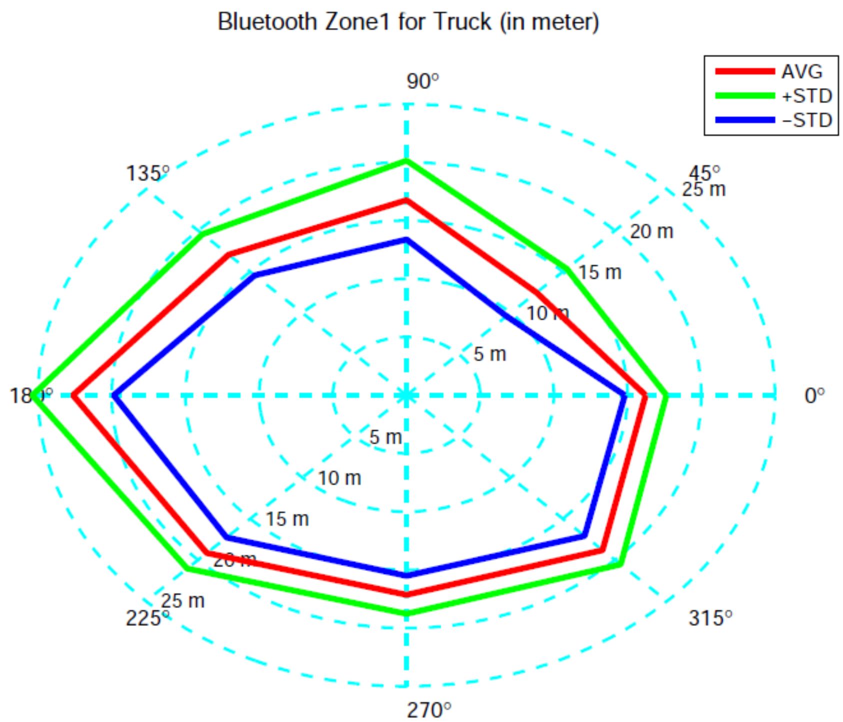

Figure 31: Average and standard deviation coverage area for Bluetooth proximity sensing systems deployed on a truck (zone 1)

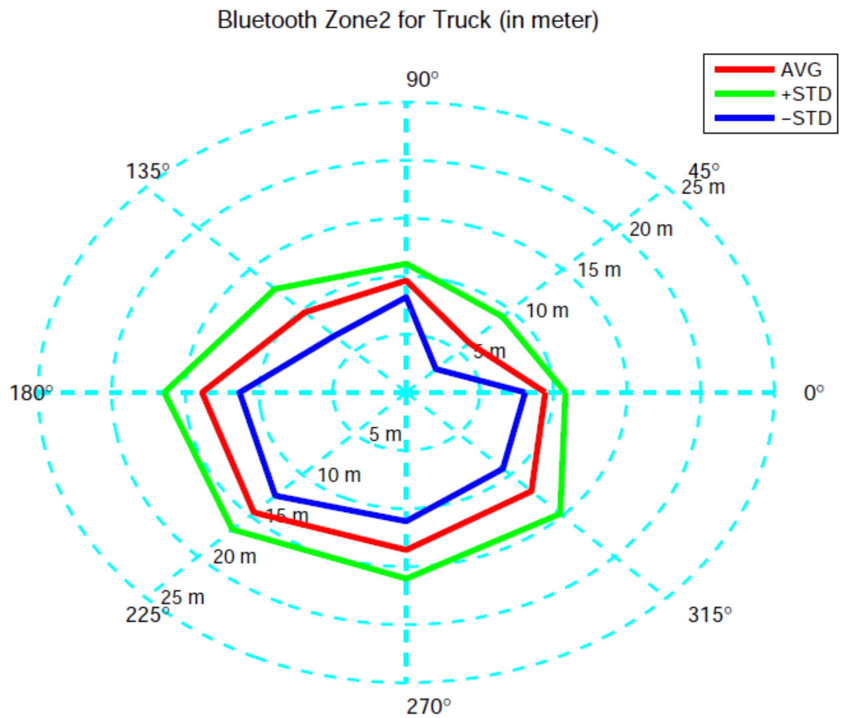

Figure 32: Average and standard deviation coverage area for Bluetooth proximity sensing systems deployed on a truck (zone 2)

