

ACTIVE CONSTRUCTION SAFETY LEADING INDICATOR
DATA COLLECTION AND EVALUATION

by

IBUKUN GABRIEL AWOLUSI

ROBERT G. BATSON, COMMITTEE CHAIR
ERIC D. MARKS, COMMITTEE CO-CHAIR
GARY P. MOYNIHAN
PAULINE D. JOHNSON
ALEXANDER M. HAINEN
CALI M. DAVIS

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ABSTRACT

The construction industry continues to experience an increased rate of workplace injuries and fatalities when compared to other U.S. industrial sectors. Construction workers often face safety and health risks throughout the construction process because of these dangerous working environments. Current safety practices, which are largely passive in nature, have not yielded the desired optimum results. Further improvements are necessary to enhance construction safety through the implementation of proactive safety strategies. This research seeks to evaluate how construction safety performance can be enhanced during the construction phase through the application of active construction safety leading indicators and sensing technologies. A near miss data collection and analysis framework is created and implemented for the management of safety leading indicator information. An objective evaluation of wearable technology systems for personalized construction safety monitoring is presented together with a model for integrating wearable sensors for multi-parameter safety performance monitoring. The characteristics of wearable devices and safety metrics capable of predicting safety performance and management practices are identified and analyzed. Strategies for the evaluation, selection, and implementation of vehicle intrusion sensing technologies for highway work zone safety are provided. The major contributions of this research involve the scientific data for collecting and evaluating safety leading indicators and innovative technologies, as well as an implementation guide for their application in construction. This research also provides best practices for construction management personnel that allows for the implementation of innovative safety technologies, as well as the use of collected data and information in operational procedures, safety training, and education.

DEDICATION

This dissertation is dedicated to my dear parents, Mr. Olusegun Lucas Awolusi and Mrs. Modupe Juliana Awolusi for their unwavering love and support.

LIST OF ABBREVIATIONS AND SYMBOLS

AFAD	Automated Flagger Assistance Device
ALDOT	Alabama Department of Transportation
AOA	Angle of Arrival
AWARE	Advanced Warning And Risk Evasion
ARTTS-NMA	Autonomous Real-Time Tracking System of Near Miss Accidents
BLS	Bureau of Labor Statistics
CAA	Civil Aviation Authority
CDC	Center for Disease Control and Prevention
CII	Construction Industry Institute
CO ₂	Carbon dioxide
DoD	Department of Defense
DOT	Department of Transportation
ECG/EKG	Electrocardiogram
ECM	Eindhoven Classification Model
EEG	Electroencephalography
EMG	Electromyography
EPC	Engineer-Procure-Construct
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GNSS	Global Navigation Satellite System

GPS	Global Positioning System
GSR	Galvanic Skin Response
HKOSH	Hong Kong Occupational Safety and Health
HSE	Health and Safety Executive
IAFC	International Association of Fire Chiefs
ILO	International Labor Organization
INS	Inertial Navigation System
ITS	Intelligent Transportation Systems
JPL	Jet Propulsion Laboratory
JSA	Job Safety Analysis
LED	Light-Emitting Diode
LNG	Liquefied Natural Gas
MEMS	Micro Electro Mechanical Systems
MLB	Major League Baseball
MUTCD	Manual on Uniform Traffic Control Devices
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NFL	National Football League
NIOSH	National Institute of Occupational Safety and Health
NRC	Nuclear Regulatory Commission
NSC	National Safety Council
NWZSIC	National Work Zone Safety Information Clearinghouse

OECD	Organisation for Economic Co-operation and Development
OSHA	Occupational Safety and Health Administration
PDA	Personal Digital Assistant
PMU	Peripheral Management Unit
PPE	Personal Protective Equipment
PSA	Portable Site Alarm
PSD	Personal Safety Device
PSM	Physiological Status Monitoring
PtD	Prevention through Design
PWS	Proximity Warning System
RF	Radio Frequency
RF	Reference Point
RFID	Radio Frequency Identification
RSS	Received Signal Strength
SHRP	Strategic Highway Research Program
TDOA	Time Difference of Arrival
TOA	Time of Arrival
UHF	Ultrahigh Frequency
UWB	Ultra-Wide Band
VOC	Volatile Organic Compound
WBAN	Wireless Body Area Network
WTIWC	Wearable Technologies Innovation World Cup

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CONTENTS

ABSTRACT	ii
DEDICATION	iii
LIST OF ABBREVIATIONS AND SYMBOLS	iv
ACKNOWLEDGMENTS	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
CHAPTER 1 INTRODUCTION	1
1.1 Overview.....	1
1.2 Motivation and Research Objectives	3
1.3 Dissertation Organization	5
CHAPTER 2 LITERATURE REVIEW	7
2.1 Construction Industry Incident Statistics	7
2.2 Construction Safety Performance Measurement	9
2.3 Safety Leading Indicators	11
2.4 Near Miss	13
2.5 Wearable Technology in Construction	14
2.6 Work Zone Safety.....	15
2.7 Problems and Research Needs Statement	16
CHAPTER 3 RESEARCH METHODOLOGY	18
3.1 Introduction.....	18

3.2 Research Objective, Scope, and Hypothesis.....	19
3.2.1 Objective	19
3.2.2 Scope.....	20
3.2.3 Hypothesis.....	21
3.3 Research Framework	21
3.4 Near Miss Data Collection and Analysis	22
3.5 Wearable Technology Review	23
3.6 Work Zone Intrusion Technologies Evaluation.....	24
CHAPTER 4 NEAR MISS DATA COLLECTION AND ANALYSIS FRAMEWORK FOR CONSTRUCTION.....	25
4.1 Introduction.....	25
4.2 Near Misses as Safety Leading Indicators	26
4.3 Near Miss Reporting Across Industries	27
4.4 Research Needs Statement.....	29
4.5 Research Method	29
4.6 Results and Discussions.....	30
4.6.1 Near Miss Data Collection and Analysis Framework.....	30
4.6.2 Case Study	35
4.7 Conclusion	38
CHAPTER 5 WEARABLE TECHNOLOGY FOR PERSONALIZED CONSTRUCTION SAFETY MONITORING.....	39
5.1 Introduction.....	39
5.2 Wearable Technology Systems and Sensors	40
5.3 Wearable Technology in Other Industries	41
5.4 Wearable Technology in Construction	43

5.5 Research Needs Statement.....	44
5.6 Research Method	45
5.7 Results and Discussion	47
5.7.1 Construction Safety and Health Hazards	47
5.7.2 Performance Characteristics of Wearable Technologies	60
5.7.3 Integrated Wearable Technology for Construction Safety Performance Monitoring..	69
5.8 Conclusion	71
CHAPTER 6 ACTIVE WORK ZONE SAFETY USING EMERGING TECHNOLOGIES	73
6.1 Introduction.....	74
6.2 Work Zone Safety Statistics	76
6.3 Work Zone Intrusion Technologies	76
6.4 Previous Assessments of Intrusion Alarms for Work Zone Safety	78
6.5 Research Needs Statement.....	79
6.6 Research Method	80
6.7 Conceptual Review Results	81
6.7.1 Review of Applicable Work Zone Intrusion Technologies	81
6.8 Experimental Procedure and Results	90
6.8.1 Experimental Set-up and Data Collection.....	90
6.8.2 Experimental Evaluation Results	93
6.9 Implementation Guide	100
6.9.1 Step 1: Assign Champion	101
6.9.2 Step 2: Select Technology	102
6.9.3 Step 3: Educate Employees.....	103
6.9.4 Step 4: Disseminate Information	103

6.9.5 Step 5: Maintain System	104
6.10 Conclusion	104
CHAPTER 7 CONCLUSIONS	106
7.1 Concluding Remarks.....	106
7.2 Contributions and Impacts	109
7.3 Limitations and Future Research	110
REFERENCES	111

LIST OF TABLES

Table 2.1: Leading indicators used in construction	12
Table 4.1: Eindhoven Classification Model (ECM) for human errors in construction	33
Table 4.2: Correlation coefficient analysis	36
Table 4.3: Near miss categorization using Eindhoven Classification Model (ECM).....	37
Table 5.1: Safety performance metrics for construction safety and health hazards	48
Table 6.1: Applicable and commercially available work zone intrusion technology systems	82
Table 6.2: Selection guide for work zone intrusion detection devices	102

LIST OF FIGURES

Figure 2.1: Number of fatalities and non-fatal incidence rate in construction industry	8
Figure 3.1: Three-pronged research approach	19
Figure 3.2: Research framework.....	22
Figure 4.1: Stages for near miss data collection and analysis framework	31
Figure 4.2: Flow of near miss information	34
Figure 5.1: Review framework for wearable technology in construction	46
Figure 5.2: Accuracy of selected proximity detection wearable devices.....	64
Figure 5.3: Cost of selected proximity detection wearable devices.....	68
Figure 5.4: Sensors and systems for personalized wearable technology	70
Figure 6.1: Research methodology framework.....	80
Figure 6.2: SonoBlaster alarm unit	83
Figure 6.3: Traffic Guard Worker Alert System.....	86
Figure 6.4: Intellicone alarm system.....	89
Figure 6.5: Test bed for experimental trials.....	91
Figure 6.6: Layout of the experimental trials site	92
Figure 6.7: Sound level of the radio-based and pneumatic/microwave alarms	94
Figure 6.8: Results of worker's reaction time.....	95
Figure 6.9: Results of vehicle stopping time	97
Figure 6.10: Results of vehicle stopping distance	98

Figure 6.11: Summary of experimental results 99

Figure 6.12: Steps for implementation of work zone intrusion alert systems 101

CHAPTER 1

INTRODUCTION

This chapter presents an overview of safety performance in the construction industry along with background to the study of the implementation of active safety leading indicators and sensing technologies in the construction environment. The research motivation created from current efforts in enhancing safety for construction workers, as well as the objectives derived from the research needs, are presented in this chapter. This chapter ends with an outline of this dissertation.

1.1 Overview

When compared to other U.S. industry sectors, the construction industry continues to experience a high number of workplace fatalities and injuries. As an industry, construction has averaged 949 fatalities per year over the past years, indicating that much improvement is still necessary to achieve zero injuries, illnesses, and fatalities (BLS 2016a). One such improvement can be found in the collection and measurement of safety data. Historically, the construction industry has defined safety performance through the measurement and assessment of lagging indicators such as injuries, illnesses, and fatalities. These lagging indicator safety measures must be reported to the Occupational Safety and Health Administration (OSHA) to assess the state of construction safety (OSHA 2015). One major limitation of assessing worker safety performance using lagging indicators is that accidents must occur before hazards or unsafe worker behavior can be identified and mitigated.

An alternative form of safety metrics called leading indicators assesses safety performance by gauging processes, activities, and conditions that define performance and can predict future results (Hinze et al. 2013). One such safety leading indicator is a near miss, which is defined as an incident where no property damage and no personal injury occur, but where, given a slight shift in time or position, damage and injury easily could have occurred (OSHA 2015). The major advantage of measuring leading indicators such as near misses is that data can be collected and analyzed without the requirement of a lagging indicator (i.e. injury or fatality) to occur.

Due to the hazardous working environments at construction sites, workers frequently face potential safety and health risks throughout the entire construction process (Seo et al. 2015). Construction safety has been traditionally measured and managed reactively by taking actions in response to adverse trends in injuries (Hallowell et al. 2013). These methods are costly, prone to data entry errors, and result in data sets that are too small for effective and successful project control (Teizer and Vela 2009). To overcome the limitations of these conventional efforts, automated safety monitoring using wearable technology is considered one of the most promising methods for accurate and continuous monitoring of safety performance on construction sites (Park et al. 2016). Automated monitoring systems can acquire data, convert it into structured data, and immediately deliver the data to project managers who can take action (Rebolj et al. 2008).

Additionally, work zone injuries and fatalities have continued to increase in recent times (FHWA 2016). For example, construction work zones on roadways are hazardous areas and motorists are exposed to unfamiliar situations in a normally familiar setting; such unexpected unfamiliarity could lead to accidents (Bathula et al. 2009). Improvement is necessary for

highway construction projects to experience less fatalities, injuries, illnesses, and financial loss due to accidents. During the past few years, through the Strategic Highway Research Program (SHRP) and other initiatives, several innovative devices have been developed that assist drivers in recognizing the presence of a work zone environment (Carlson et al. 2000). These new devices range from fairly simple devices, such as portable rumble strips, to the more sophisticated Intelligent Transportation Systems (ITS)-related in-vehicle warning technology. But there is still a need to deploy new cutting-edge technologies for improving work zone safety in infrastructure construction and maintenance.

1.2 Motivation and Research Objectives

Most construction organizations rely on failure data to monitor performance, an approach in which improvements or changes are only determined after something has gone wrong (HSE 2006). Effective management of major hazards requires a proactive approach to risk management. Thus, it is vital to have information to help ascertain whether critical systems are operating as intended. Transitioning to an emphasis on leading indicators and sensing technologies to confirm that risk controls continue to operate is an important step forward in the management of major hazard risks (HSE 2006). Linear causation models suggest that accidents are the end result of a sequence of events. The Domino Theory and the Loss Causation Models for example provide sound motivation to collect and analyze leading indicators data. Previous researchers have also found that a majority of serious injuries to workers can be successfully prevented (Hinze 2002; Huang and Hinze 2006; Hecker et al. 2005; Hinze and Wilson 2000).

The measurement of leading indicators in the construction industry, as well as continuous data collection and analysis, have the potential to positively impact decision making in safety

management (Pradhananga and Teizer 2013). If data would be more rapidly updated, safety personnel could take faster preventive actions and potentially prevent hazardous conditions before they occur. Therefore, the safety goal should be to put adequate efforts in place to achieve zero injuries, because all serious injury to workers can be successfully prevented (Hinze 2002; Huang and Hinze 2006). Automated safety observations using sensing technologies such as physiological monitoring devices can be used proactively to identify an existing hazard before an injury, illness, or fatality occurs.

The primary objective of this research is to evaluate the effectiveness of implementing safety leading indicators and sensing technologies to enhance construction safety performance. To achieve this main objective, the following secondary objectives are proposed:

- Create and implement a near miss data collection and analysis framework to enhance safety performance on construction sites;
- Provide an evaluation of wearable technology systems for personalized construction safety monitoring;
- Create a model for integrating wearable sensors for multi-parameter safety performance monitoring in construction;
- Provide a conceptual analysis and an experimental evaluation of intrusion sensing technologies for highway work zones;
- Provide strategies for selecting and implementing intrusion sensing technologies for active work zone safety;
- Create a set of best practices for construction management personnel that allows implementing innovative safety technologies as well as the use of collected safety leading indicators data and information in operational procedures, safety training, and education.

1.3 Dissertation Organization

This dissertation investigates and provides strategies for active monitoring of construction safety performance through the implementation of leading indicators and technologies. The following is an outline of how this dissertation is structured.

Chapter 1 gives an overview of construction safety and background to the study. The motivation and research objectives derived from the current safety practices and needs for improvements are also presented.

Chapter 2 provides a review of incident statistics and safety performance measurement in the construction industry. Detailed discussions on safety leading indicators including near miss, wearable technology in construction, and highway work zones safety are presented. The research problems and needs statement are also presented.

Chapter 3 presents the research methodology adopted for this study. The research objectives, scope, and hypothesis are described. A framework for the overall research is also presented.

Chapter 4 presents a near miss data collection and analysis framework for the construction industry. The framework provides a methodology for reporting and analyzing near misses as well as disseminating information for worker safety education and training.

Chapter 5 provides an evaluation of wearable technology systems for personalized construction safety monitoring. A model for integrating wearable sensors for multi-parameter safety performance monitoring in construction is also presented.

Chapter 6 presents a conceptual analysis and an experimental evaluation of intrusion sensing technologies for highway work zones. Strategies for selecting and implementing intrusion sensing technologies for active work zone safety are also provided.

Chapter 7 summarizes the research findings and concludes the dissertation. It also discusses the future research extensions and opportunities as well as the limitations of the research.

CHAPTER 2

LITERATURE REVIEW

The construction industry continues to rank as one of the most hazardous work environments, recording the highest rates of occupational injuries, illnesses, and fatalities when compared with other industrial sectors in the U.S. Although attention has been given to construction safety research, much effort is still needed to enhance safety performance on construction sites. This research focuses on creating and testing research strategies and framework to potentially enhance construction safety through the implementation of safety leading indicators and sensing technologies. This review presents statistics of current injuries and fatalities as well as safety performance measurement in the construction industry. It also discusses active construction safety leading indicators and explores the concepts of near miss data collection and analysis, wearable technology in construction, and highway work zone safety. The research problems are discussed and a research needs statement derived from the findings of this literature review is also presented.

2.1 Construction Industry Incident Statistics

The construction industry continues to experience high occupational injury, illness, and fatality rates and is one of the most hazardous work environments in the U.S. (Bansal 2011; HKOSH 2013; HSE 2014; BLS 2015a). In the U.S construction industry, the number of fatalities increased from 738 in 2011 to 899 in 2014 (BLS 2016a).

Organizations such as OSHA establish standards and regulations in an attempt to improve safety for construction workers. Construction companies in the U.S. are required to report all fatalities, injuries, and illnesses that occur during the construction process or as a result of the work environment (OSHA 2011). OSHA categorizes reported accidents as the following: 1) occupational fatality, 2) non-fatal injury, or 3) non-fatal illness. Incidents are further classified as to severity - OSHA recordable injuries and lost time/days away from work cases. Despite improvements in safety performance over the past few decades, the construction industry still accounts for an injury and illness rate that is greater than the all-industry average. The construction industry had the highest count of fatal injuries in 2014, recording 899 fatal injuries (see Figure 2.1), about 9% greater than the number of fatal injuries recorded the previous year and representing the largest number of fatal work injuries in private construction since 2008 (BLS 2016b; BLS 2016c). Also, the private construction industry recorded in 2014 a non-fatal occupational injury and illness rate (total recordable cases per 100 full-time workers) of 3.6, which is 0.4 higher than the overall private industry rate of 3.2 (BLS 2015b).

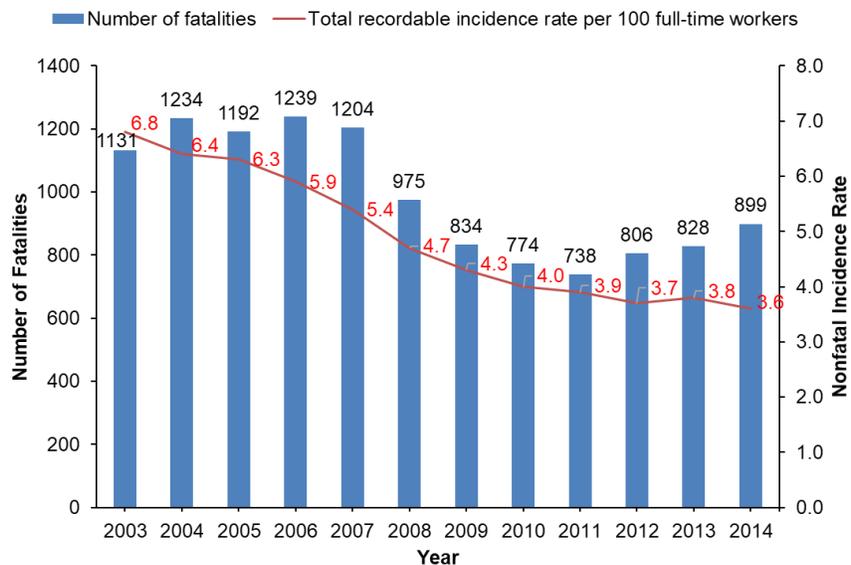


Figure 2.1: Number of fatalities and non-fatal incidence rate in construction industry

Furthermore, it was estimated that construction fatalities resulted in approximately \$10 billion worth of loss due to direct and indirect costs between 1992 and 2002 (CDC 2006; NSC 2008). According to this study, the average cost of each construction fatality during that time duration was \$864,000 (CDC 2006). In 2007, fatal and non-fatal injuries cost the industry approximately \$6 billion and \$186 billion respectively (Leigh 2011). The higher rate of injuries and illnesses has been partly attributed to the complex, dynamic, and transient nature of construction projects (Hallowell 2012). These statistics evidently show an urgent need to reduce the prevalence of fatal and non-fatal injuries in construction (Seo et al. 2015). A systematic and comprehensive effort is therefore required to manage the safety and health of workers on construction sites.

2.2 Construction Safety Performance Measurement

Construction safety performance has traditionally been measured by “after-the-loss” type of measurements, such as accident rates, injury rates, and costs (Grabowski et al. 2007). However, most of these methods are reactive or subjective approaches because accident statistics only show the performance of safety management efforts in the past (Dagdeviren et al. 2008) and are reactionary. The fundamental goal of measuring safety performance is to intervene in an attempt to mitigate unsafe behaviors and conditions that can lead to accidents on construction sites.

The term “indicators” is used to mean observable measures that provide insights into a concept that is difficult to measure directly; a safety performance indicator is a means for measuring the changes over time at the level of safety as the result of actions taken (OECD 2003). An indicator is a measurable and operational variable that can be used to describe the

condition of a broader phenomenon or aspect of reality. An indicator can be considered any measure (quantitative or qualitative) that seeks to produce information on an issue of interest (Reiman and Pietikainen 2012). Safety indicators can play a key role in providing information on organizational performance, motivating people to work on safety, and increasing organizational potential for safety.

The probability of injuries or accidents can be described as a joint outcome of near misses, unsafe conditions (i.e. hazardous equipment or environment), unsafe actions (i.e. at-risk behaviors), and chance variations as theorized by Heinrich's safety pyramid. The safety pyramid depicts the concept that a multitude of minor incidents (such as hazardous conditions and at-risk behaviors) are required for one major incident to occur. Data from these minor injuries or leading indicators can be analyzed to predict safety performance and can help preclude major injuries or fatalities on construction sites.