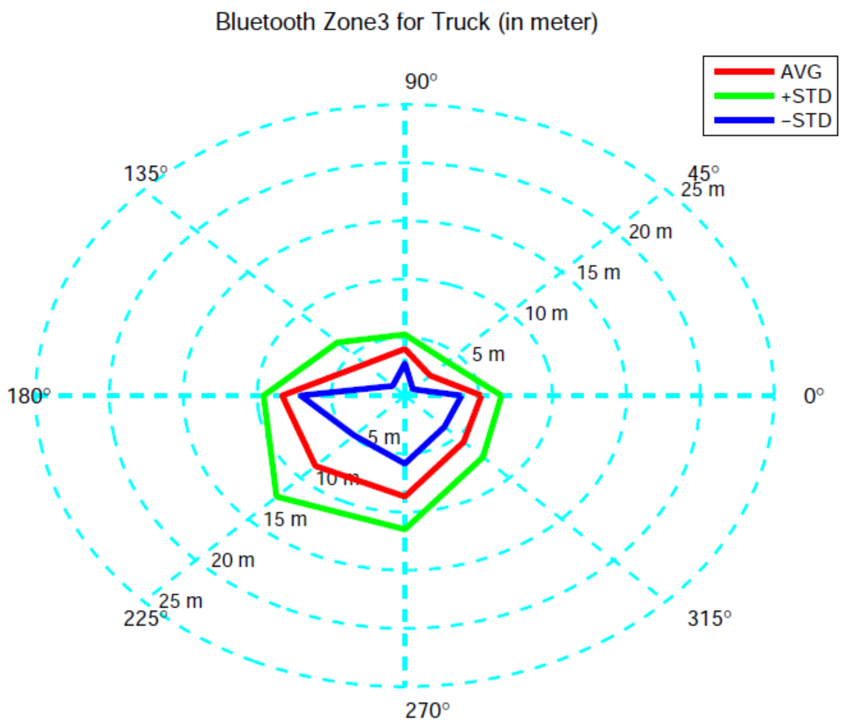

Figure 33: Average and standard deviation coverage area for Bluetooth proximity sensing systems deployed on a truck (zone 3)

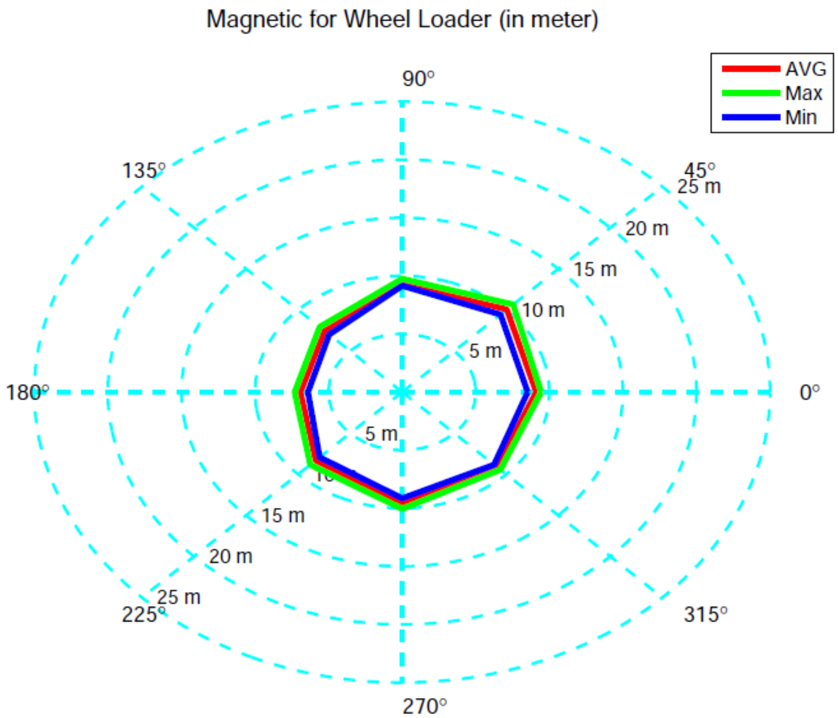

Figure 34: Average, minimum and maximum coverage area for Magnetic proximity sensing systems deployed on a wheel loader

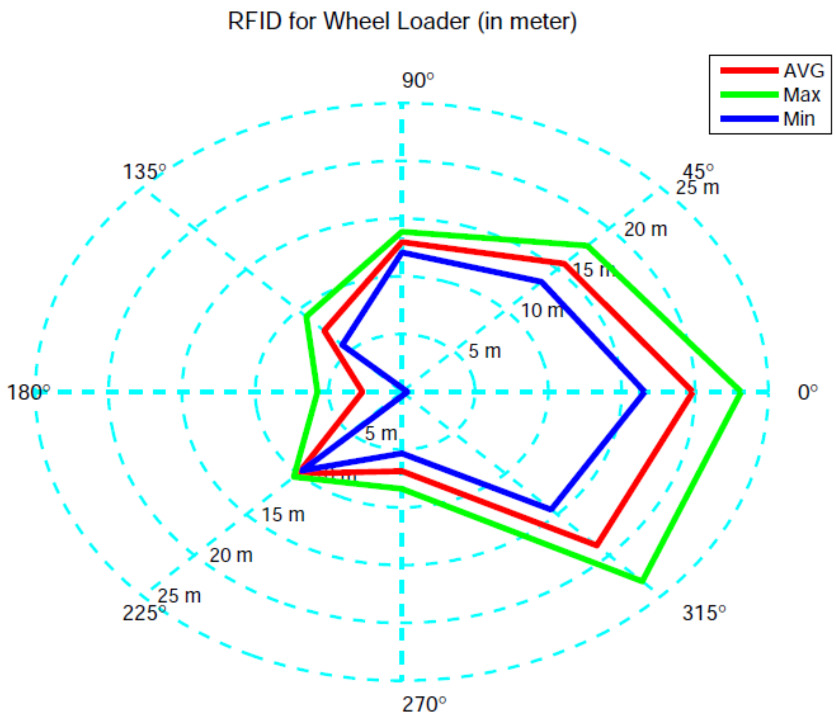

Figure 35: Average, minimum and maximum coverage area for RFID proximity sensing systems deployed on a truck