Performance measurements can either be reactive monitoring or active monitoring (HSE 2006). The former means identifying and reporting on incidents, and learning from mistakes, whereas the latter provides feedback on performance before an accident or incident occurs. Safety performance metrics can be divided into lagging and leading indicators (Hallowell et al. 2013). Lagging indicators are related to reactive monitoring and show when a desired safety outcome has failed, or when it has not been achieved (Oien et al. 2011). Leading indicators, however, are a form of active monitoring which determines if risk control systems are operating as intended (Fearnley and Nair 2009). Leading indicators are measurements linked to preventive actions while lagging indicators are linked to the outcome of an injury or accident (Toellner 2011). Construction safety leading indicators are discussed in the following section.

2.3 Safety Leading Indicators

Construction companies are required to document work-related accidents (OSHA 2013). These metrics are termed lagging indicators and are unable to reflect if a hazard has been mitigated, the severity of an event, or the event causation (Lindsay 1992; Flin et al. 2000). Leading indicators are measurements of processes, activities, and conditions that define performance and can predict future results according to Hallowell et al. (2013), at least where leading indicator requirements have been developed. Leading indicators pertain to measures of behaviors, practices, or conditions that influence construction safety performance (CII 2012). Unmitigated high-risk situations, including near misses and proximity to heavy construction equipment, will result in a serious or fatal injury if allowed to continually exist (Krause et al. 2010).

Leading indicators of safety performance are used as predictors of safety performance to be realized. They are used as inputs that are essential to achieve the desired safety outcome (Øien et al. 2011). While lagging indicators are safety measures of performance on past projects, leading indicators are directly related to the project that is to be undertaken and are concentrated on the safety management process (Hinze 2005). Leading indicators give the probability that a safe project will be delivered by providing the opportunity to make changes as soon as there is an indication that the safety program has a weakness (Hinze et al. 2013). Leading indicators of safety performance can be classified as being passive or active. The common leading indicators used in construction are near miss reporting, worker observation (to determine unsafe conditions and acts), job site audits, stop work authority, housekeeping, safety orientation and training, etc. as shown in Table 2.1.

Table 2.1: Leading indicators used in construction

Leading Indicators	Description
Worker Observation Process (Hallowell et al. 2013)	<ul style="list-style-type: none"> • Common techniques used to evaluate ongoing tasks in construction. • Unsafe conditions and acts that contribute to injury, property damage, or equipment failure can be identified, recorded and used to monitor and predict safety performance.
Near Miss Reporting (Hallowell et al. 2013)	<ul style="list-style-type: none"> • Defined as an incident where no property damage and no personal injury were sustained, but where, given a slight shift in time or position, damage and injury easily could have occurred. • Near misses are measurements of processes, activities and conditions that assess safety performance and can predict future results. • Near miss reporting is used as a safety management tool in many other industries within the U.S. private sector.
Project Management Team Safety Process Involvement (Hallowell et al. 2013)	<ul style="list-style-type: none"> • Demonstration of leadership and commitment via active management walking around. • Senior management and supervisors are encouraged to participate in site safety walks. • Management plays a key role in promoting a positive safety culture. • Allocating resources, time, and inspections.
Job Site Audits (Hinze 2005)	<ul style="list-style-type: none"> • Systematic measurement and evaluation of the way in which an organization manages its health and safety program against a series of specific and attainable standards. • Conducted to identify problem areas including unsafe conditions and unsafe behaviors. • The results can predict trends to show that safety is improving or that jobsite safety is decreasing.
Stop Work Authority (Hallowell et al. 2013)	<ul style="list-style-type: none"> • Workers are expected to stop any work they consider to be unsafe until they feel it is safe to proceed. • Stop work authority is to be clearly communicated to workers in initial orientation and at regular intervals throughout each project.
Housekeeping Program (Hallowell et al. 2013)	<ul style="list-style-type: none"> • Helps achieve a further reduction in the occurrence of jobsite accidents. • The level of housekeeping at a given site is an indicator of safety at that site.
Safety Orientation and Training (Hinze 2005)	<ul style="list-style-type: none"> • Helps workers become aware of project hazards. • The nature of the orientation will help to determine the probable success of delivering a safe project. • The orientation training should be provided to all individuals who will be working on site, including the field employees, subcontractors' employees, and all salaried personnel on site.

Passive safety leading indicators are safety strategies that are generally implemented before the construction phase begins, to set the project up for success (CII 2012). According to Hinze et al. (2013), passive indicators provide an indication of the probable safety performance to be realized within a firm or on a project. They provide information on the extent to which projects have been set up for success (CII 2012). Although passive indicators may be somewhat predictive on a macro scale, they are less effective at being predictive on a short-term basis, which implies that the process being monitored by passive leading indicators cannot generally be altered in a short period of time (Hinze et al. 2013).

Active safety leading indicators are measures of safety strategies made during the construction phase that can indicate the status of safety on the project and trigger adjustments (CII 2012). Active monitoring provides feedback on performance before an accident or incident occurs (HSE 2006). Active leading indicators are those which are more subject to change in a short period of time (Hinze et al. 2013). They give an indication of the safety potential of the project and provide signals when adjustments need to happen to keep the project on course for an incident and injury-free project (CII 2012).

2.4 Near Miss

Safety performance has historically been measured using lagging indicators such as illnesses, injuries, and fatalities that are caused by an unsafe act or hazard (OSHA 2013). The U.S. Department of Labor defines a near miss as an incident where no property damage and no personal injury were sustained, but where, given a slight shift in time or position, damage and injury easily could have occurred (OSHA 2015). Neither the U.S. Department of Labor nor OSHA currently require private companies to report near miss data (OSHA 2011).

Many companies and entities interested in near misses implement near miss reporting programs within their organizations. For instance, The University of Texas health care system implemented their “close-call reporting system” that allows users to anonymously submit reports so as not to be identified by their supervisor (Martin et al. 2005). Close-calls (i.e. near misses) reported in this system are categorized based on human factor principles. The collected data is used to identify and mitigate areas of vulnerability. Examples of the close-call categories include blood transfusion, diagnostic test procedures, equipment and devices, falls, medication, other treatment, surgery, therapeutic procedures, and contributing factors (Martin et al. 2005). This system, like many others, allows for an online entry and database to ensure prompt analysis and dissemination of results (Cabraia et al. 2010).

2.5 Wearable Technology in Construction

Traditional approaches of measuring safety performance indicators are largely manual in nature and based on subjective opinions (Hinze 2005; Teizer and Vela 2009; Hinze et al. 2013). These approaches rely on massive manual data collection efforts; consequently, data is collected at a low frequency (e.g., once a month) and when incidents occur (Navon 2005; Choudhry et al. 2007). Among real-time project monitoring methods, a good number have strong applications for safety. Wearable technology is one of these that can be used to collect and track metrics of safety and health hazards on construction sites in an attempt to enhance safety performance.

The purpose of safety and health monitoring is to ensure there is effective measurement and management of construction workers’ safety practices against the existing safety plans and standards (Seo et al. 2015). Unfortunately, the temporary nature of construction sites and project organizations makes the use of standard industrial monitoring systems impractical for

construction (Navon and Sacks 2007). Active monitoring of workers' physiological data with wearable technology may allow for the measurement of heart rate, breathing rate, and posture (Cheng et al. 2012). Among other engineering application areas, automatically monitoring the location and trajectories of people can be useful for safety, security, and process analysis (Teizer and Vela 2009). Wearable technologies in particular may enable the continuous monitoring of a wide range of vital signals that can provide early warning systems for workers with high-risk health issues (Bonato 2009; Ananthanarayan and Siek 2010).

2.6 Work Zone Safety

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 2015). The limited work space and dynamic environment contribute to the densely-populated nature of highway work zones. A multitude of interactions between pedestrian workers, construction equipment, and passing vehicles occur in roadway work zones. The close proximity of these interactions causes hazardous situations for pedestrian workers and can result in pedestrian worker injury or fatality (Marks and Teizer 2013).

In 2014, highway work zones accounted for nearly 24 percent of non-recurring congestion, or 888 million vehicle hours of delay (FHWA 2016), on U.S. roadways. It is not surprising then, that an average of 595 work-zone-related fatalities have occurred annually the last five years. In addition to fatalities, work zone crashes also cause damage to valuables and injuries to workers (FHWA 2016). These facts indicate the importance of proper safety planning

and management of work zone projects and thus the need for more strategic ways to reduce and eventually eradicate these fatalities and delays.

Although effective, most existing safety tools and best practices are considered passive (e.g. safety cones and guard rails); once installed they do not assist personnel in making real-time decisions. Active sensing and alert devices are needed in highway work zones and in transportation infrastructure construction and maintenance. Continuous data collection of resources (workforce, equipment, material, etc.) can lead to innovative solutions; for example, providing technology to alert construction personnel in real-time when entering hazardous work zones or when getting in close proximity to each other. Overall, little automated data collection and analysis has been performed in monitoring resources and active work zone safety.

2.7 Problems and Research Needs Statement

The review of safety statistics in the construction industry indicates that the industry is still plagued with high rates of injuries, illnesses, and fatalities. Construction companies suffer financial loss, productivity loss, and immeasurable loss such as emotional or crew morale when these accidents occur. These accidents occur because of the harsh and dynamic nature of construction jobsites, the inadequate control of the interactions between workers, and prevalence of moving vehicles and heavy equipment found on construction jobsites and work zones. Controls such as active safety leading indicators (including sensing technologies) that have proven beneficial in other industries have not been efficiently and fully implemented to manage safety in the construction industry. Research and existing practices for hazardous situations in the construction industry are currently lacking in the following areas:

- A functional framework and scientific data for the management of near miss information;

- An evaluation of wearable technology systems for personalized construction safety monitoring and a model for integrating wearable sensors for multi-parameter safety performance monitoring in construction;
- An experimental evaluation of intrusion sensing technologies for highway work zones;
- Strategies for selecting and implementing intrusion sensing technologies for active work zone safety;
- Best safety practices for construction management personnel that allows for the implementation of innovative safety technologies, as well as the use of collected safety indicators data and information in operational procedures, safety training, and education.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter defines the foundational components for this research and describes in detail the methodology for each of the research components. The research objective, scope, and hypothesis as well as the research framework are presented and discussed. The remaining sections within this chapter cover the methodology for the proposed near miss data collection and analysis, evaluation of wearable technology for personalized safety monitoring in construction, as well as the evaluation of the implementation of emerging technologies for work zone safety.

3.1 Introduction

Capturing and analyzing safety leading indicators using a strategic approach including sensing technologies can provide a significant improvement in measuring safety performance. The ultimate goal of this research is to evaluate the benefits of leveraging technology to collect, analyze, and disseminate safety leading indicator information to enhance worker safety performance on construction sites. Automated collection, analysis, and dissemination of safety leading indicator data of specific hazardous situations has the potential to be implemented in construction. This research follows a three-pronged approach, which provides a fundamental and comprehensive understanding of how safety leading indicator data can be collected, analyzed, and disseminated on construction sites. Each interdependent research area is shown in Figure 3.1.

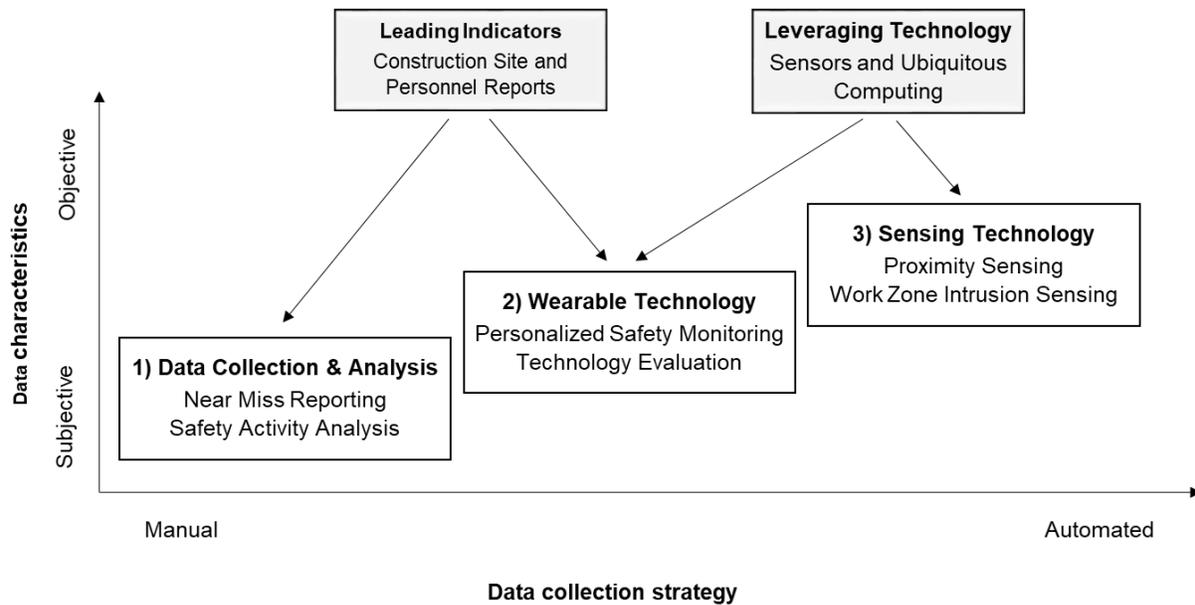


Figure 3.1: Three-pronged research approach

3.2 Research Objective, Scope, and Hypothesis

In order to understand the main objective, secondary objectives, and methodology of this research, certain research components must be defined. These research components are discussed in the following subsections.

3.2.1 Objective

The primary objective of this research is to evaluate the effectiveness of implementing safety leading indicators (including sensing technologies) on construction sites and highway work zones to enhance construction safety performance. To achieve this main objective, the following secondary objectives are proposed:

- Create and implement a near miss data collection and analysis framework to enhance safety performance on construction sites;

- Provide an evaluation of wearable technology systems for personalized construction safety monitoring;
- Create a model for integrating wearable sensors for multi-parameter safety performance monitoring in construction;
- Provide a conceptual analysis and an experimental evaluation of intrusion sensing technologies for highway work zones;
- Provide strategies for selecting and implementing intrusion sensing technologies for active work zone safety;
- Create a set of best practices for construction management personnel that allows for the implementation of innovative safety technologies, as well as the use of collected data and information in operational procedures, safety training, and education.

These secondary objectives are necessary to achieve the overall objective of this research. To achieve these goals, the research work is divided into three major components: 1) near miss data collection and analysis framework for construction, 2) wearable technology for personalized construction safety monitoring, and 3) active work zone safety using emerging technologies.

3.2.2 Scope

The scope of this research covers the evaluation of the effectiveness of implementing safety leading indicators, including sensing technologies, to enhance construction safety performance on construction sites and highway work zones. The scope included private construction companies and government entities involved in funding, regulating, or carrying out construction works in the U.S. Data and information gathered from private construction companies was checked to ensure they do not contain any proprietary information.

3.2.3 Hypothesis

After reviewing the existing research and current practices regarding the level of injuries and fatalities in the construction environment, as well as the insufficient application of safety leading indicators including sensing technologies, the following hypotheses were generated and tested using the research methodology described in this chapter:

- Near miss incidents can be collected and analyzed and scientific data for the management of near miss information can be provided;
- Wearable technology can be implemented for personalized safety monitoring in construction;
- Strategies for selecting and implementing intrusion sensing technologies for active work zone safety can be provided;
- A set of best practices for implementing safety leading indicators including sensing technologies, can be provided to enhance safety performance in construction.

3.3 Research Framework

The research methodology follows a framework that is derived from the need to capture and analyze safety data in order to mitigate injuries, illnesses, and fatalities on construction sites. The framework utilizes the previously mentioned three categories of research (near miss reporting, wearable technology, and work zone intrusion technology) to implement proactive safety performance measurement strategies on construction sites. This approach is geared toward promoting the use of active safety leading indicators and sensing technologies for safety performance measurement. An overview of the research framework is provided in Figure 3.2. Columns of the framework detail conceptual review and program creation, data collection and

analysis, as well as the recommendation and implementation strategy of each research component.

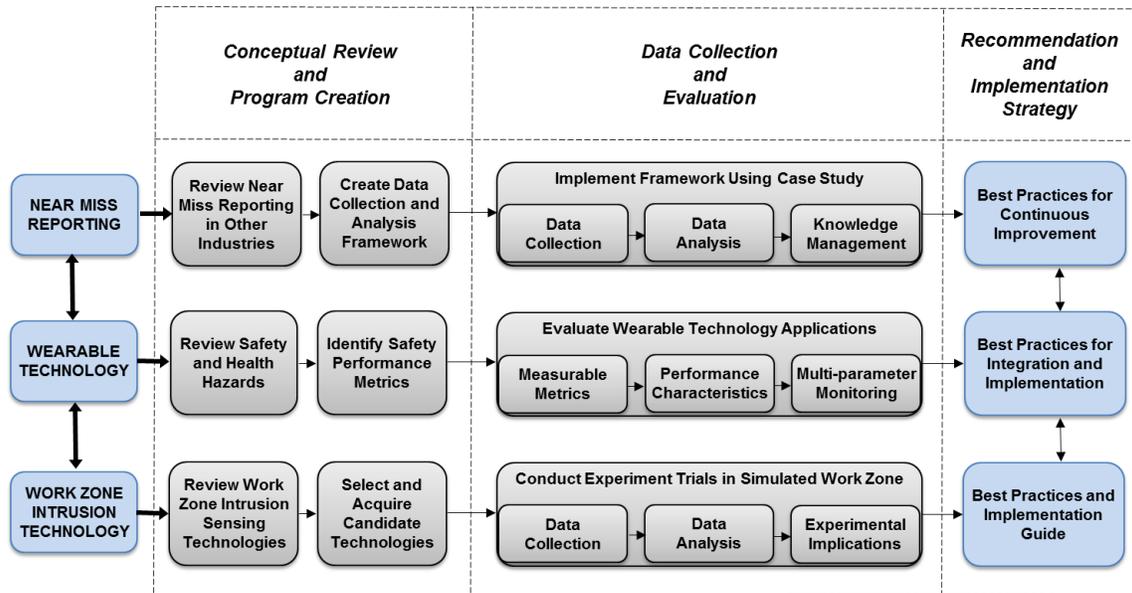


Figure 3.2: Research framework

3.4 Near Miss Data Collection and Analysis

Near miss incidents in the construction environment cover a collection of hazards. A model for a near miss management program called “near miss data collection and analysis framework” was created as the basic methodology for site safety managers and construction management personnel to collect and analyze near miss reports. This framework implemented a management system for near miss data that is a vital component in the data flow within a near miss reporting program. Stages for this framework of converting near miss data into information, and ultimately into knowledge for dissemination, were presented.

A case study for implementing the near miss data collection and analysis framework on a construction project was conducted. In the case study, the number and rate of near miss reporting was tracked fifteen weeks before and after the implementation of the near miss data collection

and analysis framework. The various categories of near miss situations were identified and each category (or nature of incident) was developed from a review of construction safety statistics, previous research, and field experience. The near misses reported were categorized and analyzed. A correlation study using Kendall tau rank correlation coefficient as described in Sen (1968) was used to determine the connection between the number of near misses reported and OSHA defined recordable injuries (within the same workplace and period) after the near miss data collection and analysis framework were implemented.

3.5 Wearable Technology Review

The first step of the procedure employed in this aspect of the research involved reviewing the present state of knowledge of wearable technologies across industries, identifying applicable wearable technology systems and sensors, codifying literature and specifications related to each potential candidate technology, and describing the impact of the human factors on the technology, in accordance with prevailing theory. Construction safety and health hazards were reviewed to identify the metrics that can be captured and processed by the wearable technologies to measure and monitor safety performance. A comprehensive review of each division of safety metrics, the safety performance metrics that can be measured and monitored, and the applicable wearable technology systems and sensors were presented. Additionally, commercially available wearable technology systems and sensors were critiqued based on the performance characteristics required of functional, personalized wearable devices. A model was created for integrating wearable systems and sensors for interoperability and multi-parameter monitoring to capture and track several safety performance metrics.

3.6 Work Zone Intrusion Technologies Evaluation

A review of intrusion sensing technologies from existing research, applications, and manufacturers' documents was conducted to identify the different categories of intrusion technology systems. The different types of applicable intrusion technology devices under each of the categories were identified and assessed using selected evaluation metrics. The review culminated in the selection of candidate commercially available technologies, which were then evaluated using experimental trials to assess their implementation for work zone safety.

The experimental investigation included preliminary testing and field experimental trials. The preliminary testing was first carried out to test if the technologies function and provide the required alerts. Experimental field trials were then carried out to implement the technologies for work zone safety in a simulated work environment. An implementation guide was created for integrating innovative sensing technologies for work zone safety in the construction and maintenance of transportation facilities projects.

CHAPTER 4

NEAR MISS DATA COLLECTION AND ANALYSIS FRAMEWORK FOR CONSTRUCTION

With a high number of workplace injuries and fatalities, the construction industry continues to rank as one of the most hazardous work environments. Much improvement in employee safety performance is still required to achieve zero injuries, illnesses, and fatalities on construction sites. One systematic method of achieving this is through the collection and analysis of safety data such as near misses. This research provides best practices for collecting and analyzing near miss information. A near miss management program for assessing collected near miss data is created so that lessons learned from reported near misses can be applied to mitigate future hazards on construction sites. Results from a construction site case study for the implementation of the created framework indicate that near miss reporting and analysis can enhance workers' safety performance on construction sites.

4.1 Introduction

The construction industry continues to experience a high number of workplace injuries and fatalities when compared to other U.S. industrial sectors. Although the number of fatalities experienced by the construction industry has been declining over the past twenty years, the rate of decrease has been slowing down, becoming almost stagnant in recent years (ILO 2003). As an industry, construction has averaged 1,010 fatalities per year for the past years, indicating that much improvement is still needed to achieve zero injuries, illnesses, and fatalities (BLS 2013a).

One such improvement can be found in the collection and measurement of safety data.