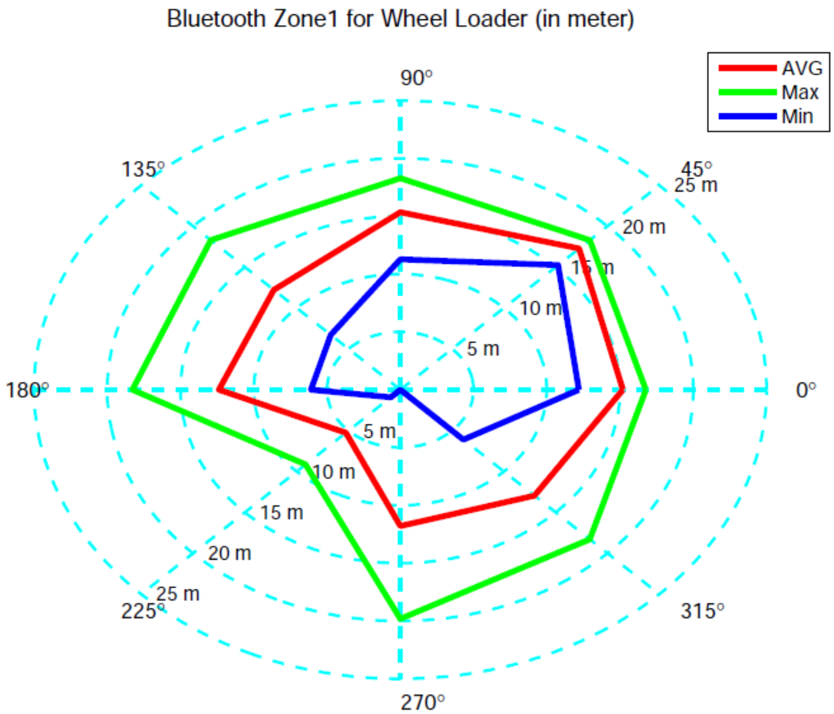

Figure 36: Average, minimum and maximum coverage area for Bluetooth proximity sensing systems deployed on a wheel loader (zone 1)

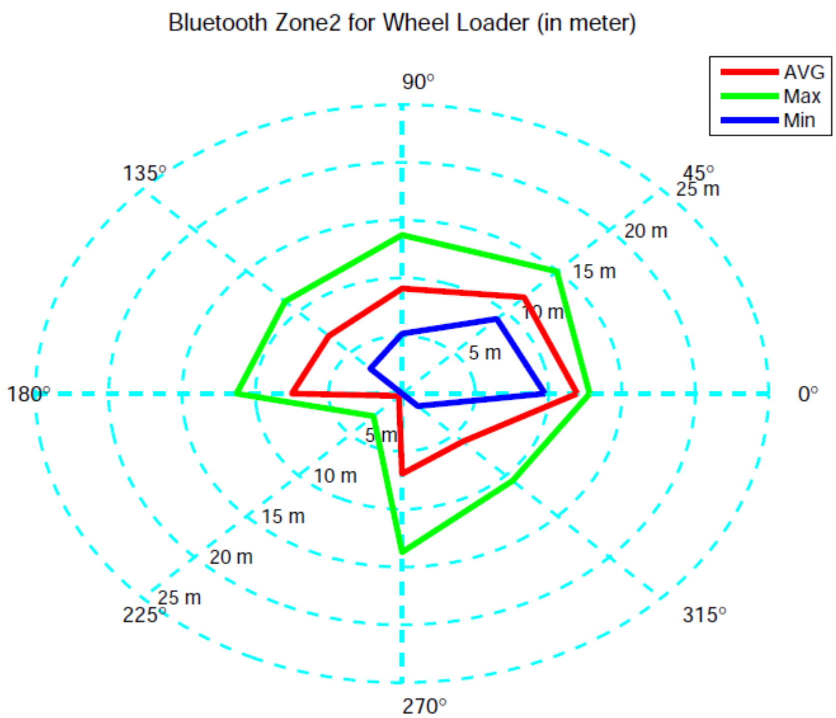

Figure 37: Average, minimum and maximum coverage area for Bluetooth proximity sensing systems deployed on a wheel loader (zone 2)

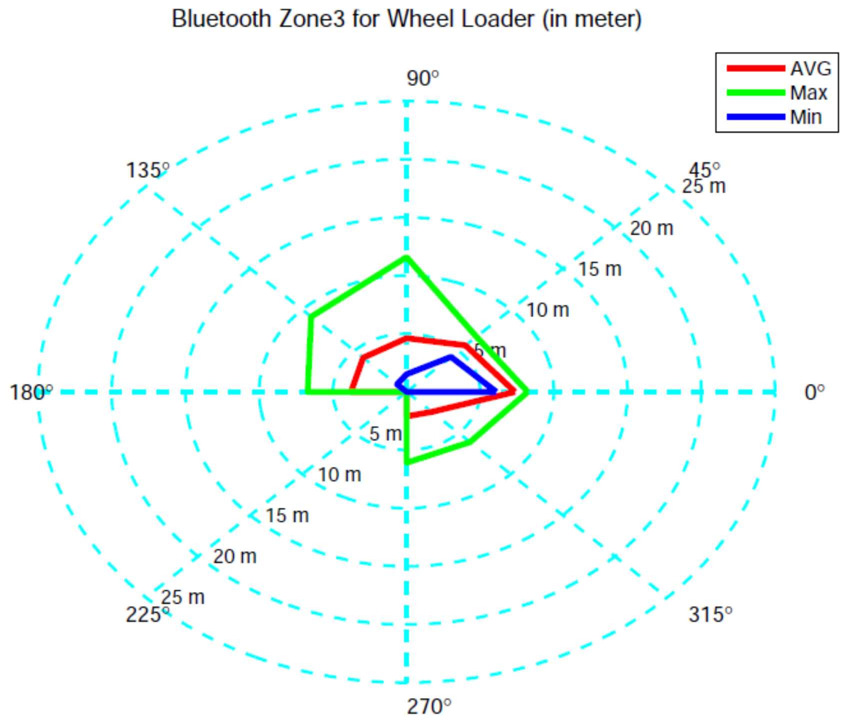

Figure 38: Average, minimum and maximum coverage area for Bluetooth proximity sensing systems deployed on a wheel loader (zone 3)

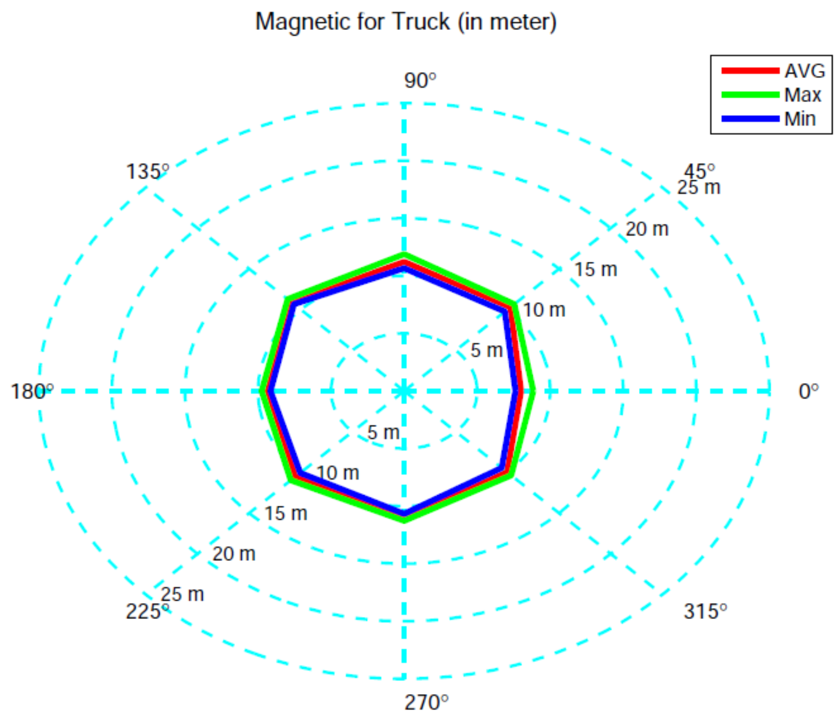

Figure 39: Average, minimum and maximum coverage area for Magnetic proximity sensing systems deployed on a truck