Leading indicators (such as near misses) can proactively assess safety performance using processes, events, and conditions that define performance and can predict future results (Hinze et al. 2013). To achieve the goal of accident prevention programs, a more proactive approach to safety data analysis, including the identification of precursors (such as near misses) and data utilization through improved analytical techniques, is required (Moynihan et al. 2000). The objective of this section is to present the results of research in the development, deployment, and effectiveness of using a near miss management program on construction sites. The intended goals of this section are to present a near miss management program and demonstrate the quantitative effect of the implementation of a near miss management program applied to a multi-billion-dollar construction project and its proof of effectiveness, thus encouraging the use of this methodology in the field.

4.2 Near Misses as Safety Leading Indicators

Since near misses require a meaningful or actionable metric, they are categorized as an active safety leading indicator and must be quantifiable. The requirements for a near miss actionable leading metric include the following: 1) data must be numeric, 2) data must be easily understood, 3) data must be perceived as credible, 4) data must signal the need for action, 5) data must be related to other indicators, and 6) data must not generate unintended consequences (Hallowell et al. 2013). In the past, near misses were reported as single events or instances rather than hours or worker exposure (Hinze and Godfrey 2003). Construction site personnel can be educated on strategies to prevent future accidents through near miss reporting (Cambraia et al. 2010).

All safety leading indicators should have a consistent measurement procedure so that data recorded and analyzed is meaningful to the end user. Such a measurement procedure would include:

- Personnel knowledgeable about the process to be measured;
- Personnel trained to collect information and data in a consistent fashion;
- A defined methodology for information and data collection;
- A defined frequency and schedule for information and data collection;
- Tools formatted for the consistent collection of information and data;
- A repository for the information and data.

4.3 Near Miss Reporting Across Industries

Near miss reporting has been widely used in a variety of industries throughout the U.S. and the world for some time now. A company in the offshore drilling business realized exceptional decreases in lost time accident rates when they implemented a near miss program; they found that a near miss reporting rate of 0.5 near misses/person/year correlated with a 75% reduction in lost time injury rates (Phimister et al. 2003).

The process of collecting and analyzing near miss data has been studied in the chemical process industry (Schaaf and Kanse 2004). The study also investigated human behavior associated with reporting near misses and the associated barriers. Within the chemical processing industry, the U.S. Nuclear Regulatory Commission (NRC) has collected and reviewed near miss reports for nuclear reactors since 2000 (Donovan 2011).

The aviation industry also benefits from the practices of near miss reporting. Aircraft Proximity Hazard (Airprox) is an aviation industry term for a near miss (CAA 2013). The

primary objective of Airprox reporting is to improve flight safety with regards to identified hazards and lessons learned from near miss occurrences. An Airprox is a situation where the distance between aircraft, as well as their relative positions and speed, have been such that the safety of the aircraft involved was compromised (CAA 2013). Safety recommendations were focused on limiting the risk of recurrence of a specific Airprox event.

The Fire Fighter near miss reporting system is another distinct industry adopting near misses as an opportunity to learn. The near miss database is managed by the International Association of Fire Chiefs and funded by the Federal Emergency Management Agency's (FEMA) Assistance to Firefighters grant (IAFC 2015). This anonymous reporting database is designed to accept near miss reports from fire departments from around the country. The database is open for review and the lessons learned and experiences from the firefighting community are shared for any interested parties. A similar database is also available for law enforcement officials (Leo Near Miss 2015).

Another study on near miss reporting in the medical field concerning transfusion medicine (Callum et al. 2001) collected data on human errors and near misses at a blood bank. Three of the most concerning events were 1) samples collected from the wrong patient, 2) mislabeled samples, and 3) requests for blood for the wrong patient (Callum et al. 2001). Similar studies were conducted on nursing home environments as well (Wagner et al. 2006).

The construction industry has been slower to adopt near miss reporting when compared to other industries in the U.S. private sector (Cabraia et al. 2010), but there are some notable exceptions. A large manufacturing company in the United States uses an Autonomous Real-Time Tracking System of Near Miss Accidents (ARTTS-NMA) on construction sites (Caterpillar 2013). This system uses ultrasonic technology for outdoor and indoor real-time location tracking,

sensors for environmental surveillance, Radio Frequency Identification (RFID) for access control and worker information, and wireless sensor networks for data transmission (Wu et al. 2010). The goal is to automatically identify a specific type of hazard as the approximate cause of a near miss event and alert safety personnel before the same situation occurs in the future.

4.4 Research Needs Statement

The Bureau of Labor Statistics (BLS) maintains a database of lagging indicator data including workplace fatalities, injuries and illnesses, but does not require near miss reporting. Several other industrial sectors collect and analyze near miss data for potential safety improvement. Many of these industries maintain an industry-wide near miss reporting database so that all industry personnel can learn from one another's near miss information. Part of the reasons impeding the wide-spread adoption of near miss reporting programs are fear of retaliation, anticipated barriers, and miscommunication that the more near misses are being reported, the poorer safety performance can be expected on the project. Therefore, research is needed to identify the most effective methods for assessing non-injury causing events such as near misses through a review of practices in order to present evidence that near miss reporting programs can have a positive impact in reducing injuries on large construction projects.

4.5 Research Method

The research approach involves the development of near miss data collection and an analysis framework, as well as a case study for implementing the created framework on a construction project. In the case study, the rates of near miss reporting, first aid cases, and recordable injuries as defined by OSHA were tracked fifteen weeks before and after the

implementation of the near miss data collection and analysis system. There was an average of 250 craft workers employed on the project, 24 first-line supervisors, and 4 safety personnel on site. A correlation study using the Kendall tau rank correlation coefficient was used to determine the connection between the number of near misses reported and OSHA defined recordable injuries after the near miss data collection and analysis system was implemented.

4.6 Results and Discussions

The results and discussion of the findings of this research are presented in this section. The created near miss data collection and analysis framework provides a methodology for construction site safety managers and other management personnel to convert the near miss data that was collected into usable safety information. The case study was carried out as an intervention to assess the effectiveness of the near miss data collection and analysis framework in improving safety performance on a construction site.

4.6.1 Near Miss Data Collection and Analysis Framework

This high-level model for a near miss management program is presented as the basic methodology for site safety managers and construction management personnel to collect, analyze, and use safety data in an effective environment. This framework implements a management system for near miss data and can be a vital component in the data flow within a near miss reporting program. Stages for this framework of transitioning near miss data to information and ultimately knowledge for dissemination are presented in Figure 4.1 and further described below.

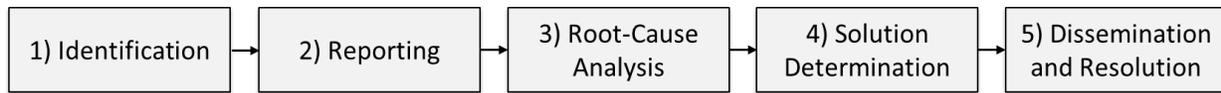


Figure 4.1: Stages for near miss data collection and analysis framework

4.6.1.1 Step 1: Identification

This step occurs when construction site personnel recognize an unsafe event or set of conditions on a construction site. Employees should be trained to identify near misses and how they differ from lagging indicators (e.g. injuries and illnesses). If the near miss is of high severity or danger is imminent, the worker should execute the stop work authority and mitigate any hazards immediately.

Similar to hazard identification, construction workers should be trained as an extension of existing safety training programs to identify and report near miss events. For example, when workers are educated about proper Personal Protective Equipment (PPE) for working at heights, they should also be instructed on how to identify and report cases in which fellow workers are not wearing PPE while working at heights. The success of a near miss reporting program largely depends on the ability and motivation of individuals to identify and report near misses on construction sites.

4.6.1.2 Step 2: Reporting

Construction site personnel that identify a near miss must report the event to their immediate supervisor through a near miss reporting system. This reporting system can either use electronic or paper-based reporting depending on the construction site constraints. Both systems should allow for anonymity of employees if they so choose. Both system options must be accompanied with database capabilities to house the collected near miss data. Although required

near miss report criteria may vary between companies, a set of standard criteria is essential for each report (e.g. company name, event date, time, location, description). Automated near miss reporting programs allow for photos with the report. Additional information might include recording the supervisor's name, job/craft, possible consequences, corrective measures taken, whether further action is required, and whether the event was reported to the observer's supervisor.

4.6.1.3 Step 3: Root-Cause Analysis

Determining the factors that contributed to the near miss occurrence is the next step in the evaluation process. When the near misses are being reported, it is important that a consistent measure of categorization is used so that similar near misses are categorized accordingly, regardless of who is taking in the report. One such categorization scheme was initially used by van der Schaaf (1992) in his doctoral thesis work, *Near Miss Reporting in the Chemical Process Industry*. A construction-specific Eindhoven Classification Model (ECM) was developed for the categorization of the near misses. The types of categories are classified as either a skill-based, rule-based, or knowledge-based factor (see Table 4.1).

Table 4.1: Eindhoven Classification Model (ECM) for human errors in construction

Factor	Category	Definition
Skill-based	Slips	Failure in highly developed motor skills such as using a hammer but missing the nail.
	Tripping	Failure in whole body movements such as climbing a ladder, tripping on even ground, swinging arm, or kicking something.
Rule-based	Qualifications	Asking someone to do something in which they have limited experience or knowledge.
	Coordination	A lack of coordination between two construction groups such as walking into a barricaded area or groups not coordinating with each other on work assignments.
	Verification	The incomplete assessment of something on the worksite such as using equipment which hasn't been inspected or using the wrong materials at the wrong time.
	Identification	Failures that result from faulty task planning such as hazards not identified on the job safety analysis (JSA) or hazardous conditions that remain unrecognized.
	Monitoring	Improper identification controls such as checks or calibration.
	Compliance	Procedure which are not followed, off task, or shortcuts.
	Construction	Correct design which was not constructed properly or was set up in inaccessible areas and not constructed to plan.
	Protocol	Failures relating to the quality and availability of the protocols within the department (too complicated, inaccurate, absent or poorly presented).
Knowledge-based	Knowledge	Inability of a person to apply their existing knowledge to a new situation, for example they were unaware of a rule.
Other	External	Technical failures beyond the control and responsibility of the investigating organization.
	Mechanical	Failures involved with mechanical issues beyond the control of the personnel in the field.
	Culture	Failures resulting from collective approach and its attendant modes of behavior to risks in the investigating organization.

4.6.1.4 Step 4: Solution Determination

Once near misses have been categorized, solutions are presented taking into account the severity and consequences of the preceding near miss events. Simple, non-complex or life-threatening events are treated as an exchange of information. More significant events are treated differently but only after threats to life safety are removed and the site is rendered safe. These more complex events may involve changes in strategy on site and may involve the use of

systematic root-cause analysis methods or work groups in order to find resolution. A simple human error determination using the ECM, in many cases, will direct the type of remedial actions needed in the field to prevent recurrence of the unsafe condition or behaviors.

4.6.1.5 Step 5: Dissemination and Resolution

The corrective actions, ideally, will have been employed in the field following the near miss events and the work area will have been left in a safe state. In many cases, the reported near miss may not have required a “stop work” action or other lifesaving measures. The incident may have happened, been corrected, and workers in the area will have continued their jobs. If a near miss happens, but is not reported, then the lesson learned is only of consequence for those in the immediate area. The broader audience (including all other site personnel) should be informed of the reported near miss and corrective actions taken; both of these steps should be communicated as soon as possible (i.e. the next day’s tool box talks if possible). Figure 4.2 presents the flow of information for a single reported near miss.

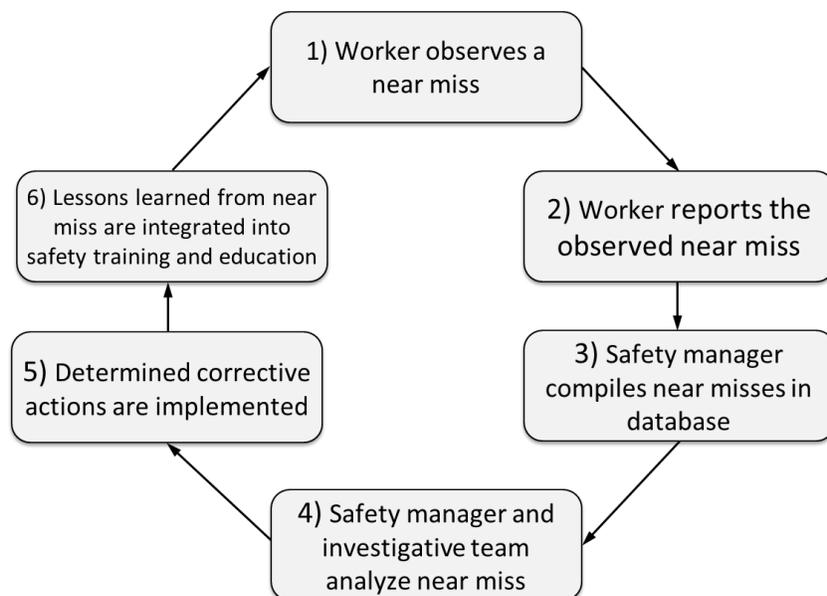


Figure 4.2: Flow of near miss information

Safety managers should integrate learned lessons from the reported near miss into existing safety training. This step allows for the worker who reported the near miss to receive feedback on how the situation was corrected. By educating construction site personnel from other projects on lessons learned from near misses, safety performance of workers can be enhanced.

4.6.2 Case Study

A near miss data collection and analysis system was implemented on a large-scale Liquefied Natural Gas (LNG) construction project located in North America. The multi-billion-dollar Engineer-Procure-Construct (EPC) project had a sophisticated, mature safety program, and recordable and lost-time rates that were stable and low [compared to other construction projects in their North American Industry Classification System (NAICS)] but nonetheless stagnant.

The rates of near miss reporting, first aid cases, and other recordable injuries as defined by OSHA were tracked fifteen weeks before and after the implementation of the near miss data collection and analysis framework. The Mann-Whitney statistics (Ruxton 2006) were used to correlate collected safety data. The rates of near miss reporting increased significantly after the implementation of the framework. No statistically significant change was experienced between the values of first aids experienced before and after implementation. However, the number of OSHA recordable injuries differed after the implementation of the near miss data collection and analysis framework. A correlation study using the Kendall tau rank correlation coefficient (Sen 1968) identified the connection between the number of near misses reported and OSHA defined recordable injuries after the near miss data collection and analysis framework was implemented (see Table 4.2). Values marked in italicized font denote a correlation value that is statistically

significant at the 0.05 level (1-tailed test). The numbers marked in bold show a correlation value that is statistically significant at the 0.01 level (1-tailed test).

Table 4.2: Correlation coefficient analysis

		Near Misses Reported	First Aid Count	OSHA Recordable Injury Count	First Aid Rate	OSHA Recordable Injury Rate
Near Misses Reported	Correlation Coefficient	1.000	<i>-0.281</i>	-0.373	-0.207	<i>-0.320</i>
	Significance (1-tailed)		0.019	0.008	0.056	0.014

Significant differences were identified between the number of first aid reportable cases before and after the implementation of the near miss data collection and analysis system. The significance of the increase in near miss reported allowed for a favorable testing situation where it was theorized that an increase in near miss reporting would impact the rates of first aid cases and recordable injuries in a negative correlation. Significant differences were also identified between the measures of near miss reporting after the implementation of the framework on the construction site. The project experienced a 100% decrease in OSHA recordable cases during the time of the near miss intervention. The increased reporting of near misses experienced was attributed to management’s investment and ownership of the implemented program as well as a significant effort to educate employees about the near miss program, including training on identifying near misses, the reporting process, and benefits of reporting. No incentives were provided to employees for quantity or quality of near miss reports.

The rates of near misses reported were found to be negatively correlated with the number of recordable first aid cases ($r(30) = -0.281, p < 0.05$) and the counts of recordable injury cases ($r(30) = -0.373, p < 0.01$). The rates of near misses reported were found to be less correlated with recordable first aid cases than with recordable injury cases. One possible explanation for

this could be that first aid cases seem to have a more random distribution. A first aid case could include dust blown into the eye, treatment for a bug sting, a heat rash, or any other conceivable event that could befall a person while at work. Recordable injuries are events that are more action oriented and usually are the result of a larger release of energy such as a slip and fall, hitting one’s thumb with a hammer, or suffering a laceration while at work. This could be further investigated by research stemming from this initial attempt.

The ECM adopted for construction safety was used to categorize near misses reported. Types and frequencies of near misses reported after the near miss data collection and analysis system implementation are shown in Table 4.3. The number of incidents per category of pre-implementation and post-implementation of the near miss data collection and analysis framework are also presented in Table 4.3.

Table 4.3: Near miss categorization using Eindhoven Classification Model (ECM)

Causal Factor	Categories	Frequency		Total Frequency	Percent
		Pre-Implementation	Post-Implementation		
Skill-based	Slips	9	41	50	4.5
	Tripping	7	17	24	2.2
Rule-based	Coordination	5	118	123	11.0
	Verification	10	56	66	5.9
	Identification	21	264	285	25.6
	Monitoring	0	4	4	0.4
	Compliance	37	478	515	46.2
	Construction	5	6	11	1.0
	Protocol	0	1	1	0.1
Knowledge-based	Knowledge	3	8	11	1.0
Other	External	2	1	3	0.3
	Mechanical	5	15	20	1.8
	Culture	0	1	1	0.1
Total				1114	100.0

The top five near miss categories were identical across the pre-intervention and post-intervention samples and are reported in order from highest to lowest: compliance, identification, slips, trips, and verification (McKay 2013). In view of this, a safety and health management program would have a target rich environment in considering where to apply limited resources, considering that the top five near miss types are related to human error and are active errors, but this needs to be tested on other projects.

4.7 Conclusion

The strength of the near miss reporting data collection and analysis system lies in its ability to generate useful safety information for a given construction site. During this evaluation period, near miss information was consistently presented to the entire workforce in the form of plan-of-the day meetings, toolbox talks or other similar pre-work task planning sessions. The ability to collect, analyze, and disseminate safety information allows for hazardous events and conditions to be mitigated before a lagging indicator occurs.

The primary contribution of this section of the research is the correlated link between the number of near misses collected and the decreased incidents of first aid cases and recordable injuries on a construction site. The ECM was modified to categorize near miss events specific to construction sites for the first time, at least at the time of this publication. This initial research step provides a foundation for future research in near miss reporting on construction site injuries. Future research could include correlating near miss reporting to expected severity and risk exposure and the creation of predicted variables or outcomes.

CHAPTER 5
WEARABLE TECHNOLOGY FOR PERSONALIZED CONSTRUCTION SAFETY
MONITORING

The construction process is considered a very risky endeavor because of the high frequency of work-related injuries and fatalities. The collection and analysis of safety data is an important element in measurement and improvement strategy development. The adoption of wearable technology has the potential for a result-oriented data collection and analysis approach in order to provide real-time information to construction personnel. The objective of this research is to provide a comprehensive review of the applications of wearable technology for personalized construction safety monitoring. The characteristics of wearable devices and safety metrics thought to be capable of predicting safety performance and management practices are identified and analyzed. The review indicates that the existing wearable technologies applied in other industrial sectors can be used to monitor and measure a wide variety of safety performance metrics within the construction industry. Benefits of individual wearable sensors or systems can be integrated based on their attributes for multi-parameter monitoring of safety performance.

5.1 Introduction

The high rate of fatalities in the construction industry remains a major concern of both practitioners and researchers. Out of 4,386 total worker fatalities in private industry in 2014, 899 were in construction, indicating that over one in five worker deaths are construction related

(OSHA 2016; BLS 2016a). Among industry sectors, workers in construction face the highest risk of occupational injuries and illnesses (OSHA 2017). Despite the adoption of safety procedures and programs such as those developed and required by the Occupational Safety and Health Administration (OSHA), the rates of fatal and non-fatal construction injuries and illnesses have plateaued the past 10 years.

Given the high proportion of fatal and non-fatal accidents occurring in the construction industry, construction companies constantly seek novel strategies that promote safety (Demirkesen and Arditi 2015). Because of the transient and dynamic nature of construction, organizations must be able to quickly adapt to change by effectively capturing, storing, and disseminating new strategies that prevent injuries (Hallowell 2012). Thus, new technologies may be candidates for safety advancement. Although technology has undoubtedly played a major role in the improvement of construction processes, its application for personalized construction safety monitoring has not been fully explored (Cheng et al. 2012).

In this section, the various applications of wearable technology for personalized construction safety monitoring and trending are reviewed. The specific objectives were to identify, catalog, and analyze attributes of wearable technology and resulting data thought to be capable of predicting construction safety performance and management practices.

5.2 Wearable Technology Systems and Sensors

Wearable technologies are based of different systems ranging from radio-frequency identification (RFID), magnetic field, radar, ultra-wide band (UWB), ultrasonic, sonar, Bluetooth, Global Positioning System (GPS) (from Global Navigation Satellite System (GNSS)), laser, video and static camera, electrocardiogram (ECG/EKG), and electromyography (EMG).

Sensors like galvanic skin response (GSR), accelerometers, gyroscopes, and magnetometers constitute a body sensor network. The evolution of digital and mobile technology has transformed many aspects of our lives with many examples that demonstrate the current and potential uses of wearable technology in the field of healthcare (Sultan 2015). Innovations in sensor technology have been essential to the implementation of body sensor networks and have been combined with progress in short-range communication technologies such as ultra-wideband radio technology and Bluetooth which have enabled the implementation of wearable computing devices (Bonato 2010).

5.3 Wearable Technology in Other Industries

Different categories of wearable technology have been applied across industries such as health care, manufacturing, mining, and athletics. Some of these technologies have shown signs of positive benefits (Anzaldo 2015) and efforts are being made by both researchers and industry experts to improve on these technologies and learn from their initial implementation.

With the advent of computing platforms with low power consumption and low cost sensors, wearable technology has been increasingly used in health-related research to promote physical activity (Ananthanarayan and Siek 2010). Significant progress in computer technologies, solid-state micro sensors, and telecommunication has advanced the possibilities for individual health monitoring systems to collect and analyze human physiological metrics. A variety of compact wearable sensors is currently available (Bonato 2009; Beecham Research 2016). Advances in miniature sensors and wireless technology have made available a new generation of monitoring systems that allow one to record physiological data from individuals carrying on daily activities in the home and outdoor environments (Bonato et al. 2003).