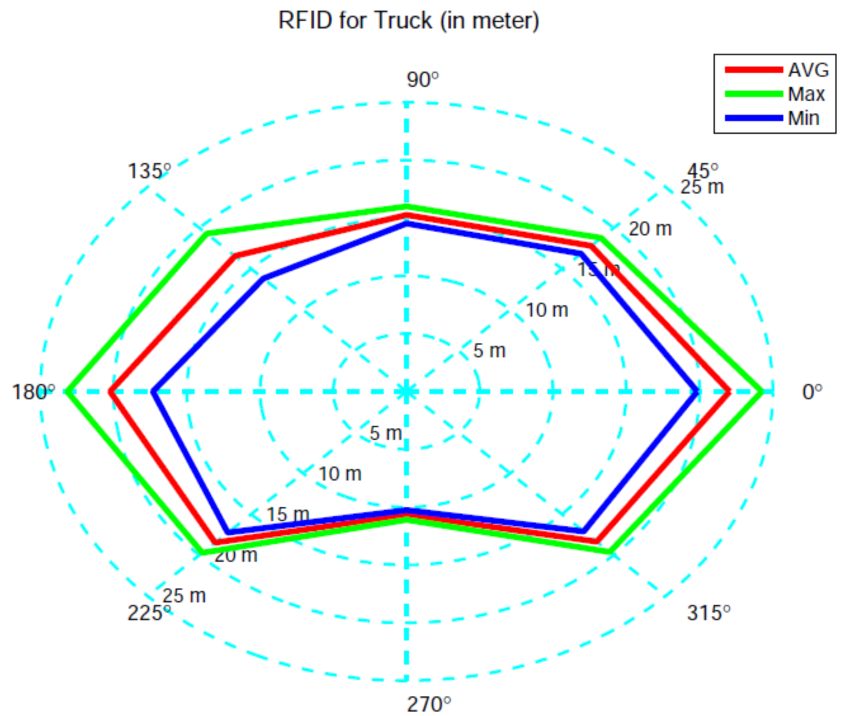

Figure 40: Average, minimum and maximum coverage area for RFID proximity sensing systems deployed on a truck

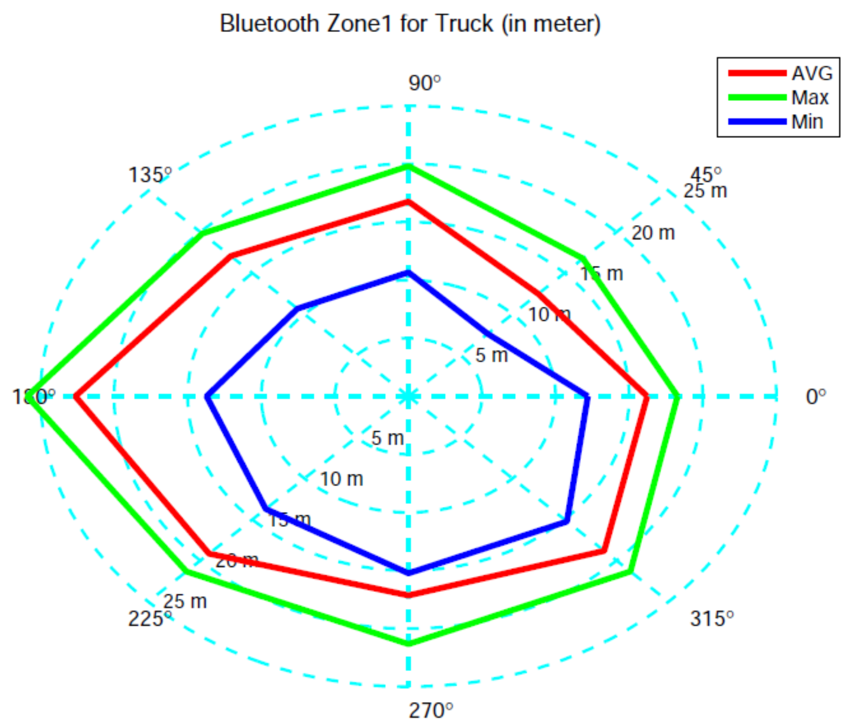

Figure 41: Average, minimum and maximum coverage area for Bluetooth proximity sensing systems deployed on a truck (zone 1)