Similarly, remote patient monitoring allows people to keep track of their health while avoiding unnecessary visits to the doctor.

In the business sector, several companies took inspiration from the seminal work achieved by researchers at the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA-JPL) and developed systems-based body sensor networks for commercialization (Bonato 2009). One such device provides wellness applications, wireless activity monitors, and health tracking devices that continuously track data such as heart rate, activity, respiration, body temperature, and posture in order to lower healthcare costs and increase productivity (Silverstein 2014; Hamshar 2014). These applications are geared toward increasing knowledge transfer, productivity, and security within business operations including controlled access, customer services, remote supervision, and stock allocation (Maddox 2014; Beecham Research 2016).

In sports and fitness, wearable technologies are being used widely for tracking performance through smooth and unobtrusive measurements (WTIWC 2015). Wearable technologies such as GPS watches, heart rate monitors and pedometers are commonly used to obtain real-time information about performance (Darwish and Hassanien, 2011; WTIWC 2015). Wearable technology is being incorporated into a multitude of equipment used by professional athletes to monitor not only their performance, but also their safety (Guta 2014). For example, sensors are used in the helmets of National Football League (NFL) players to detect concussions and smart compression shirts that have been wired to measure arm movement and technique to determine a pitcher's effectiveness in Major League Baseball (MLB). Also, wristband wearable GPS sport watches are commonly used in the game of golf during practice sessions to improve swing mechanics (Anzaldo 2015). Other existing applications of wearable technologies in the

sport and fitness sector are related to an active lifestyle, including fitness monitoring, outdoor navigation, body cooling and heating, virtual coaching, and sport performance (Beecham Research 2016).

In security applications, police officers, firefighters, and paramedics are testing wearable technologies to provide remote communication support and feedback with the ability to access information hands-free while carrying out essential tasks (Friedman 2015c). Additionally, for personal security, lighting technologies and protective clothing are being used to enhance visibility and attract attention.

In the mining industry, a proximity warning system (PWS) based on the GPS and peer-to-peer communication was also developed to prevent collisions between mining equipment, small vehicles, and stationary structures (Ruff and Holden 2003). The concept of GPS-based proximity warning for mining equipment entails the use of differential GPS receivers so that the equipment operators are aware of other vehicles or workers nearby.

Wearable technologies are also increasingly influencing people's daily activities in terms of gaming and in the tools used to operate household devices or other gadgets used in communicating (WTIWC 2015). This technology involves applications related to interacting with computing resources, including data/media access, interactive gaming, responsive learning, and shared experience (Beecham Research 2016).

5.4 Wearable Technology in Construction

As opposed to other industries, the application of wearable technology in construction is at the nascent stage. In fact, there are very few documented cases of application of wearable technology in the construction industry (Cheng et al. 2012). One of the very few applications

was the evaluation of a method for testing proximity detection and alert systems to promote safety on construction sites (Marks and Teizer 2012; Wang and Razavi 2016; Fang et al. 2016). Also, hands-free systems were employed to monitor workers and increase their situational awareness by continuously collecting data on the jobsite, detecting environmental conditions, and the proximity of workers to danger zones (Friedman 2015a). The lack of wide-spread implementation is due, in part, to a lack of reliable data supporting their potential benefits.

Recently, the construction industry has begun to use mobile devices to access and share project data from remote work sites (Friedman 2015b). Although the construction industry may have been slow in adopting trends in mobility and automation tools and other technologies that can increase efficiency (Friedman 2015b), wearable technologies could uncover possibilities for improvement in construction (Kallie 2016). Thus, there is great potential for the implementation of wearable technology for personalized safety monitoring in the construction industry.

5.5 Research Needs Statement

In the construction industry, workers are exposed to hazards that are difficult to measure for reasons closely related to the way construction tasks are executed. Not only does the location for any group of workers change, each construction site evolves as construction proceeds, changing the hazards workers face on a daily basis (McDonald et al. 2009). Most of the existing data collection approaches are manual and are faced with major challenges related to accurate recording, interpretation, and efficiency (Teizer and Vela 2009). Wearable technologies offer a non-intrusive solution that provides objective, real-time data that can be used to make efficient and proactive decisions. Wearable technology adopts a concept of a safety management system that enables workers to monitor and control their health profile via real-time feedback, so that the

earliest signs of safety issues arising from health problems can be detected and corrected (Sung et al. 2005). Wearable sensors can also provide safety managers with quantitative measures of subjects' status on construction sites, thus facilitating decisions made concerning the adequacy of ongoing interventions and possibly allowing for prompt modification of the strategy if needed (Bonato 2009). Despite the potential benefits of such strategies, few approaches have been identified in the literature and there is yet to be an organized effort to collect and investigate these methods (Hallowell et al. 2013).

This research contributes to the body of knowledge by providing a comprehensive review of wearable technology systems and examining their application potential for personalized construction safety monitoring and trending. This study also provides an evaluation of the features of wearable devices, the safety data that can be obtained, and the potential benefits of using wearable technology to mitigate injuries and illnesses on construction sites.

5.6 Research Method

This research was conducted by first reviewing the present state of knowledge of wearable technologies across industries, collating literature and specifications related to each of the technology systems and sensors candidates, and describing the impact of the human factors on the technology, in accordance with prevailing theory. The construction safety and health hazards were reviewed to identify the metrics that can be captured and processed by the wearable technologies to measure and monitor safety performance. The literature review revealed four divisions of measurable safety performance metrics: 1) physiological monitoring; 2) environmental sensing; 3) proximity detection; and 4) location tracking. A comprehensive review of each of these four divisions, the safety performance metrics that can be measured and

monitored, and the applicable wearable technology systems and sensors is presented. Additionally, commercially available wearable technologies were critiqued based on the performance characteristics required of functional personalized wearable devices. An online search was carried out to identify the leading manufacturers of wearable technologies as well as documented research on wearable technology applications across the globe. Information about wearable devices from the manufacturers' specifications documents and published research works were collected and evaluated. A model for the integration of the different wearable systems and sensors into the design of functional wearable devices for personalized safety performance monitoring in construction was also presented and discussed. A framework showing the review methodology adopted in this research is illustrated in Figure 5.1.

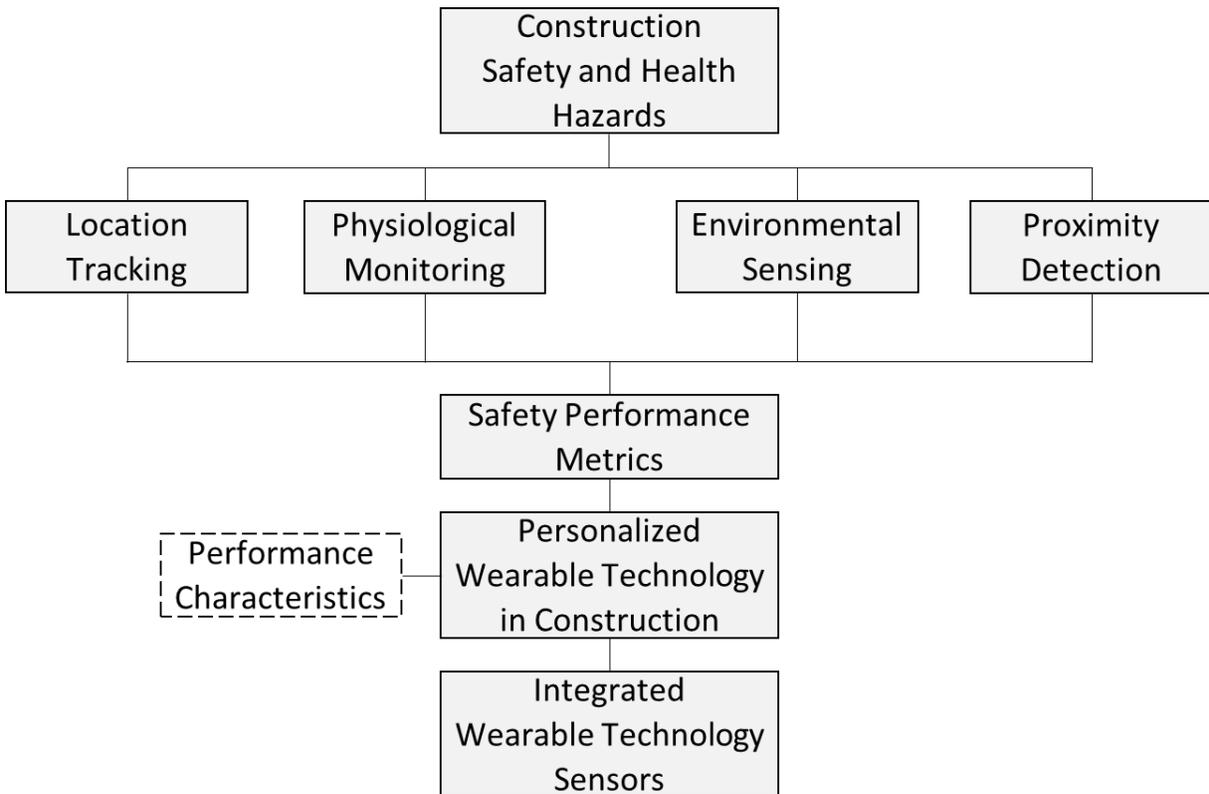


Figure 5.1: Review framework for wearable technology in construction

5.7 Results and Discussion

The results of this review study are presented and discussed in different sections based on the research methodology framework. Critical findings of each review, including the wearable technology systems and sensors thought to be the most promising for applications in construction safety monitoring and trending, are presented.

5.7.1 Construction Safety and Health Hazards

About 6.5 million people work at approximately 252,000 construction sites across the U.S. on any given day (OSHA 2017). These workers are exposed to a variety of safety and health hazards that increase the potential for becoming sick, ill, and even disabled for life. The fatality injury rate for the construction industry is higher than the national average in this category for all industries (BLS 2016b; OSHA 2017). Injury and illness rates on construction sites have been on the rise over the past five years (BLS 2015a). Some of the potential safety and health hazards for construction workers include falls from heights due to improper erection of scaffolding or use of ladders; repetitive motion injuries; heat exhaustion or heat stroke due to body temperatures rising to dangerous levels; and being struck by moving equipment working in close proximity to workers (OSHA 2017). Table 5.1 presents these safety and health hazards as well as the measurable metrics associated with the hazards. The corresponding divisions of the measurable safety performance metrics are also provided for proper deployment of wearable technologies for the collection and analysis of the metrics required for the mitigation of the hazards.

Table 5.1: Safety performance metrics for construction safety and health hazards

	Construction Site Hazards		Metrics
	Safety Hazards	Health Hazards	
Physiological Monitoring	Slips, trips, and falls from height.	Stress, heat, cold, strain injuries (carpal tunnel syndrome, back injuries), skin diseases (absorption), cuts (injection), breathing or respiratory diseases, toxic gases.	Heart rate, heart rate variability, respiratory rate, body posture, body speed, body acceleration, body rotation and orientation, angular velocity, blood oxygen, blood pressure, body temperature, activity level, calories burn, and walking steps.
Environmental Sensing	Slips, trips, fire and explosions.	Chemicals (paints, asbestos, solvents, chlorine), molds, noise, heat, cold, radiation, vibration, toxic gases.	Ambient temperature, ambient pressure, humidity, noise level, light intensity, air quality.
Proximity Detection	Caught-in or -between, Struck-by moving vehicle or equipment, electrocution.	Chemicals (paints, asbestos, solvents, chlorine), molds, noise, heat, cold, radiation, vibration, toxic gases.	Object detection, navigation, distance measurement, and proximity detection.
Location Tracking	Caught-in or -between, Struck-by, confined spaces, cave in, electrocution.	Chemicals (paints, asbestos, solvents, chlorine), molds, noise, heat, cold, radiation, vibration.	Worker location tracking, materials tracking, and vehicle/equipment location tracking.

5.7.1.1 Physiological Monitoring

One application of wearable systems is the monitoring of physiological parameters in a mobile environment (Anliker et al. 2004). For instance, wearable devices targeting the sport and recreational market have been very successful. Wearable devices offer many benefits to professional athletes, amateur athletes, fitness consumers, and wellness programs. Some of these benefits include player safety assessment tools, workout injury prevention, and metrics of physical conditioning and performance (Anzaldo 2015). Recent technological advances in integrated circuits, wireless communications, and physiological sensing allow miniature,

lightweight, ultra-low power, and intelligent monitoring devices for health monitoring. A number of these devices can be integrated into a wireless body area network (WBAN), a new enabling technology for health monitoring (Jovanov et al. 2005).

Construction site workers often encounter various health risks as a result of the austere and dynamic work environments that can impact the safety performance and overall performance of construction workers (Gatti et al. 2011; Awolusi and Marks 2016). Commercially available physiological status monitoring (PSM) systems can reliably collect physiological properties of people in outdoor environments (Gatti et al. 2011). For example, it has been demonstrated that physiological data such as heart rate, breathing rate, body posture, body speed, and body acceleration can be automatically recorded and analyzed using a PSM system and GPS tracking device to assess construction equipment operator's health (Awolusi et al. 2016; Shen et al. 2017). An extensive set of physiological sensors may include an ECG/EKG (electrocardiogram) sensor for monitoring heart activity, an EMG (electromyography) sensor for monitoring muscle activity, an EEG (electroencephalography) sensor for monitoring brain electrical activity, a blood pressure sensor, a tilt sensor for monitoring trunk position, a breathing sensor for monitoring respiration, and movement sensors used to estimate user activity (Jovanov et al. 2005). These metrics give an indication of a construction worker's stress level and health status that are measures of safety performance of the workers.

Based on the commercially available wearable technologies reviewed, the ECG/EKG sensors seem to have wider use in the monitoring and measurement of physiological metrics. The ECG/EKG measures heart rate, heart rate variability, respiratory rate, blood pressure, and body temperature. An electrocardiogram (ECG or EKG) is a test that checks for problems with the electrical activity of the heart. It shows the heart's electrical activity as line tracings on paper. It

is one of the most widespread systems for the monitoring of cardiac activity and the information provided by an ECG is related to heart electrical activity (Zito et al. 2008). The review also shows that infrared technology is another system used in wearable sensors to monitor and calculate heart rate, analyze activity level, and track fitness performance. Infrared wireless is the use of wireless technology in devices or systems that convey data through infrared radiation. Infrared is electromagnetic energy at a wavelength or wavelengths somewhat longer than those of red light. According to the review, the commercially available infrared sensors are often used in conjunction with Bluetooth technology for connectivity and they are compatible with common operating systems for mobile devices such as Android and iOS. For example, in the smart shirt technology, the Bluetooth technology enables the data detected from the smart shirt to be delivered to a Personal Digital Assistant (PDA) and analyzed (Cheng et al. 2004). Radar systems have also been used in the monitoring of heart activity in a non-invasive and contactless way for the patient. Microwave Doppler radars have been used to detect the respiratory rate (Zito et al. 2008).

A gyroscope may be used to determine the rotation of different parts of the body. The review indicates that gyroscopes monitor activity by measuring body rotation and angular velocity while magnetometers (i.e. magnetic field sensors) are useful in determining orientation relative to the earth's magnetic north. The gyroscope, accelerometer, and magnetometer are usually combined because each of the sensors has its own unique strength. For instance, a magnetometer has poor accuracy for fast movement, but with zero drift over time, while a gyroscope reacts quickly to changes. Recently, some inexpensive in-chip inertial sensors, including gyroscopes and accelerometers, have gradually found practical applications in human motion analysis (Liu et al. 2010). The technology of Micro Electro Mechanical Systems

(MEMS) boosts the development of miniature and low-powered inertial sensors, accelerometers and gyroscopes in order to analyze human movement based on kinematics (Zhang et al. 2011). As a skill assessment and acquisition tool, gyroscope sensors have been used as wearable devices to determine the peak of the upper arm internal rotation, wrist flexion, and shoulder rotation during the forward motion of tennis athletes (Ahmadi et al. 2010). Gyroscopes appear to be more reliable in the measurement of angles, therefore, can more accurately identify functional activities and the emerging movement patterns (Wagenaar et al. 2011). In addition, it has been argued that the combination of different technologies provides the most optimal activity monitor platform.

Patel et al. (2012) reported that when wearable sensors are used to improve balance control and reduce falls, data analysis procedures could be exclusively developed to detect falls via processing of motion and vital sign data. In this situation, ambient sensors could be used as wearable sensors to improve the accuracy of falls detection (Patel et al. 2012). Bourke et al. (2008) used a tri-axial accelerometer embedded in a specially made vest to detect falls, while Bianchi et al. (2010) implemented a barometric pressure sensor as an alternative measure of altitude to differentiate real fall events from normal activities of daily living. Yavuz et al. (2010) also developed a fall detection system that relied upon the accelerometers available in smart phones and incorporated different algorithms for robust detection of falls. Some researchers have also developed an automatic fall detection system in the form of a wrist watch (Patel et al. 2012). This device implements functionalities such as wireless communication, automatic fall detection, manual alarm triggering, data storage, and a simple user interface (Patel et al. 2012).

The evaluation of the existing wearable technologies also reveals that there is a limited application of ultrasound technology for the monitoring of physiological metrics in construction.

For example, Lewis et al. (2013) designed and evaluated a wearable self-applied therapeutic ultrasound device that can be worn by construction workers on their shoulder to reduce chronic myofascial pain. Ultrasonic sensors have also been developed for monitoring muscle contraction.

The review also identified the capabilities of ANT+ in enabling effective communication between wearable systems for the monitoring of physiological metrics (such as heart rate, calorie burn, and workout). ANT+ is a wireless sensor network protocol, designed to enable communications between self-powered devices in an extensible network environment, easing the collection, automatic transfer and tracking of sensor data for monitoring of all personal wellness information (Belchior et al. 2013). ANT+ helps the devices to interoperate and build an ecosystem by implementing device profiles which are ANT+ protocol-branded standards (Mehmood and Culmone 2016). Current ANT+ profiles are available for the following devices: heart rate monitor, foot pod, bicycle speed and cadence, bicycle power, weight scale, multi-sport speed and distance (Belchior et al. 2013). With ANT+, multiple applications can be run simultaneously using different sensors. For instance, running distance can be tracked with one application while blood glucose level is concurrently monitored with another application.

5.7.1.2 Environmental Sensing

The nature of the construction work environment is such that it poses both health and safety risks to workers. This is not only because most of the activities are performed outdoors, making workers experience considerable exposure to weather elements, but the construction processes also involve the use of hazardous materials in form of chemicals, gases, and solid materials. Automated sensing of these injurious materials and inclement weather elements is necessary. The monitoring of environmental parameters in a diffused fashion is of paramount

interest in various fields such as environmental safety, health, and security purposes. A lot of work has been completed on the development of smart sensors and wireless sensor networks based on silicon technology, targeting different types of application (Briand et al. 2011). For instance, making sensors small, Bluetooth or Wi-Fi enabled, and easily worn by workers performing their normal daily activities can considerably increase the amount and precision of environmental data (Treacy 2013), particularly in the construction environment which is ever-evolving.

More generally, it is now possible to use environmental sensors to measure a range of concerns, including air quality, barometric pressure, carbon monoxide, capacitance, color, gas leaks, humidity, hydrogen sulfide, temperature, and light (Swan 2012). The capacitive sensor has been applied in different systems as a stud finder, a liquid level monitor, or a proximity monitor. Various sensing principles have been integrated on a polyimide foil, such as capacitive and resistive read-outs for the detection of several types of environmental parameters, including temperature, humidity, reducing and oxidizing gases, and volatile organic compounds (VOCs) (Briand et al. 2011). These sensors on plastic foils are required to realize intelligent RFID tags for environmental monitoring.

There are also integrated environmental sensors that support a broad range of emerging high-performance applications such as navigation, barometric air pressure, humidity, ambient air temperature sensing functions, and air quality measuring (Bosch Sensortec 2017). Some of these sensors are specifically designed for various applications in the field of mobile devices and wearable technologies, and can be implemented in construction. Workers can be monitored while doing their normal work while at the same time having the ability to see highly localized, real-time data on things like temperature, hazardous gases, particulate levels in the air and possible

toxic chemical leaks (Treacy 2013). Other environmental sensors that can be used in wearable devices are gyroscope, light sensors, noise sensors, humidity sensors, temperature sensors, and gas sensors, among others (Sensirion 2017).

5.7.1.3 Proximity Detection

Considering the high rate and severity of contact injuries, there is need for strategic monitoring and analysis of the states of construction entities so that potential collisions can be prevented in a timely manner (Wang and Razavi 2016). The construction industry needs a wireless, reliable, and rugged technology capable of sensing and alerting workers when hazardous proximity issues exist (Marks and Teizer 2012). Moreover, the advancements of sensing technologies greatly prompt the development of collision avoidance systems (Wang and Razavi 2016). A real-time proximity detection and warning system capable of alerting construction personnel and equipment operators during hazardous proximity situations is needed to promote safety on construction sites (Marks and Teizer 2012).

Many proximity avoidance systems have been developed by utilizing various technologies, such as an ultrasonic-based sensor (Choe et al. 2014), radio frequency (RF) sensing technology (Chae and Yoshida 2010; Teizer et al. 2010), radar (Choe et al. 2014; Ruff 2006), and a GPS (Oloufa et al. 2003) to prevent contact accidents, particularly for accidents due to being struck by equipment.

The review of the existing wearable technologies shows RFID to be the most commonly used system for proximity detection. RFID is the projection of radio waves and signals to transmit data and conduct wireless data retrieval and storage to identify the status of workers and object contents (Yin et al. 2009). It consists of two components, a unique identification tag

installed onto or into the object to be identified and a reader or tag detector that senses for the unique transmitted frequency and ID of a tag (Ruff and Hession-Kunz 2001). No direct contact between a RFID reader and the tagged item is needed as it uses radio waves that can be classified as low, high, ultrahigh frequencies (UHF) ranging from 125 kilohertz to 5.875 Giga Hertz. According to Roberts (2006), three frequency ranges are generally used for RFID applications. In general, low-frequency passive tags have an effective range of approximately 30 centimeters, high-frequency passive tags around 1 meter, and UHF passive tags from 3 meters and 5 meters. Where greater range is needed, such as in container tracking and railway applications, active tags can boost the signal to a range of 100 meters. This review also indicates that a wearable RFID technology could have up to a 500 meter (1500 feet) read range. This “read range” is far greater than the 15 to 25 meters obtained from the RFID technology 10 years ago by Goodrum et al. (2006) in their study. In addition to reading data, it is possible to write data back to the RFID tag, which greatly increases the interaction between items, system, and people. The principal advantages of the RFID system are the non-contact, non-line-of-sight characteristics of the technology. Tags can be read through a variety of visually and environmentally challenging conditions such as snow, ice, fog, paint, grime, inside containers and vehicles and while in storage (Roberts 2006). All these advantages enable better real-time information visibility and traceability (Lu et al. 2011).

UWB also proves to be another effective technology used in wearable technology systems for proximity detection. UWB uses short nanosecond bursts of electromagnetic energy in the form of short pulse radio frequency waveforms over a large bandwidth, less than 500 megahertz (Saidi et al. 2011). Compared to RFID technology, UWB transmits data over a large bandwidth, which makes it less prone to signal interference and easier to pass through walls

(Fang et al. 2016). UWB has been proven to possess unique advantages including longer range, higher measurement rate, improved measurement accuracy, and immunity to interference from rain, fog, or clutter when compared to other technologies like RFID or ultrasound (Cheng et al. 2011). The distinct advantages of UWB technology make it ideal for a variety of applications on construction sites, either independently or as part of an integrated system with one or more of the other available tracking and monitoring technologies (Shahi et al. 2012).

The other technologies used in wearable devices for proximity detection are radar, magnetic field, ultrasound, GPS, sonar, and Bluetooth. Ultrasound, the science of sound waves above the limits of human audibility, has the possibility for precise measurement. Ultrasonic sensors produce ultrasonic frequencies (between 16 kilohertz and 1 gigahertz) that humans cannot hear, making them ideal for quiet environments. They consume less energy or power, are simple in design, and are relatively inexpensive. While ultrasonic sensors exhibit good resistance to background noise, they are still likely to erroneously respond to some loud noises. Proximity ultrasonic sensors require time for the transducer to stop ringing after each transmission burst before they are ready to receive returned echoes. Thus, sensor response times are typically slower than other technologies by about 0.1 seconds. Density, consistency, and material as well as changes in the environment such as temperature, pressure, and air turbulence can distort an ultrasonic sensor's readings.

Magnetic field generators can be used to establish magnetic fields around an equipment. A sensor worn by a worker provides a measurement of the magnetic flux density that is used to estimate the proximity to the machine (Li et al. 2012). In the operation principle of magnetic proximity detection systems, a sinusoidal (or modulated) current at a carrier frequency between 10 kilohertz and 100 kilohertz flows through a generator consisting of a wire coil wound around

a ferrite core to establish a magnetic field (Li et al. 2012). A magnetic sensor worn by a worker detects the magnetic signal and measures the magnetic flux density on three orthogonal axes. These readings are used to calculate the total magnitude of the magnetic flux density which is then used to estimate the distance from the machine. When compared with other technologies adopted for unsafe-proximity detections, a GPS-aided Inertial Navigation System (INS) sensor has the advantages of ease of use and high accuracy in performance. A GPS-aided INS sensor can provide 3D position, speed, and orientation directly to meet the demands of the model; these measures can be considered as a limitation of technologies such as ultrasound, infrared, and RF sensing technologies (Wang and Razavi 2016).

Most of these technologies provide some form of warning signals to workers when they are close to heavy equipment. These signals could be visual, vibratory, or audible warning signals. The choice of the type of signal chosen is also dependent on the type of task being carried out on the construction site. These proximity zones could either be within warning zones with limited risks or within danger zones, which constitutes regions of high risks.

5.7.1.4. Location Tracking

Various tasks in the planning, designing, and execution phases of construction projects heavily rely on a wide range of location data, such as worker and equipment location data for safety planning and management, and material location data for progress tracking (Fang et al. 2016). Effective planning and control for complex construction projects requires reliable material tracking, effective supply chain visibility, and accurate progress estimation (Shahi et al. 2012). Accurate, reliable, and frequent information about the location of equipment, materials, and workers can help the manager to make the best decision possible based upon actual conditions

(Teizer et al. 2007; Torrent and Caldas 2009). Locating and tracking resources is critical in many industrial applications for monitoring productivity and safety. In construction, various technologies such as GPS, RFID, and RF localization have been proposed for monitoring safety performance (Saidi et al. 2011). All these applications highlight the importance of real-time location and progress tracking technologies (Shahi et al. 2012).

Localization and tracking technologies have been applied to identify undetected obstructions in blind spots (Fullerton et al. 2009) and have also been utilized in the tracking of workers to manage factors related to human error, such as lack of hazard recognition (Hallowell et al. 2010). The accuracy of localization and tracking is heavily influenced by signal availability, but it is very difficult to maintain enough signal availability on construction sites (Lee et al. 2012). Localization techniques, in general, utilize metrics of the received radio signals (RRSs). The most traditional received signal metrics are based on measurements of angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), or received signal strength (RSS) from several reference points (RPs). The reported signal metrics are then processed by the positioning algorithm for estimating the unknown location of the receiver, which is finally utilized by the application. The accuracy of the signal metrics and the complexity of the positioning algorithm define the accuracy of the estimated location (Papapostolou and Chaouchi 2011).

The evaluation of existing wearable technologies proves GPS to be the predominant technology used for location tracking. GPS technology is one of the most promising and attention-drawing techniques as it utilizes satellites to precisely locate coordinates (Cheng et al. 2004). The system consists of three prime components: 1) GPS satellites, 2) earth control, and 3) user receiver. Apart from its use for location and tracking of resources, it has been used in

proximity warning systems to prevent collision between workers and equipment. GPS is a well-known satellite-based positioning system used for tracking users in outdoor environments (Papapostolou and Chaouchi 2011), although it lacks the capacity to penetrate indoor environments (Khoury and Kamat 2009).

This review also identified UWB as another sensing technology for precise location tracking in construction. It is of the widely used wireless network technologies for real-time location system and has been found to be the most reliable and accurate real-time indoor position tracking technology compared with Wi-Fi and wireless mote sensors (Cho et al. 2010). UWB technology is a tag-based sensor technology for tracking multiple resources. Little post-processing is required since workers' 2D or 3D trajectories are actively sensed through wearable tags (Yang et al. 2011). The UWB system is a network of receivers and tags communicating with each other over a large bandwidth greater than 500 megahertz. The tag transmits UWB radio pulses that enable the system to find its 3D position coordinates (Shahi et al. 2012). Unlike other technologies, it is less prone to signal interference and easily passes through obstructions because it transmits data over a large bandwidth.

RFID technology is used in many industries for asset tracking, proximity detection, and security applications. RFID technology has been used in the health care industry to improve patient monitoring and safety, increase asset utilization with real-time tracking, reduce medical errors by tracking medical devices, and enhance supply-chain efficiencies (Zhu et al. 2012). Other technologies used for location tracking to a very minimal extent are sonar, magnetic field, and radar.

5.7.2 Performance Characteristics of Wearable Technologies

Wearable devices are expected to have some performance characteristics or meet certain design criteria necessary for their optimum operation. Some of these characteristics (or variables) include size and weight of sensors, power source, computation capability, sensor location and mounting, and wireless communication range and transmission. The review of the performance characteristics thought to be relevant in the design and choice of wearable technologies for applications in construction is presented as follows.

5.7.2.1 Size and Weight of Device

The size and weight of a device are certainly part of the most important attributes considered in the design and choice of wearable technology because a device must be small and lightweight before it can be considered wearable. The issue of size and weight particularly becomes more significant in the use of wearable devices by construction workers who usually carry a few necessary tools needed to execute their task. In order to also achieve non-invasive and unobtrusive continuous monitoring of workers' health and activities, wireless sensors must be lightweight and small. Wearable devices should be small enough to fit on any asset without interrupting the completion of work objectives (Cheng et al. 2011), and best incorporated into the clothing or accessories (such as watches, wristbands, reflective vests) normally worn by the workers.

It is, however, important to note that a battery's capacity is directly proportional to its size. This correlation means that the size and weight of sensors is predominantly determined by the size and weight of batteries (Jovanov et al. 2005; Anastasi et al. 2009; Li et al. 2010). Also, the requirements for extended battery life directly oppose the requirement for small size and low

weight. The sizes of the wearable technologies reviewed ranged from 1.67 inches by 1.32 inches by 0.43 inches to 4.8 inches by 2.31 inches by 0.56 inches, which means they were neither obtrusive nor conspicuous. As pointed out by Darwish and Hassanien (2011), one can expect that further development of technology and advances in miniaturization of integrated circuits and batteries will help developers to decrease the overall size of wearable sensors.

5.7.2.2. Power Source

Power source, power consumption, and energy efficiency are important factors also considered in the design and selection of wearable technologies. The operating profile of wearable devices differs significantly from mobile devices like smartphones. Much of the time a device is in ultra-low power standby-mode and at different times wakens to active-mode where power consumption is much higher (Anzaldo 2015). Wearable sensors have to be extremely power efficient, because frequent battery changes for multiple wearable sensors would likely hamper users' acceptance and increase the cost (Jovanov et al. 2005). Furthermore, low power consumption is very important as we move toward future generations of implantable sensors that would ideally be self-powered, using energy extracted from the environment. To better manage power consumption, direct memory access can be power-optimized with a dedicated Peripheral Management Unit (PMU) (Anzaldo 2015).

Diligent power and battery management design techniques are needed to achieve ultra-low operating power and long operating life from the smaller size and lower capacity batteries used in wearable devices. Also, intelligent on-sensor signal processing has the potential to save power by transmitting the processed data rather than raw signals, and consequently to extend battery life (Jovanov et al. 2005). The technologies also have varying operating voltage and

power consumption. Since most construction activities are performed outdoors, wearable devices that use alternative power sources such as solar cells can be developed. A notable company has launched clothing with solar cells to charge devices. The clothing can simply be adapted to function as reflective vests worn by construction workers. Kinetic energy-powered gadgets which can be used by mobile workers have also been developed while body heat has been used to power small light-emitting diode (LED) lights on a ring.

5.7.2.3 Sensing and Sensitivity of Device

The sensing process in a wearable device is generally accomplished by sensors which collect data that can be passed to the storage system, if present (Ananthanarayan and Siek 2010). A personal server can then be used to collect sensor readings, process and integrate data from various sensors, provide better insight into the users' state, and then provide an audio and graphical user-interface that can be used to relay early warnings or guidance, and secure communication with remote servers in the upper level using Internet services (Jovanov et al. 2005).

The sensitivity of the sensor devices is especially important when users wear these sensors in harsh environments such as the construction environment. The heavy equipment, materials, and structures typically found on construction sites may impact the sensitivity of these wearable devices. Sweat produced by construction workers can also affect the transducers of the sensor devices negatively, causing a reduction in the sensitivity of the body-worn sensors or requiring recalibration of the sensors (Darwish and Hassanien 2011). For instance, sensitivity to sunlight and need for line-of-sight are shortcomings of infrared when it comes to its application in construction. Also, magnetic fields may be interfered with by metallic objects in the

environment, which can decrease the accuracy of measurements (Fahn and Sun 2010). These issues are considered in the choice of technology system for developing wearable devices because technologies that are not affected by these conditions would be favored over other ones. Additionally, there is need for the designers of these wearable devices to improve their designs and ensure the devices provide maximum resistance to the interference that might be encountered on construction sites.

5.7.2.4 Multi-Parameter Monitoring

As discussed earlier in this paper, several safety performance metrics are required to be measured and monitored using different wearable technologies or sensors to mitigate the safety and health hazards associated with the construction process (OSHA 2017). The existing applications of wearable technologies in construction and other industries have demonstrated that wearable technology systems are capable of measuring multiple parameters all in a single device. For instance, multiple physiological sensors used to monitor similar metrics such as heart rate, heart rate variability, and respiratory rate can share a single wireless network node. In addition, physiological sensors can be interfaced with an intelligent sensor board that provides on-sensor processing capability and communicates with a standard wireless network platform through serial interfaces (Jovanov et al. 2005). The ANT+ protocol also permits interoperability between different sensors, which enables the simultaneous tracking of different metrics using one system. From the commercially available wearable devices reviewed, some of the physiological monitoring technologies such as ECG/EKG and gyroscope are used in conjunction with the GPS technology to concurrently track the location of the user. Bluetooth technology is also used in conjunction with some of the other technologies for connectivity.

5.7.2.5 Accuracy and Precision

Accuracy is defined as the statistical difference between the estimate or measurement of a quantity and the true value of that quantity (U.S. DoD 2008) while precision is how close the measured values are to each other. For instance, location accuracy is how much the estimated position is deviated from the real position while precision is the percentage of time the location system provides the given accuracy (Tesoriero et al. 2010). Wearable technologies should be capable of accurately and precisely recording the activities that are associated with monitored work tasks (Cheng et al. 2011). This accuracy in measurement is one of the major advantages the application of wearable technologies for data collection and analysis has over the human errors that might be involved in a more traditional approach.

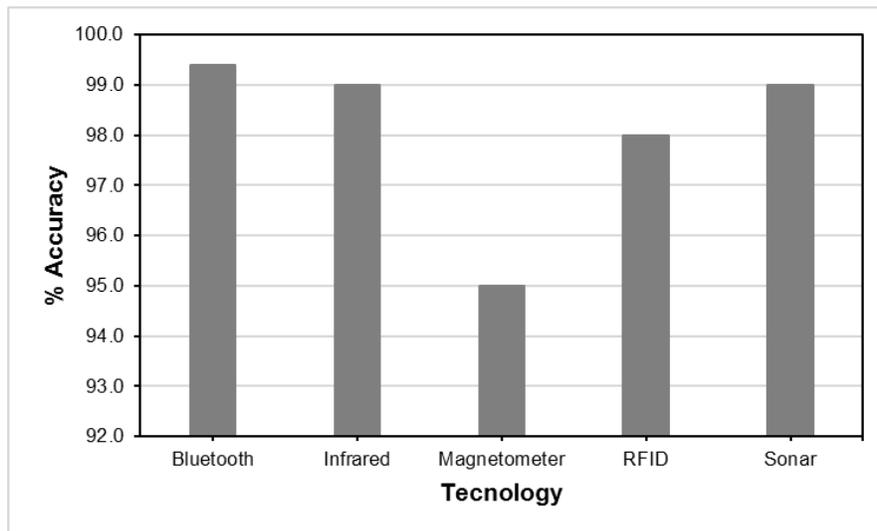


Figure 5.2: Accuracy of selected proximity detection wearable devices.

According to reported findings and specifications published by the manufacturers of the wearable devices evaluated, the accuracy of selected wearable devices for proximity detection defined by the percentage of measured detection distance to the true distance varies between 95.0

and 99.0% for magnetometer and Bluetooth respectively (Figure 5.2). Also, the percentage accuracy of a location tracking wearable device based on GPS defined in terms of the pseudorange (i.e. an approximation of the distance between a satellite and a GNSS receiver) was reported to be 95%.

5.7.2.6 Frequency Band

To enhance operation and communication on a harsh and dynamic construction site, there is need for an appropriate frequency band for efficient wireless networking. The frequency band greatly influences the accuracy of distance and speed measurements. For instance, a high frequency signifies that more vibrations are produced than it is for a low frequency over the same time. This information implies that a high frequency produces a higher speed because of low amplitude. Therefore, higher reading range and speed are achieved when the frequency is increased (Lee et al. 2012).

5.7.2.7 Storage

Storage is required in order to collect and store data so that the derived information can be made available from the processed data (Ananthanarayan and Siek 2010). Wearable devices need more memory capacity because of the increased number of sensor elements, the need for mobile software applications, and the rise of edge analytics (Anzaldo 2015). Edge analytics is a method of data collection and analysis in which an automated analytical computation is executed on data at a sensor, network switch or other device instead of waiting for the data to be sent back to a centralized data store. More sensors create more data volume, which increases communication network traffic between wearable devices and edge access points. The data

throughput over local area networks must be minimized to reduce communication link congestion. By moving analytics processing closer to the device, there will be less network data traffic and, thus, less congestion, which is one of the primary benefits from edge analytics (Anzaldo 2015). The device should be able to perform an analysis of all measurements online, presenting them in appropriate form to both wearer and remote base station (Anliker et al. 2004). The data collected by using the existing wearable technologies is usually stored either on the wearable device or more accurately in its cloud software. The storage of data collected with wearable devices is a serious concern because high risks might be involved if the data is carelessly stored and then stolen through a data breach by a malicious third party.

5.7.2.8 Data Processing and Transmission

This layer of the wearable system involves processing tools needed to analyze the data generated by the hardware sensors. This data generated may need to be processed in a variety of stages depending on the metrics collected. Additionally, several stages or levels of data processing may occur before the processed information gets to the end-user with some localized (i.e. close to the hardware) while others may involve further processing after being transmitted to the Internet (Swan 2012). Thus, this layer or platform also provides interfaces for information exchange to and from the wearable device.

The simplest form of data processing will be in the proximity detection system in which the sensors may need to just detect hazardous materials, chemicals, or equipment and then alert workers. A more complex processing will be one that can also distinguish the type of hazard detected so that it can be relayed to the worker with another layer within the system. Other forms of processing, such as those for location tracking and physiological monitoring, may also involve

non-localized processing that occurs after the data has been transmitted to the Internet. The data transmission process may use any of the available standard communication protocols including Wi-Fi, Bluetooth, ANT+, and ZigBee. Raw and processed data may also need to be transmitted through any of the protocols for storage in the cloud for easy accessibility.

5.7.2.9 Device Location and Mounting

Although the purpose of the measurement does influence sensor location, researchers seem to disagree on the ideal body location for sensors (Jovanov et al. 2005). In general terms, the closer the wearable device is to the signal it is collecting, the stronger the accuracy. This means that a wearable sensor worn for example on the chest can sense heart signals with high accuracy. Commercially available wearable devices come in form of smart wristbands, watches, shirts, headbands, necklaces etc. Although there is a rising number of wearable devices attached to the body, worn on the head or around the neck, most wearable devices are commonly worn on the wrist. Wristband wearable devices have the highest consumer interest level and this is evident in the mounting positions of the wearable technologies evaluated. Recently, the integration of wearable devices into jewelry such as watches, pendants, and rings has been on the rise. Other examples of miniature wearable devices are skin-worn wearable patches which are secured directly on the skin, preventing the need for straps, buckles or bands. These body-worn patches come in variety of forms ranging from transparent films on the skin to miniature shells that stick to various parts of the body. To increase the acceptance of wearable devices by construction workers, the devices should be incorporated into clothing or gadgets (such as safety vest, shoes, watches, and wristband) normally worn by the workers on daily basis.

5.7.2.10 Cost and Maintenance

Wearable technologies should have low implementation and maintenance cost, while also being rugged enough to withstand a harsh environment and project lengths of up to several years (Cheng et al. 2011). The cost of wearable devices is hinged on many factors, ranging from the metrics to be assessed, the sensors used, hardware requirements, power source etc. From the commercially available wearable technologies reviewed, the cost of selected wearable devices for proximity detection ranges from \$35 for Bluetooth to \$1,159 for RFID as shown in Figure 5.3.

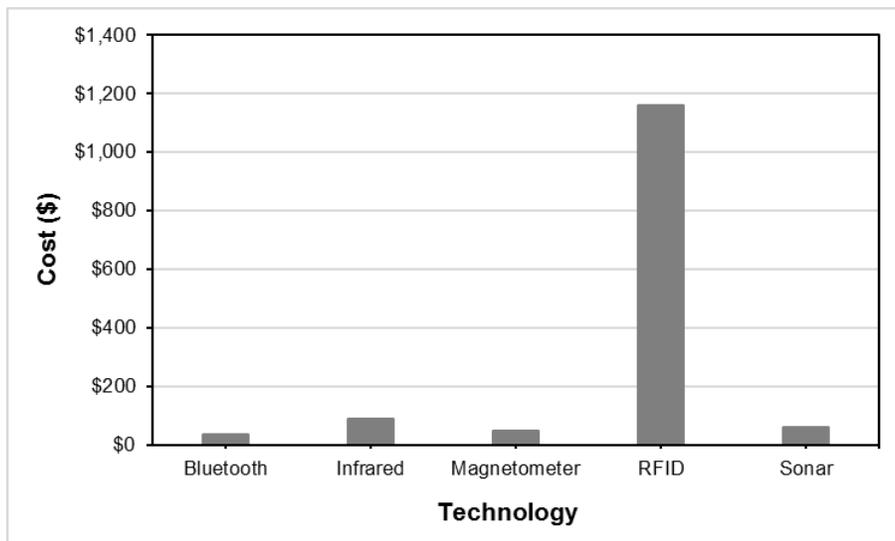


Figure 5.3: Cost of selected proximity detection wearable devices.

5.7.2.11 Social Issues

Social issues of wearable systems include privacy, security, and legal issues. Due to the communication of health-related information between sensors and servers, all communication over wireless networks should be encrypted to protect users' privacy (Jovanov et al. 2005). Wearable devices are vulnerable to security threats; hence, strong security measures are critical

to protect against malicious attacks that can corrupt or steal data. Security is needed to protect intellectual property such as proprietary algorithms that could reside on a wearable device. Secure authentication prevents device cloning and offers counterfeit protection for peripherals (Anzaldo 2015). The systems of wearable technology should provide less invasive technology, but with the highest possible safety and security standards for all project stakeholders while at work (Cheng et al. 2011).

5.7.3 Integrated Wearable Technology for Construction Safety Performance Monitoring

This study has identified that different kinds of wearable sensors and systems can be used to measure and monitor a wide variety of safety performance metrics. Some of these sensors can monitor more than one parameter, while others are complementary. However, these systems or sensors still have certain limitations which may be difficult to control if, for instance, a system or sensor is used in isolation. The strengths and weaknesses of each of these wearable sensors or systems have been evaluated and the integration of two or more of these sensors or systems for multi-parameter monitoring is obviously a good way to achieve maximum benefits from these technologies.