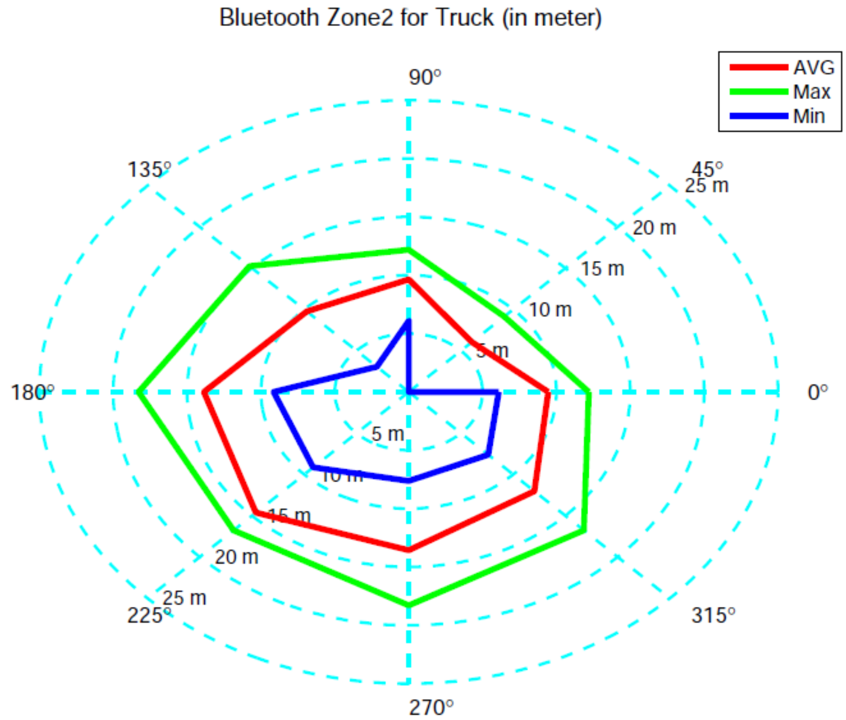

Figure 42: Average, minimum and maximum coverage area for Bluetooth proximity sensing systems deployed on a truck (zone 2)

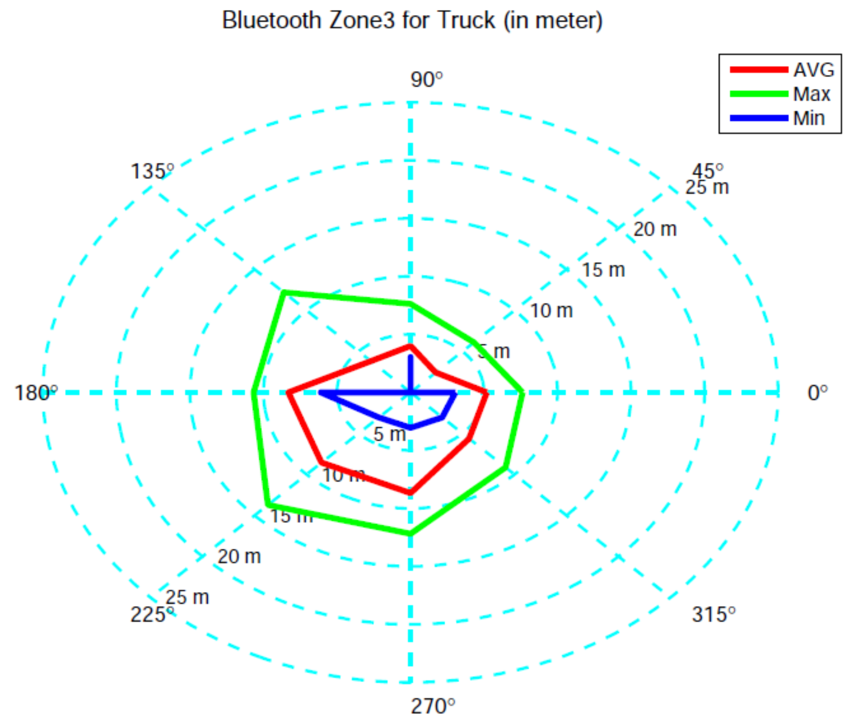

Figure 43: Average, minimum and maximum coverage area for Bluetooth proximity sensing systems deployed on a truck (zone 3)