Figure 5.4 presents the wearable sensors and systems that can be used to measure and monitor the safety performance metrics evaluated in this study. It illustrates how the sensors can be integrated for multi-sensor platforms and multi-parameter monitoring. The trend in wearable technology is moving towards multi-sensor platforms that incorporate several sensing elements. For example, the standard for the next generation of personalized self-tracking products appears to be some mix of an accelerometer, GSR sensor, temperature sensor, and possibly a heart rate sensor (from which heart rate variability may be calculated) (Swan 2012).

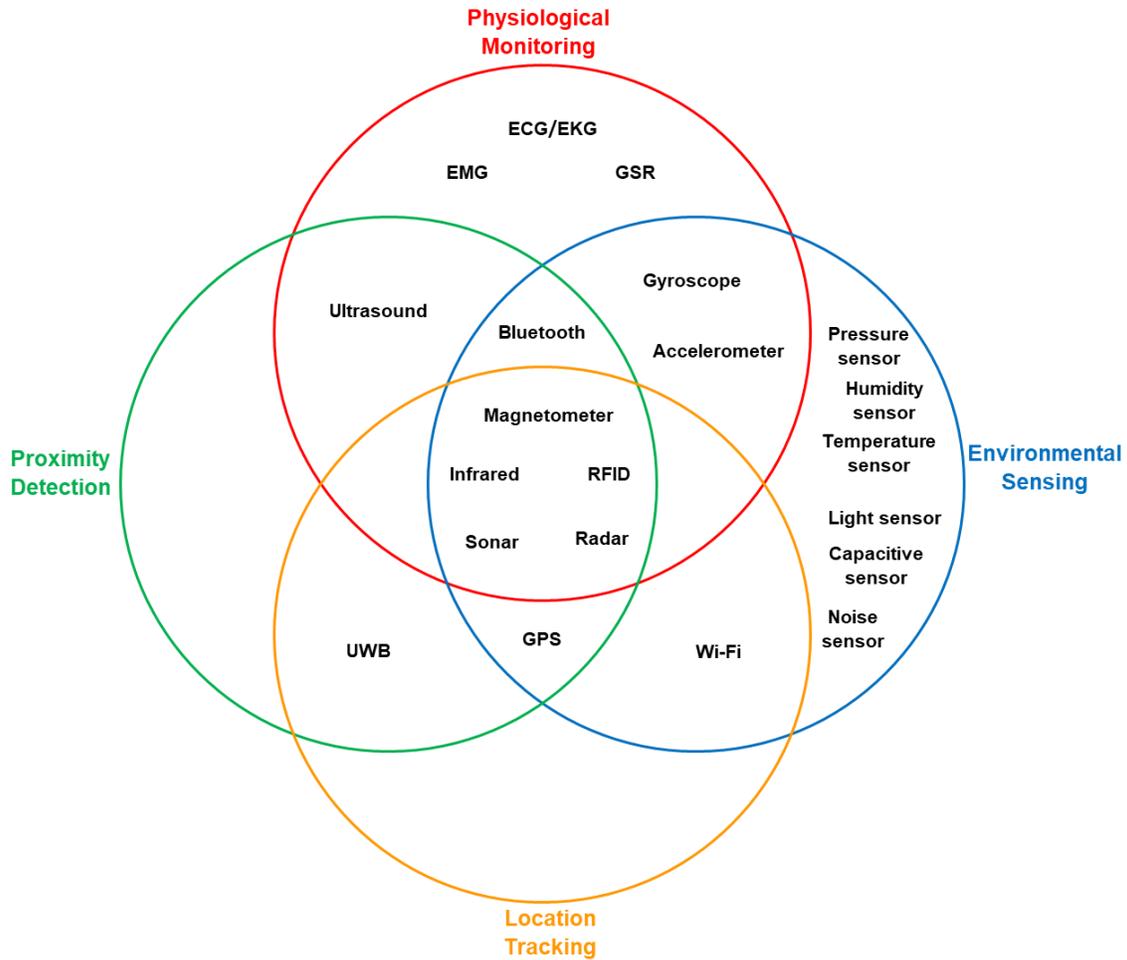


Figure 5.4: Sensors and systems for personalized wearable technology

Instead of placing a single type of sensor in multiple locations on the human body (i.e. single-modality multi-location) as seen in most wearable devices, multiple sensor types using a multi-modal sensor to collect data from a single body location (i.e. multi-modality single-location) can be used (Zhang and Sawchuk 2012). The rationale behind this idea is to select sensors that are complementary, such that a wider range of activities can be recognized. For example, using an accelerometer and a gyroscope together can differentiate whether the person is walking forward or walking left/right, while such a classification fails if accelerometers are used alone. Moreover, this multi-modal sensor could be incorporated into existing mobile devices

such as mobile phones. Integrating sensors into devices people already carry is likely to be more appealing to users and achieve greater user acceptance.

Additionally, the benefits derived from the use of ANT+ technology to achieve interoperability between different sensors can be taken advantage of in developing such multi-parameter monitoring wearable devices. As the wearable devices get smaller, they gain efficiency and become more powerful. The integration of several sensors in the design of wearable devices would create a holistic procedure for monitoring safety performance as it would reduce the number of safety gadgets the workers would have to use to monitor different parameters. As depicted in Figure 5.4, infrared, magnetometer, radar, RFID, sonar, Bluetooth, and GPS rank high as wearable sensors or systems with multi-parameter applications. Some of the findings of this study can be considered in developing prototypes of construction-specific wearable devices for personalized safety monitoring.

5.8 Conclusion

This chapter provides a review of the applications of wearable technology for personalized construction safety monitoring and trending. A comprehensive evaluation of the features of wearable technology and the resulting safety metrics thought to be capable of predicting safety performance and management practices is presented. The review showed that a wide variety of wearable technologies is being used in other industries to enhance safety and productivity, while few applications are observed in the construction industry.

Knowing that the various sectors where wearable technologies have been greatly applied are not high risk industrial sectors like construction, there is an urgent need to change the status quo in terms of the application of wearable technologies in construction. It is time for

construction stakeholders and professionals to strongly embrace these emerging trends in technological development so that safety performance can be enhanced drastically. This review has identified potential applications of wearable devices for capturing and monitoring various metrics responsible for the common injuries and fatalities on construction sites. The review completed in this study indicates that the sensors and systems used in the existing wearable technologies applied in other industrial sectors can also be implemented to measure and monitor a wide variety of safety performance metrics in construction.

Per the findings of this review, a few of the sensors and systems used in commercially available wearable devices have certain strengths and weakness which can be managed effectively by the constructive integration of two or more of the sensing systems to achieve complementary benefits. Also, wearables devices with multiple sensor types in which a multi-modal sensor can be used to collect data from a single body location (i.e. multi-modality single-location) have been suggested for use in construction. Technology developers should intensify efforts in working on ways to derive meaning from multiple sensors integrated into a wearable device, to give a holistic view of how the body is moving or performing across multiple devices and sensors. The findings of this study can be used to integrate different wearable sensors and systems that can be used to design construction-specific wearable devices. Prototypes developed can be tested for their effectiveness for personalized safety monitoring. Further research in this area could include the selection of candidate wearable devices from the commercially available ones that can be applied to construction or developing prototypes for construction-specific wearable devices based on the findings of this study and performing experimental testing to ascertain their effectiveness.

CHAPTER 6

ACTIVE WORK ZONE SAFETY USING EMERGING TECHNOLOGIES

Highway construction work zones are hazardous environments characterized by a dynamic and limited work space. A host of interactions between workers, passing commuter vehicles, and moving construction equipment occurs in highway work zones, fostering dangerous situations that can result in injury or death. Active strategies, such as the deployment of intrusion sensing and alert technologies in highway work zones and in transportation infrastructure construction and maintenance, can be effective at mitigating these unforeseen conditions. The main objective of this study was to conduct both conceptual analysis and experimental evaluation of intrusion sensing technologies for work zone safety. To achieve the objectives of this research, an exploratory review of the applicable technologies was conducted to identify the intrusion technologies that can be implemented for work zone safety. An objective assessment of each technology was provided based on selected evaluation metrics to elicit their capabilities. Candidate commercially available technologies were selected and evaluated using field experiments in simulated work zones. The findings of the study indicate that a limited number of the applicable technologies exists and the selected commercially available technologies evaluated have the capabilities to effectively provide alerts to highway work zone personnel when a hazardous situation is present. This research contributes to the body of knowledge by providing strategies for selecting and implementing intrusion sensing technologies for active work zone safety.

6.1 Introduction

Work zone safety is a major concern for many community members, including government agencies, legislatures, and the traveling public (Ullman et al. 2008; Chambless et al. 2002). Transportation infrastructure provides many social benefits to any society and plays a critical role in the proper functioning of the economy (Andrijcic et al. 2013). The need to maintain and rehabilitate existing roadway systems rises as traffic volume increases and highway infrastructure ages (Cerezo et al. 2011). Thus, the maintenance, reconstruction, and constant upgrading of these infrastructures are pivotal to meeting the ever-increasing needs of a growing economy (Duranton and Turner 2012). The increasing number of roadway widening, rehabilitation, and reconstruction projects has made work zone safety a critical concern (Cerezo et al. 2011). This is because construction workers' exposure to hazardous conditions increases with the rising number of transportation infrastructure construction projects (Benekohal et al. 2004).

Highway construction and maintenance operations commonly require personnel to work near ongoing traffic, a situation that creates significant safety risks for both the construction employees and traveling motorists (Gambatese and Lee 2016). One commonly implemented control strategy is to place traffic control devices near work zone areas to alert motorists (Noyce and Smith 2003). However, drivers often disregard or ignore work zone traffic control devices and other warning systems which has led to serious accidents during a work zone intrusion (Hourdos 2012). Since the work environment on the highway is often chaotic and noisy, it can be difficult for personnel to spot an errant vehicle in time to take appropriate action (Fyhrie 2016). Inattentive or speeding drivers, careless workers, misplaced traffic control devices, and

hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities (Gambatese and Lee 2016; Khattak et al. 2002).

A need exists for a management approach that considers not only the implementation of active intrusion sensing technologies, but also their effectiveness in alerting both the pedestrian workers and vehicle drivers in work zones. As vehicle miles traveled, driver distraction, work zone activity, and nighttime work increase, safety incidents and work zone crashes can be expected to rise (Krupa 2010; Gambatese and Lee 2016; Pratt et al. 2001). Complex situations such as those present in work zones require active monitoring to provide real-time information about the conditions of the work environment. To reduce the incidence of and potential for incidents on highway construction and maintenance sites, some government authorities have deployed safety devices and systems to safeguard employees using intrusion alarms (Krupa 2010; Phanomcheong et al. 2010). Intrusion alarms are used primarily in temporary work zones with short work duration where adding a positive protection system such as concrete barrier is not feasible (Givechi 2015).

The purpose of this chapter is to provide an objective evaluation of the applicable intrusion technologies for work zone safety and to implement commercially available intrusion sensing technologies in a simulated highway work zone testbed through field experimentation. To achieve this, a contextual study was conducted to determine the previous applications of intrusion alarm systems for work zone safety. Information about work zone intrusion sensing technologies from the manufacturers' specifications documents and published research results were collected and evaluated. An assessment of each technology was provided based on selected evaluation metrics to elicit their capabilities. Candidate intrusion sensing technologies were selected and implemented for work zone safety using field experiments in simulated work zones.

6.2 Work Zone Safety Statistics

Over the past decade, a considerable amount of work zone crashes has occurred, leading to damage of property, injuries to workers, and loss of lives (Li and Bai 2008). In the U.S., an average of 595 work-zone-related fatalities occurred every year within the past five years (FHWA 2016). In 2014, 669 fatalities occurred in work zones nationwide, representing two percent of all highway fatalities (NWZSIC 2016). Highway work zones accounted for nearly 24 percent of all highway fatalities (NWZSIC 2016). Highway work zones accounted for nearly 24 percent of non-recurring congestion, or 888 million vehicle hours of delay in 2014 (FHWA 2016). Furthermore, more than 20,000 workers are injured in work zones each year in the U.S in which 12% result from traffic incidents (Krupa 2010). These injuries and fatalities have cost implications on the economy of the nation. In 2010 for instance, the total economic cost of motor vehicle crashes in the U.S. was \$242 billion (Blincoe 2017).

Many of the crashes near work zone areas occur when drivers fail to heed traffic warnings and control measures upstream of the work zone area, often due to distracted driving (Hourdos 2012). The cited statistics of work zone incidents indicate a great need for improved safety performance in and around construction highway work zones. This information also projects a need for more effective strategies to reduce and eventually eradicate these fatalities and delays in work zones.

6.3 Work Zone Intrusion Technologies

Work zone hazard awareness systems can be divided into three major categories: mechanical systems, electronic systems, and dedicated observers (Bryden and Mace 2002). Mechanical systems use mechanisms, such as impact-activated or pressure-activated systems, which are triggered by the physical contact or impact of intruding vehicles (Sun et al. 2007).

Electronic systems apply sensing technologies, such as laser switch systems, that require the alignment of transmitters and receivers to detect intruding objects (Liu et al. 2007). If a receiver fails to receive signals from a transmitter, the system activates an alarm. Other practices employ dedicated observers, such as workers or flaggers, to spot intrusions and trigger alarms (Tsai 2011).

Intrusion alarms are a technology which utilizes one or more sensors mounted on typical work zone barriers such that when an errant vehicle contacts a sensor, an alarm would be activated to warn workers that their protective zone has been violated (Wang et al. 2011). The concept of such systems is that the alarm mechanism would warn workers with enough reaction time to move away from the hazardous location (Wang et al. 2011). Some intrusion alarm systems consist of a detection unit and a receiving unit in which the alarm is activated when the detection unit is triggered or activated (Ozbay et al. 2012). The alarm could also possibly alert a distracted or drowsy driver and permit them to avoid the work zone or decelerate prior to reaching workers or their equipment (Wang et al. 2011).

The first set of work zone intrusion alarm systems was developed under the Strategic Highway Research Program (SHRP) where ultrasonic and infrared beams were used for detection (Wang et al. 2011; Ozbay et al. 2012). Two types of intrusion alarm systems developed by the SHRP utilized microwave and infrared wireless technology in respective models that mounted on work zone barriers (Ozbay et al. 2012). The systems used either microwave signals or beams of infrared light to connect to base units (Wang et al. 2011). When a vehicle crossed into the work zone and interrupted the signal or beams, a high-pitched alarm was sounded by the base station near the workers. A third type utilized pneumatic tubes placed on the ground such that the tubes were laid around the working area. When a vehicle drove into the area

and over the tubes, an alarm was activated (Wang et al. 2011). Other similar intrusion alarms have been developed using microwave, pressure activated tubes, and laser technologies (Ozbay et al. 2012; Khan 2007). Another type of work zone intrusion alarm system, a kinematic model, was identified by Fyhrie (2016). The kinematic models, usually mounted on a traffic cone (or other similar hardware), produce an alarm when the change in orientation angle of the cone indicates it has been tipped over (Khan 2007). This system works based on the assumption that an errant vehicle has knocked over the hardware and has entered the work area (Khan 2007).

6.4 Previous Assessments of Intrusion Alarms for Work Zone Safety

A few work zone safety devices from the Strategic Highway Research Program (SHRP) were evaluated under the direction of the Kentucky Transportation Cabinet through trial use (Agent and Hibbs 1996). Five intrusion alarm systems were evaluated, including one microwave system, one infrared system, and three pneumatic tube systems. Modifications based on feedback from various state, county, and private agencies were implemented, mostly concentrated on increasing the ease of setup and the volume of the alarm (Agent and Hibbs 1996). Although the devices were found to be durable, workers were generally not enthusiastic about using the devices. Consequently, a definitive recommendation was not made due to the continuous modifications, but devices were supposedly accepted to have potential for use on major projects, with cost being a limiting factor (Agent and Hibbs 1996).

A microwave-based alarm system was rejected by the Alabama, Colorado, Iowa, and Pennsylvania Departments of Transportation (DOTs) because of setup problems and false alarms due to difficulties in keeping the devices aligned (Carlson et al. 2000). The Iowa Department of Transportation attempts to minimize the amount of time that crews are exposed to traffic,

coupled with the time needed for setup of the intrusion alarms meant that the amount of time a crew needed to do their job was extended (Fyhrie 2016). It was noted that false alarms were so frequent that workers ignored the alerts (Trout and Ullman 1997). Although potential benefits were identified from these work zone intrusion sensing systems, multiple limiting factors have been experienced. These limitations include nuisance alerts that can desensitize work zone employees (Trout and Ullman 1997), the significant space required to install the system (Carlson et al. 2000), time and effort required for set-up (Trout and Ullman 1997), durability of the system (Carlson et al. 2000), and misalignment of the detection area (Novosel 2014).

6.5 Research Needs Statement

Although intrusion alarm systems have the potential to warn workers when an errant vehicle intrudes the work zone, existing studies show certain limitations in their capabilities, effectiveness, and wide-spread implementation. The previous applications of these systems indicate the need to improve the systems to ensure maximum benefits are derived from their deployment for work zone safety. Research needs exist to complete a conceptual analysis of the applicable intrusion sensing technologies to identify and experimentally evaluate the commercially available technologies that can be implemented to enhance work zone safety. These conceptual and experimental evaluations are expected to provide information on the capabilities of these intrusion sensing technologies in order to elicit their benefits and areas for improvement.

6.6 Research Method

The methods adopted in achieving the objectives of this research involved two parts. The first part involves the conceptual review of applicable intrusion technologies while the second aspect involves the experimental evaluation of selected intrusion sensing technologies for work zone safety. The research methodology framework is presented in Figure 6.1.

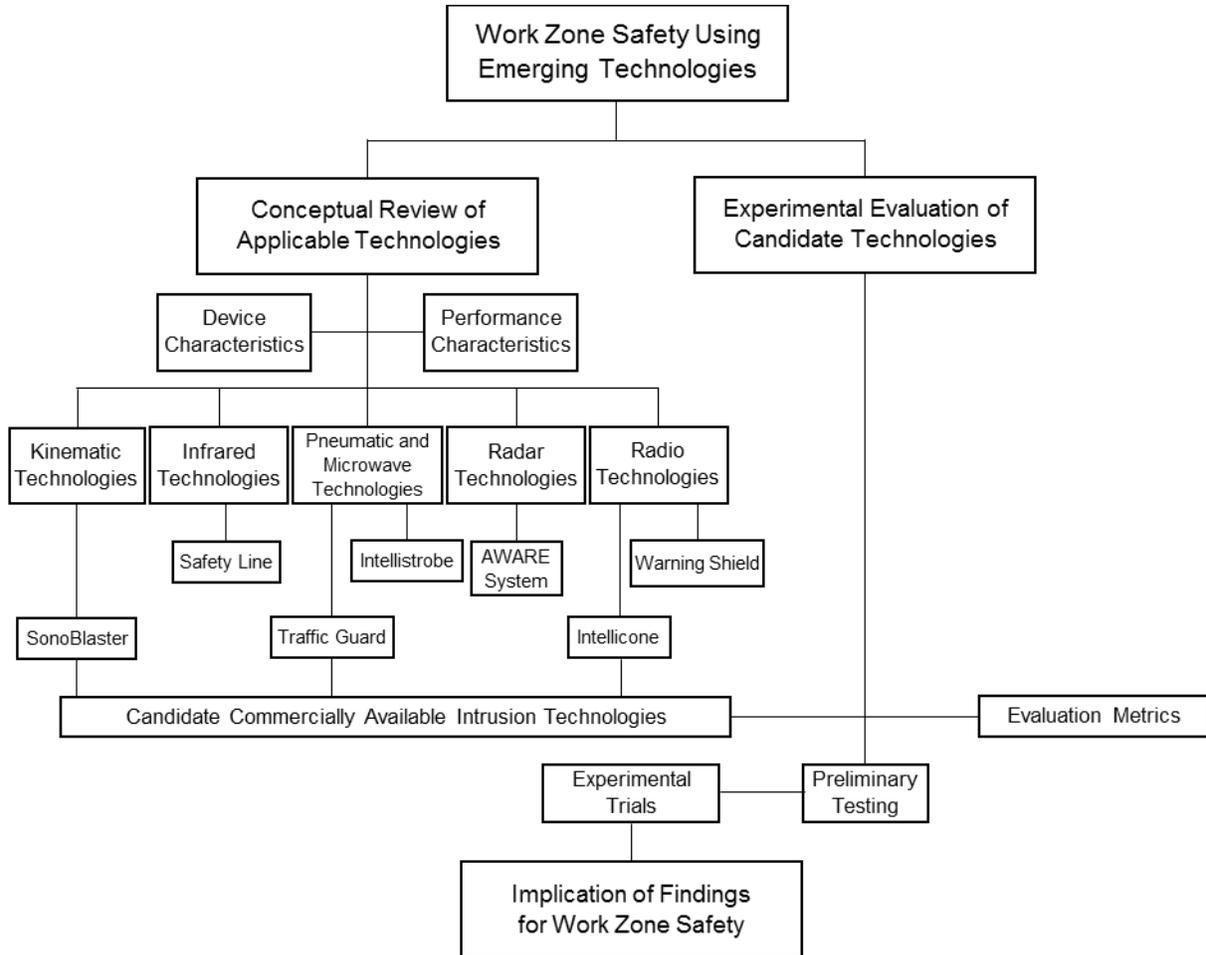


Figure 6.1: Research methodology framework

A review of intrusion technologies from previous applications and manufacturers' documents was conducted. Based on the review, these five categories of intrusion technology systems were identified: 1) Kinematic Intrusion Technology Systems, 2) Infrared-based Intrusion

Technology Systems, 3) Pneumatic and Microwave Intrusion Technology Systems, 4) Radar-based Intrusion Technology Systems, and 5) Radio-based Intrusion Technology Systems. The different types of applicable intrusion technology devices under each of these categories were identified and assessed using selected evaluation metrics. The review culminated in the selection of candidate commercially available technologies which were then evaluated using experimental trials to assess their implementation for work zone safety.

6.7 Conceptual Review Results

This section presents the results of the conceptual review of applicable work zone intrusion technologies. The assessment of applicable and commercially available work zone intrusion sensing technologies is presented based on selected evaluation metrics (i.e. device attributes and performance characteristics).

6.7.1 Review of Applicable Work Zone Intrusion Technologies

A thorough review of applicable intrusion sensing technologies indicates that a few commercially available intrusion alarm systems exist. Table 6.1 presents the applicable and commercially available intrusion sensing technologies that can be implemented in highway work zones. A comprehensive review of the technologies is also presented. The intrusion technologies in bold in Table 6.1 indicate the commercially available work zone intrusion technology systems.

Table 6.1: Applicable and commercially available work zone intrusion technology systems

System Type	Intrusion Technology	States Tested	Alert Type		
			Audible	Visual	Vibratory
Kinematic	SonoBlaster	New Jersey DOT (Krupa 2010), Kansas DOT (Novosel 2016)	Yes	No	No
Infrared-based	Safety Line	None	Yes	Yes	No
Pneumatic and Microwave	Traffic Guard Worker Alert System	None	Yes	Yes	Yes
	Intellistrobe	None	Yes	Yes	No
Radar-based	AWARE System	Missouri and Texas (Clever 2016)	Yes	Yes	Yes
Radio-based	Intellicone	Kansas DOT (Novosel 2016)	Yes	Yes	No
	Wireless Warning Shield	None	Yes	No	Yes

6.7.1.1 Kinematic Intrusion Technology Systems

Kinematic intrusion alarm systems are impact-activated devices attached to a traffic control device which produces a warning sound to alert workers when the device is struck by a vehicle (Fyhrie 2016). The SonoBlaster Work Zone Intrusion Alarm is an impact and tilt activated safety device that warns roadway workers and errant vehicle drivers simultaneously to help prevent crashes, injuries, and fatalities on roadway work zones. The SonoBlaster is usually mounted on typical traffic control devices such as work zone barricades, cones, drums, delineators, A-frames, and other barriers. Upon impact by an errant vehicle, the SonoBlaster’s built-in carbon dioxide (CO₂) powered horn blasts at 125 decibels for 15 seconds to signal workers that their protective zone has been violated, allowing them critical reaction time to escape the hazard (Transpo 2010). Figure 6.2 shows the SonoBlaster alarm system. The SonoBlaster is an entirely mechanical device which emits an auditory alarm and does not require

batteries. It is constructed entirely of hard plastic, except for the CO₂ nozzle, which is constructed of metal.



Figure 6.2: SonoBlaster alarm unit

SonoBlaster-equipped traffic cones were used with standard cones in a pilot test to close a lane of traffic for maintenance work in New Jersey (Krupa 2010). Two impact simulations were performed resulting in the sounding of the alarm, as no impacts occurred from traveling vehicles. The alarm's sound volume and duration were satisfactory during normal traffic conditions for distances of at least 60 meters, including when ear protection was worn, but no conclusion could be made about hearing the alarm during jack hammer operations. Employees indicated that several set-up procedures were difficult (Krupa 2010). Moreover, in multiple instances the alarm fired when the control knob was in the locked and unarmed position. Overall, quality control was a major issue due to problems with setting up the device and its durability. Reliability as a safety-promoting device was also an issue because of misfires. Wang (2011)

stated that the findings of a survey indicated that 44 percent of states that have tested the SonoBlaster believe the device was ineffective due to issues with false alarms and maintenance of the system.

6.7.1.2 Infrared-Based Intrusion Technology Systems

The Safety Line provides workers with a warning when a vehicle intrudes an area closed off by traffic control devices. The system consists of a transmitter, a receiver, and an alarm unit. The transmitter is placed at the start of a taper, inside the channelizing devices (Kocheva 2008) while the receiver can be placed up to 300 meters away, closest to the workers. The transmitter emits a dual infrared beam to the receiver and if a vehicle enters or intrudes the buffer area, the dual transmitted beams would be obstructed, thus causing the receiver to activate the 147 decibels air horn, alerting the workers. The system uses a sealed gel cell battery type with a three-day life span and recharging time of between 5 and 6 hours. The transmitter has the solar charger option, while the receiver has the solar charger and strobe light option. Multiple units can be linked to protect a larger area. Ozbay et al. (2012) believe that this technology has potential benefits for short-term and long-term work zones. According to Kocheva (2008), Safety Line is easy to use, rugged, lightweight, portable, completely self-contained and can be aligned in less than a minute using the alignment light emitting diodes (LEDs). Unfortunately, the Safety Line system is not commercially available and thus cannot be further evaluated using experimental trials.

6.7.1.3 Pneumatic and Microwave Intrusion Technology Systems

The pneumatic road tube intrusion alarm system involves placing road tubes or hoses on the roadway perpendicular to the flow of traffic at the beginning of the work zone. The tubes are connected to a transmitter that activates a siren and a strobe light when a vehicle drives over them (Carlson et al. 2000). A typical microwave intrusion alarm features a transmitter mounted on one drum and a receiver and siren mounted on another drum up to 300 meters away. Strobe lights can also be included in the system to alert workers under noisy conditions (Carlson et al. 2000). The Traffic Guard Worker Alert System and the Intellistrobe Automated Flagger Assistance Device (AFAD) Lane Intrusion Safety System were the two devices identified under this category of intrusion technology systems as applicable for work zone safety.

The Traffic Guard Worker Alert System consists of a lightweight, easy-to-transport pneumatic trip hose and sensor assembly that sends a signal to an alarm and flashing light up to 300 meters away (Fyhrie 2016). The pneumatic trip hose is placed ahead of or behind workers on the road, far enough away to provide ample warning if an unauthorized vehicle crosses over the hose. The flashing light and alarm alert workers so they can quickly move out of the way of an oncoming vehicle. The faster the traffic is moving, the more distance there should be between the pneumatic trip hose and work area (NWZSIC 2016). The Traffic Guard system has an additional Personal Safety Device (PSD) which produces vibratory and audible alerts to the worker in possession of it when a signal is transmitted from the impacted device to the PSD. Figure 6.3 shows the Traffic Guard Worker Alert System. The pneumatic trip hose with attached sensor uses two alkaline batteries, while the horn and light alarm assembly uses an in-built rechargeable battery and the PSD with included earpiece uses two AAA 1.5V Copper Top Alkaline Batteries (Astro Optics 2017).

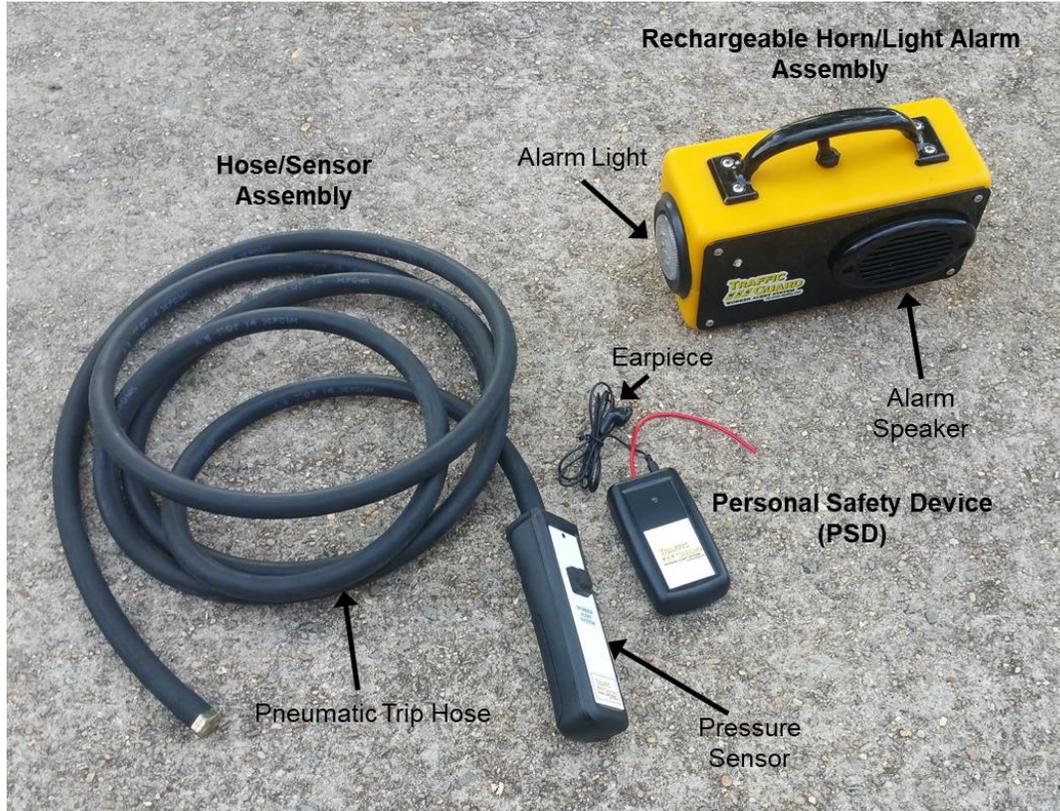


Figure 6.3: Traffic Guard Worker Alert System

The Intellistrobe system is an Automated Flagger Assistance Devices (AFAD) that is a highly visible, stand-alone unit controlled electronically from a transmitter carried by an operator located safely out of harm's way (Intellistrobe 2016). The systems conform to the Interim Approval guidelines for AFADs and have met the Federal National Cooperative Highway Research Program (NCHRP) 350 crashworthy performance criteria (FHWA 2004). A flagger for each AFAD is specified for limited line-of-site instances or distances over 250 meters. The AFAD Lane Intrusion Alarm is activated when traffic crosses the hose and enters work zone. The Modified Gate Arm allows visual confirmation for the controller. Signal heads must be covered when the system is being used for lane intrusion only (Intellistrobe 2016).

6.7.1.4 Radar-Based Intrusion Technology Systems

According to Cleaver (2016), the AWARE system is a radar-based system that can detect a potential work zone intrusion from multiple vehicles, and, simultaneously, warn an errant driver and workers who may be in harm's way. The system consists of a sensor that includes electronically-scanned radar, high-precision differential GPS, accelerometers, gyroscopes, and magnetometers for position and orientation sensing. High-definition video and several wireless interfaces are used to monitor traffic in the area. All the different components of the system work together to broadcast a warning when an intrusion is detected. A second sensor includes a tracking device that is typically strapped to the workers' hard hats, vests or armbands with high-precision position sensing, as well as wireless interfaces that receive warning signals from the other system sensor. If the worker is in the path of an oncoming threat, a vibrating motor and acoustic buzzer will alert the user that a threat is approaching. Visual and audible alerts will also be activated if a threat is detected.

The initial pilot project that used the Oldcastle's AWARE System was in Missouri. Based on the experience in Missouri and another project in Texas, the company was able to make improvements which made the system fully functional on a divided highway project in Texas, as reported by Cleaver (2016). The manufacturer of the system is now focused on making it user-friendly so that supervisors can utilize it without external assistance. The company planned to test the system on 12 more projects across eight states in 2016. The AWARE system is a trademark technology owned by Oldcastle Materials.

6.7.1.5 Radio-Based Intrusion Technology Systems

The Intellicone and the Wireless Warning Shield were the two radio-based technology systems identified in this review for work zone safety applications. The Intellicone system is a system of a base Portable Site Alarm (PSA) that acts as a signal receiver and auditory-visual alarm and a set of integrated lamps and impact sensors (Unipart Dorman ConeLITE). The impact sensors are powered by heavy duty batteries in the base of the unit and the lamps are yellow Light-Emitting Diodes (LEDs). When activated, the sensors become active and the lamps begin to flash in steady intervals. The lamps, when desired, are also intended to function as sequential lighting. These sensor units are attached to the top of a standard traffic cone or channelizer using a single bolt. Once activated, the sensors use a three-axis accelerometer to measure both tilt and impact. Signal processing algorithms are used to remove false positives. The sensors then transmit a signal using a 433-megahertz radio frequency transmitter. If the sensor is close enough to the PSA unit for it to receive the signal, the alarm will activate. If not, the signal is repeated through the sensor network, which acts as a mesh network, chaining the information until it reaches the PSA unit (Novosel 2014; Intellicone 2016). The Intellicone system has only been tested in Kansas and it is commercially available. Figure 6.4 shows the different units of the Intellicone Alarm System. The Intellicone Portable Site Alarm (PSA) uses an internal rechargeable battery, while the Intellicone Unipart Dorman ConeLITE (i.e. impact sensor) uses a 6V Carbon-Zinc Heavy Duty Lantern Battery (Intellicone 2016).

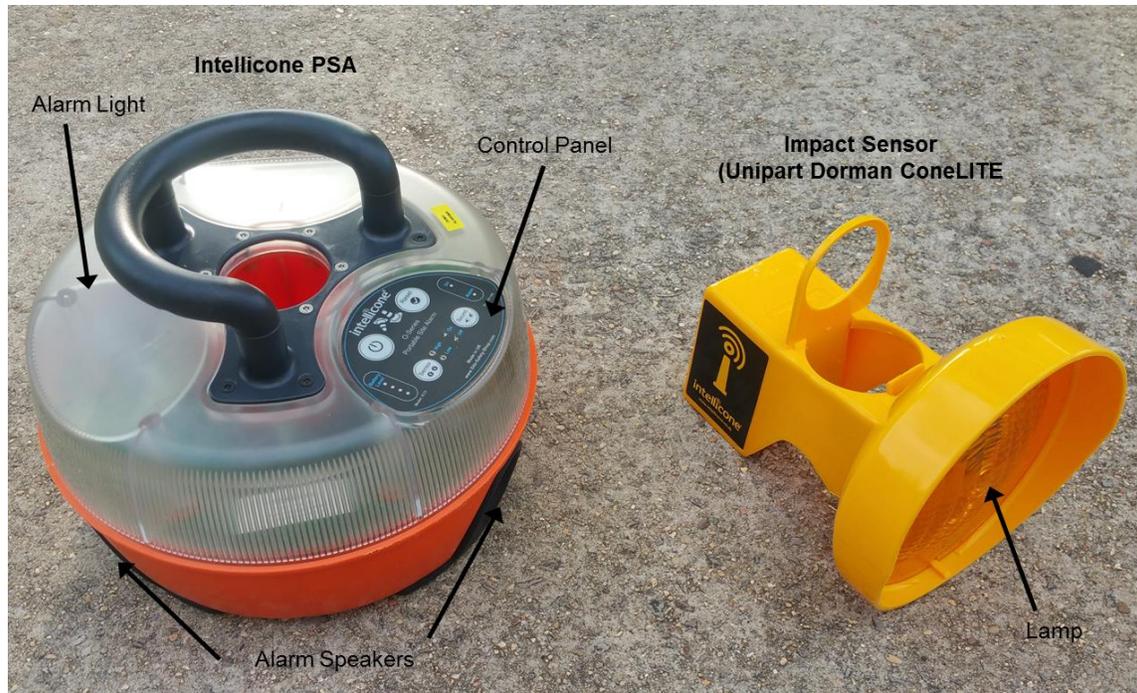


Figure 6.4: Intellicone alarm system

The wireless warning shield uses a coded repeater-style radio system. The unit, which is triggered via an internal shock sensor, transmits a radio signal that is picked up and retransmitted by the next two or three repeaters, each of which repeat as well. For a range of about 90 meters, several cones should be triggered at once, causing redundancy of repeater points. The repetition increases the reliability of the repeater chain. The signal is also picked up by any of the receiving alarm systems that are within range. These alarms, whether area alarms, personal body alarms, or headphone alarms, will all signal a “hit,” indicating possible danger (Kocheva 2008; Ozbay et al. 2012). The Wireless Warning Shield processor functions to allow for fewer false triggers. It can be mounted on almost any type of traffic control device and it is very economical. Detailed information on the performance of wireless warning shield is not available because the technology is not commercially available and has not yet been applied or tested in any work zone.

6.8 Experimental Procedure and Results

This section presents the experimental evaluation of selected commercially available intrusion technologies based on the review of applicable technologies for work zone safety. As presented in Table 6.1, one commercially available technology device was selected for each of kinematic, pneumatic/microwave, and radio-based intrusion alarm systems. Preliminary testing was first carried out on the technologies to test if they function well and provide the required alerts. Field experimental trials were then carried out to implement the technologies for work zone safety in a simulated work environment. Discussion points are provided based on findings from the implemented experimental methodologies.

6.8.1 Experimental Set-up and Data Collection

The test bed was established on an abandoned straight concrete roadway with minimal grade on the selected site for experimental trials as shown in Figure 6.5. About 300 meters of the roadway was marked out for the experimental trials. Traffic cones were placed at 6 meters intervals along the roadway for approximately 300 meters. A taper was created with the traffic cones at the beginning of the test bed to simulate a lane closure.

The setting up of the radio-based alarm involved mounting five impact sensors on consecutive traffic cones (Figure 6.5). The radio-based alarm PSA was mounted on another traffic cone located at 9 meters, 9 meters, and 15 meters from the impact sensors for set 1, 2, and 3 of the experimental trials respectively. The pneumatic/microwave alarm was set up by placing a pneumatic trip hose with attached sensor lining the traffic cones along the testbed. The horn/light assembly was located away from the pneumatic trip hose sensor. The kinematic alarm

was set up by attaching the unit to a traffic cone. Figure 6.5 shows the test bed of the experimental trials for the testing of the radio-based alarm system.



Figure 6.5: Test bed for experimental trials

A video recorder and time lapse camera were positioned to record the experimental trials. Three sets of experimental trials were conducted for each of the technologies. In the first set, a worker was made to stand at 9 meters from the alarm speaker. A member of the research team drove a vehicle at the speed of 40 kilometers per hour (25 miles per hour) and a rod protruding from the vehicle was made to hit the cone on which the impact sensor was mounted to activate the alarm. This technique was used for the testing of the radio-based and kinematic alarm technologies while the vehicle crossed over the air pressure hose to trigger the alarm during the testing for the pneumatic/microwave alarm. Figure 6.6 shows the layout of the experimental trials site for the testing of pneumatic/microwave alarm.

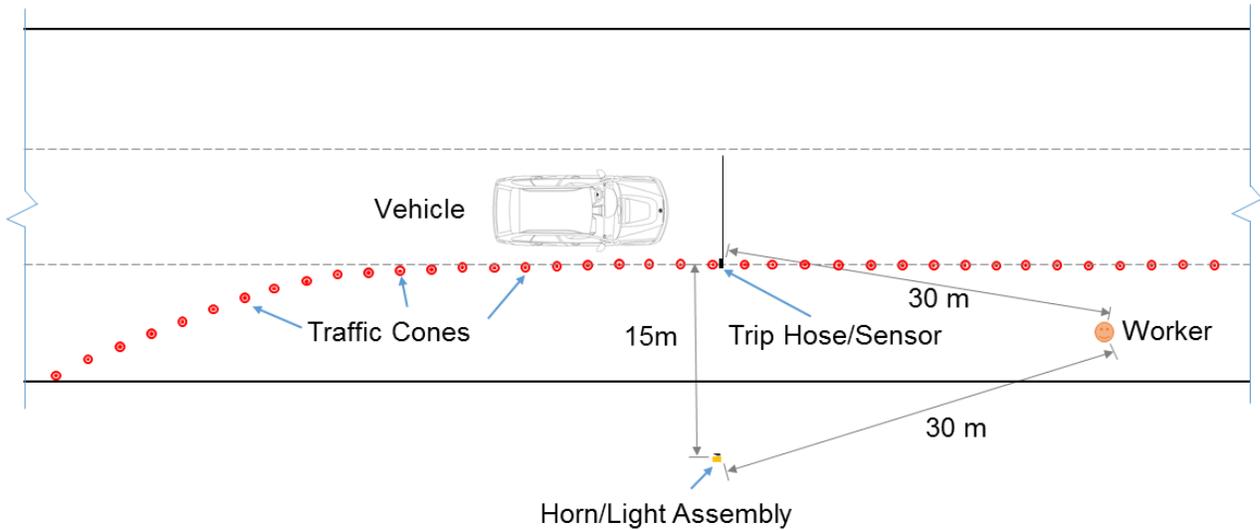


Figure 6.6: Layout of the experimental trials site

The sound level was measured from the alarm speaker to the worker's location using a sound meter and the process was repeated for a total of 15 trials. The worker's reaction time as well as the time taken for the vehicle to come to a complete stop after the impact were then extracted from the video recording. The stopping distance was also measured and computed using the vehicle speed and stopping time after the activation of the alarm. The worker stood 15 meters and 30 meters away from the alarm speaker for the second and third sets of experimental trials, respectively, while the vehicle was driven at 72 kilometers per hour (45 miles per hour) for both sets of experimental trials. The same procedure used for the first set of experimental trials was used for the remaining two sets. Attempts to test the kinematic alarm were unsuccessful as the unit did not provide the warning alarm when the cone on which it was mounted was impacted by the traveling vehicle.

6.8.2 Experimental Evaluation Results

The data analysis, results, and discussion of the experimental trials are presented in this section. The analysis of the sound level provided by the two intrusion alarm technologies is presented and discussed. The worker's reactions to the alarm technologies are assessed and discussed. The reaction of the vehicle driver was also evaluated in terms of the vehicle stopping time and the vehicle stopping distance. The implication of the experimental outcomes for work zone safety is also discussed.

6.8.2.1 Sound Levels of the Intrusion Alarm Technologies

The sound levels of the two alarm systems measured at different distances from the alarm source with the aid of a sound meter are presented in Figure 6.7. The sound meter used to measure the sound level of the alarms was calibrated using the sound decibel levels of three common noise sources. The sound levels of a handsaw, electric drill, and hair drier were used. The alarm duration of the radio-based alarm was 60 seconds which was much longer than that produced by the pneumatic/microwave alarm which lasted for just 5 seconds. The sound levels were determined by extracting the sound level at the start of the alarm, the lowest and peak sound levels as well as the sound level at the end of the alarm from the graphed sound profile. These sound level points for 15 trials were used to compute the average sound level of each of the two technologies at distances of 3 meters, 9 meters, 15 meters, and 30 meters from the alarm speaker. The results showed that the sound levels provided by these two systems were very close at the different distances as illustrated in Figure 6.7 with the radio-based alarm generally having a higher sound level than the pneumatic/microwave alarm.