APPENDIX B: MOBLE EQUIPMENT PEDESTRIAN WORKER EXPERIMENTAL RESULTS

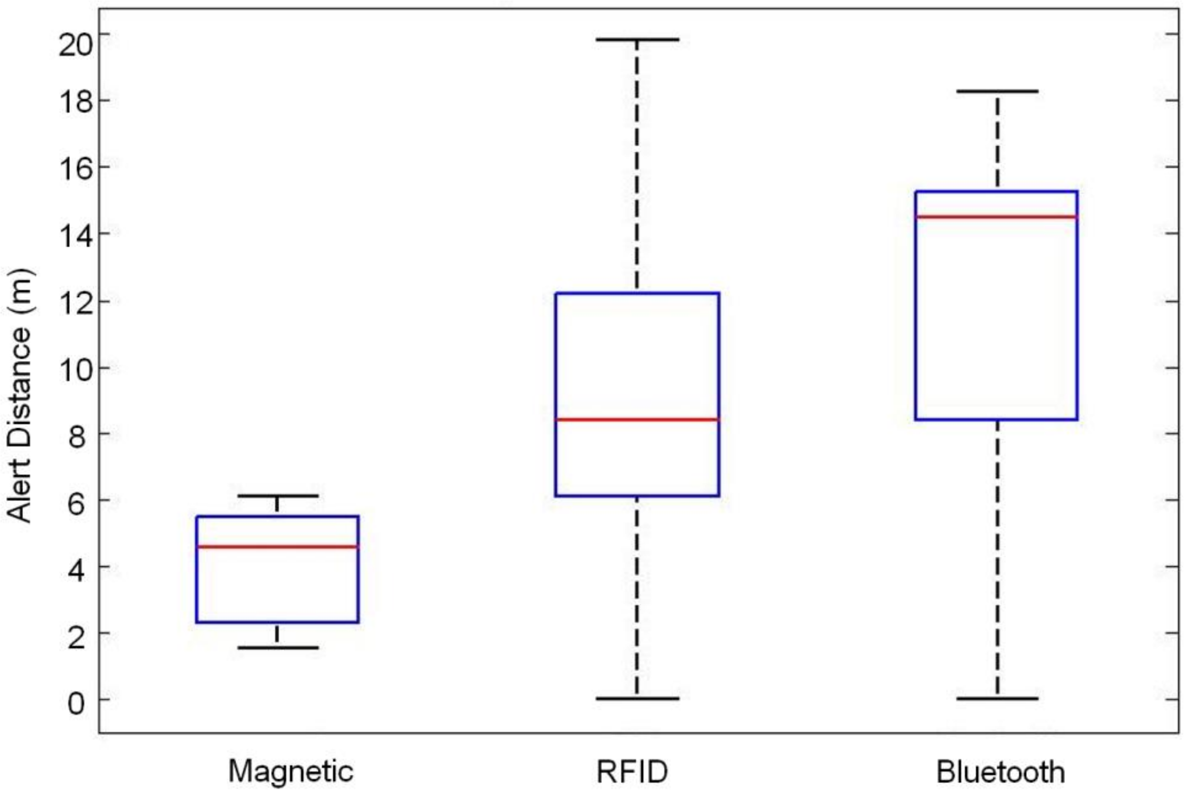

Figure 44: Box plots of proximity sensing systems for mobile wheel loader and static pedestrian worker trials