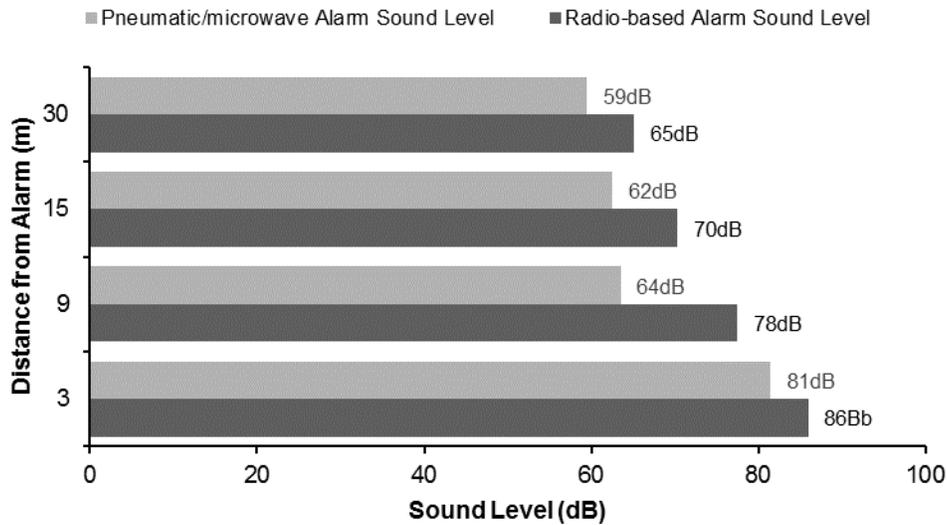


Figure 6.7: Sound level of the radio-based and pneumatic/microwave alarms

As expected, the sound level decreased as the distance of the sound meter from the alarm speaker increased with the radio-based alarm still having the louder sound level throughout the distances. The sound levels of the two alarm technologies were also tested with construction equipment (a backhoe was in use on a construction site near the test area). Although dependent on the distance of the construction equipment from the alarm source, the sound level of the two alarm technologies was found to be distinct and higher than the sound produced by the backhoe.

6.8.2.2 Worker’s Reaction to the Intrusion Alarm Technologies

The results of the worker’s reaction to the alarm produced by the two systems tested are presented in Figure 6.8. The results indicate that worker reacted to the alerts provided by both alarm technologies. The worker reacted a little faster to the radio-based intrusion alarm than the pneumatic/microwave alarm even as the distance of the alarm from the worker as well as the vehicle speed varied. The shorter reaction time recorded for radio-based alarm could be because

of the higher sound volume produced by the radio-based alarm, which may have also been amplified by the sound made from the collision of the intruding vehicle with the cone on which the impact activated sensor alarm was placed.

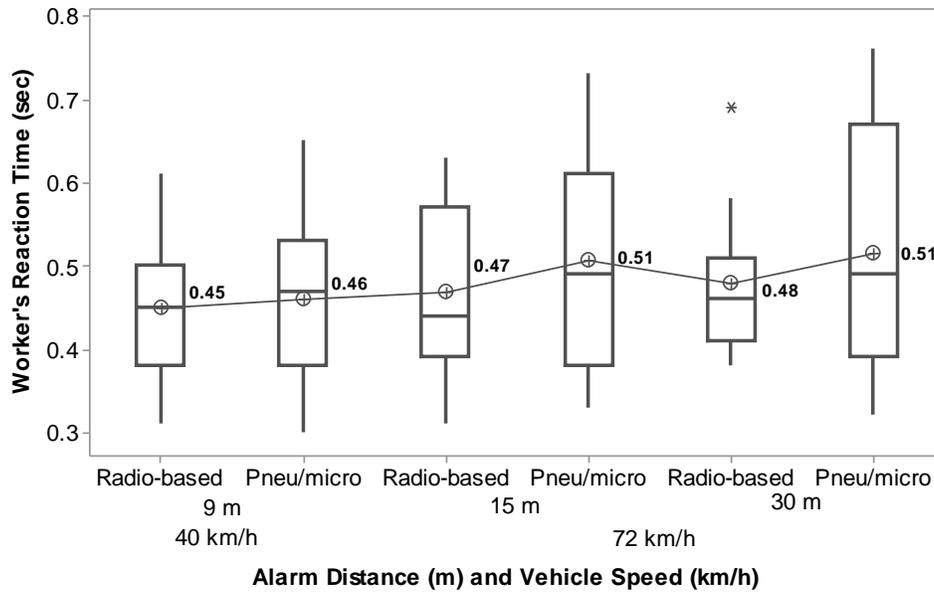


Figure 6.8: Results of worker’s reaction time

As expected, the average reaction time increased as the distance of the worker from the alarm increased as indicated in Figure 6.8. This implies that the closer the worker is to the alarm, the shorter the reaction time (i.e. the faster the worker reacts to the alarm). The results also indicate that the reaction time increased slightly with an increase in the speed of the intruding vehicle by a margin of 0.02 - 0.05 seconds, with the pneumatic/microwave alarm having the higher margin. Although the pneumatic/microwave alarm provided an extra Personal Safety Device (PDS), which gives the worker an additional vibrating alarm when a vehicle runs over the hose, this PDS was not found to be effective because the vibrating alert had delays ranging from

1 to 2.5 seconds, with an average delay of 0.37 second over the 15 trials performed in the experiment.

6.8.2.3 Response of Vehicle Driver to the Intrusion Alarm Technologies

The vehicle driver's response to the intrusion alarm technologies was evaluated in terms of the amount of time it took the driver to bring the alarm to a complete stop after hearing the sound from the alarm and possibly also observing the visual alert. The distance covered during this time was also measured and computed to establish the relative dynamic position of the intruding or errant vehicle from pedestrian workers at work zones. The vehicle stopping distance was computed using Eq. (1).

$$S_D = 0.224vt \tag{1}$$

Where S_D is the vehicle stopping distance in meters (m), v is the vehicle speed in miles per hour (mph), and t is the vehicle stopping time in seconds (sec).

Vehicle Stopping Time

The results of the vehicle stopping time at vehicle speed of 40 kilometers per hour and 72 kilometers per hour are presented in Figure 6.9. The results of the experimental trials show that the driver took a longer time to stop the vehicle when the pneumatic/microwave alarm was used than the radio-based alarm. This could be because of the higher sound volume produced by the radio-based alarm together with the impact sound when the cone is knocked down. The fact that the alarm is activated when the vehicle runs over the pneumatic trip hose in the

pneumatic/microwave alarm without a loud impact sound may not give the driver that additional alert apart from the sound produced from the alarm and the directional light from the alarm system.

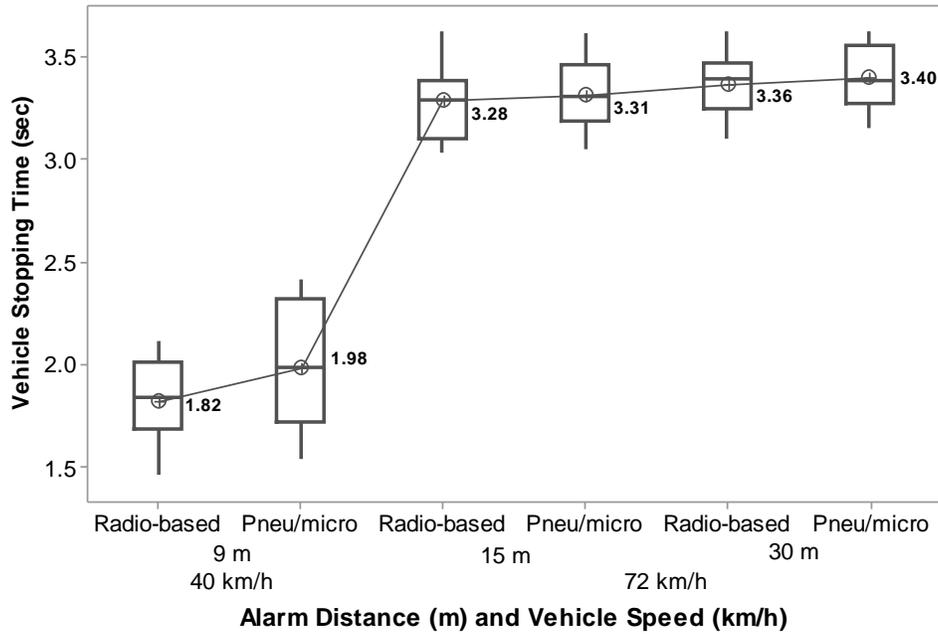


Figure 6.9: Results of vehicle stopping time

As expected, the vehicle stopping time increased as the vehicle speed was increased from 40 kilometers per hour to 72 kilometers per hour with a difference ranging between 1.42 and 1.54 seconds for the pneumatic/microwave alarm and radio-based alarm, respectively. The decision on the positioning of the alarm source should be carefully thought out because irrespective of how well the position of both the pedestrian worker and the vehicle is considered, it might be wiser to give more preference to the pedestrian worker for faster response. In this case, the worker’s response time is compared to the time taken by the driver to bring the vehicle to a complete stop. The results from the previous section indicated that the worker took an average of 0.45 seconds to respond to the alarm provided by the radio-based alarm, while it took

the driver 1.82 seconds to bring the vehicle traveling at 40 kilometers per hour (i.e. 25 miles per hour) to a complete stop. This implies that the distance covered by the vehicle in 0.45 seconds (which is approximately equal to 2.52 meters) in the direction of the pedestrian worker should be less than the position of the worker. Similarly, in the case of the pneumatic/microwave alarm, the distance covered by a vehicle traveling at 72 kilometers per hour (i.e. 45 miles per hour) in 0.51 seconds (which is ≈ 5.14 meters) in the direction of the pedestrian worker should be less than the position of the worker.

Vehicle Stopping Distance

Figure 6.10 illustrates the results of the vehicle stopping distance at vehicle speed of 40 kilometers per hour and 72 kilometers per hour when the two alarm systems were used one after the other. The experimental findings indicate that a longer distance was covered before the vehicle was brought to a complete stop when the pneumatic/microwave alarm was used than when the radio-based alarm was deployed, as depicted in Figure 6.10. This again could be because of the louder sound produced by the radio-based alarm.

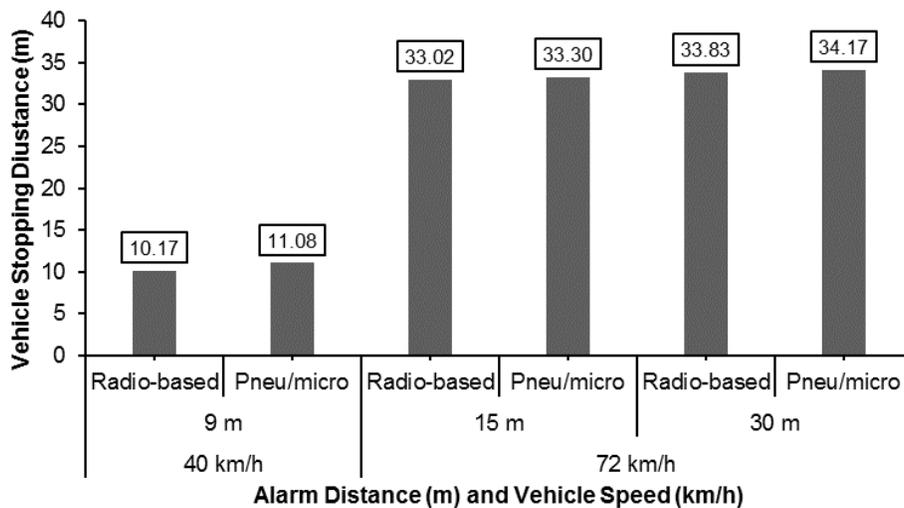


Figure 6.10: Results of vehicle stopping distance

The consideration of these vehicle stopping distances is paramount in the planning of the layout for the implementation of these intrusion alarm technologies. These distances with an extra factor of safety may perhaps be set as the minimum allowable distance between the intrusion sensor and the pedestrian workers.

6.8.2.4 Implications of the Experimental Findings for Work Zone Safety

The results of the experimental investigation imply that warning alerts can be provided to the workers and vehicle drivers around work zones when a hazardous situation occurs. This implication can be observed in the experimental results as depicted in Figure 6.11. On average, it took a worker less than 1 second to respond to warning alerts produced by the tested intrusion sensing technologies. This result is satisfactory, but cannot be considered in isolation because the response of the vehicle driver is vital in determining if the pedestrian worker is fully protected from being hit by the vehicle.

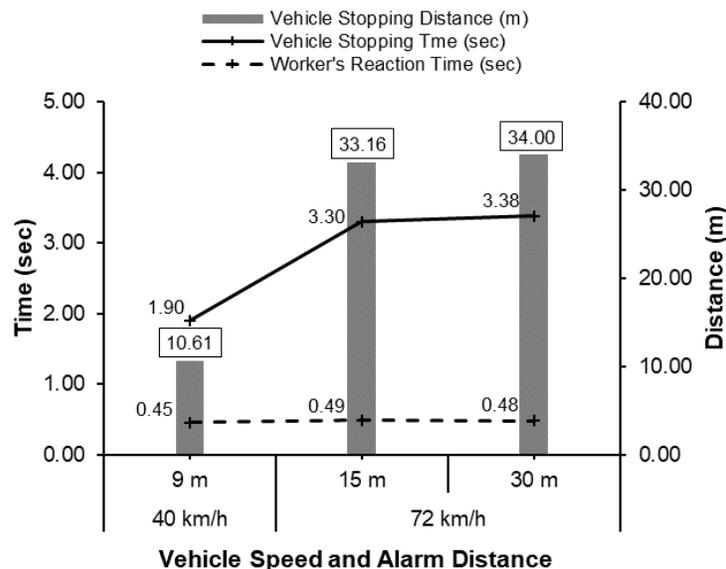


Figure 6.11: Summary of experimental results

The minimum stopping distance for a vehicle is determined by the effective coefficient of friction between the tires and the road, and the driver's reaction time in a braking situation, assuming proper operation of brakes on the vehicle. Using the results of this experimental evaluation, the work area should not be less than 10.61 meters away from the intrusion sensing device, while it should be a minimum of 34.00 meters if the posted vehicle speed is 72 kilometers per hour (i.e. 45 miles per hour). These results would have been compared to the posted stopping distances obtained from past transportation studies, but there is no uniformity in the values determined as these values vary from one document to the other.

Though the experimental findings may not be generalized because other factors not investigated may also influence the responses of workers and vehicle drivers warning alerts, it is relevant to note that these results can be used in planning the work zone layout when some of these technologies are deployed to mitigate injuries and fatalities.

6.9 Implementation Guide

Adopting new technology and innovation is vital for government entities to conduct business effectively for its employees. One major challenge of capturing and realizing the multitude of benefits produced by innovative safety technologies is the proper implementation of such systems. This guide provides recommendations and best practices for implementing intrusion sensing and alert systems for enhancing safety of workers in highway construction zones.

Highway construction zones of transportation infrastructure provide unique challenges for ensuring the safety of Department of Transportation (DOT) personnel. Construction equipment and ground workers are often required to operate at close proximity to traveling

vehicles. Highway work zone intrusion alert systems can provide real-time alerts to pedestrian workers and equipment operators when a hazard is present. Through wireless communication using various technologies and systems, work zone intrusion alert systems can provide alerts to highway work zone personnel when hazardous situations are detected.

This guide was created in an effort to effectively implement highway work zone intrusion alerts systems for work zone personnel. For proper implementation, several steps were created and discussed in this research. Figure 6.12 presents the steps for implementation. Subsequent sections of this guide describe in detail the best practices for each implementation step shown in Figure 6.12.

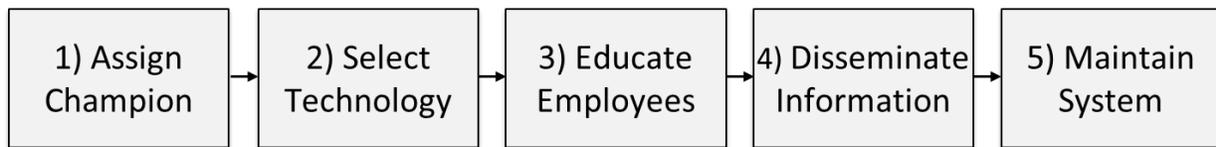


Figure 6.12: Steps for implementation of work zone intrusion alert systems

6.9.1 Step 1: Assign Champion

One of the most effective steps in implementing a highway work zone intrusion alert system for enhancing safety in highway work zones is to designate a “champion” of implementing the system. The selected champion is an employee of the DOT that is familiar with implementing systems or technologies. This person must be committed to implementing the selected technology. Although the champion may have other responsibilities, implementing this system should be one of the person’s top priorities. The champion should have the following characteristics:

- A basic understanding of the challenges of safety with DOT employees in a highway work zone;
- Previous experience with implementing systems within a DOT environment;
- A desire to understand highway work zone intrusion alert systems.

Before other steps of the implementation process, the champion must fully understand the highway work zone intrusion alert systems. The champion must read this guide and create a plan based on best practices presented.

6.9.2 Step 2: Select Technology

Based on results of the review and experimental evaluation, several recommendations have been made for selecting and implementing work zone sensing technology. The implementation of the radio-based alarm for longer tapers in construction highway work zones where traffic barrels or other longer term temporary devices are deployed is recommended. The pneumatic/microwave alarm is recommended for short tapers and short term or mobile highway work zone projects. Each manufacturer provides specific step-by-step instructions on how to deploy and maintain the highway work zone intrusion alert systems. Table 6.2 provides a selection guide for work zone intrusion detection devices.

Table 6.2: Selection guide for work zone intrusion detection devices

Situations	Radio-based Alarm	Pneumatic/microwave Alarm
Longer than one day	x	
One day or shorter		x
Taper shorter than 457.2 m (1,500 ft.)		x
Taper longer than or equal to 457.2 m	x	

6.9.3 Step 3: Educate Employees

After assigning an implementation champion and selecting a highway work zone intrusion alert system, end users of the system must be educated. DOT employees who work in highway work zones should be instructed about the value of work zone intrusion alerts, functionality of the systems, and how to maintain the devices. This educational component can be integrated into existing DOT employee training and should be tailored towards those employees who will be the end users of the systems - DOT personnel in highway work zones. The training must include the following: 1) Instructions and demonstrations of how to set-up the system, including mounting locations for all devices; 2) proper calibration of the system to the desired alert distance; and 3) explanation of the functionality of the system during use. The champion should create and organize the training materials, as well as conduct the training for the employees. Several sets of highway work zone intrusion alert systems should be available for demonstration by the employees after the information is given. After all employees have received the required training, the systems should be deployed in initial field trials before extending to all active work zone projects.

6.9.4 Step 4: Disseminate Information

Once the system is deployed in an initial field trial, workers using the system should be surveyed. Employees should be questioned about their ability to use the system, if they encountered any limitations, and suggested changes. Changes to the education, calibration, and other variables should be made by the champion based on the results of the initial trials. Feedback from employees should be acted on and communicated to the workers because they will be the end users of the system.

6.9.5 Step 5: Maintain System

The champion should implement strategies to maintain the highway work zone intrusion alert system. These strategies should include requiring workers to check the battery status before deployment (to know when a simple replacement of battery is required), maintain the system, and understand the requirements for updating training for workers utilizing the system. Workers should be re-trained or updated at least every year for usage of the highway work zone alert system.

6.10 Conclusion

The limited work space and ever-changing nature of highway construction work zones make the work environment very dangerous for pedestrian workers (Gambatese and Lee 2016; Fyhrie 2016). Active sensing and alert devices are not readily available in highway work zones and in transportation infrastructure construction and maintenance. The applicable intrusion technologies for work zone safety were reviewed in this chapter. Commercially available technologies were evaluated using experimental trials. This research contributes to the body of knowledge by providing strategies for selecting and implementing intrusion sensing technologies for active work zone safety.

Out of the seven applicable intrusion technologies reviewed, only four are commercially available. The findings of this review indicate that a few states have had difficulty in using most of the early intrusion alarm systems despite the efforts made by the device manufacturers to improve these systems. Some of the shortcomings of the technologies are lengthy set up time, false alarms, misfires, and alignment difficulties. This has continued to hinder the widespread application of these technologies for work zone safety. For instance, there were challenges with

the use of the kinematic alarm, which led to the inability of the research team to evaluate the technology at the time the radio-based and pneumatic/microwave alarms were evaluated.

The results of the experimental evaluation of the radio-based and pneumatic/microwave alarms indicate that the two technologies produce more than one type of alert which can be used to warn workers when a vehicle intrudes a construction work zone. The findings also indicate that workers and vehicle drivers responded to the warning alerts provided by these technologies as observed in the reaction times obtained in the experimental trials. As expected, the worker's reaction time was on average less than 1 second, while the vehicle stopping time was less than the posted stopping time for vehicle traveling at the same speed used in this experimental evaluation. Additionally, the performance of the two technologies evaluated by the research team was satisfactory in terms of power consumption as no issues were encountered with batteries running down. The batteries supplied the required power throughout the duration of the experiments. The technologies were relatively easy to set up and no cases of false alarms were experienced while testing the radio-based and pneumatic/microwave alarms.

By implementing a highway work zone intrusion alert system, pedestrian workers in work zones can be alerted when they are located near a hazard. The implementation guide provides best practices associated with implementing and maintaining a highway work zone intrusion alert system. These technology systems as well as others can provide an additional layer of safety protection for DOT personnel in hazardous work environments.

CHAPTER 7

CONCLUSIONS

This chapter presents the summary and concluding remarks for this research. The concluding remarks are structured to address the research needs statement as well as the research hypothesis presented in Chapter 3 of this dissertation. Major findings of the research, its contributions and impacts, identified limitations, and future research extensions of this work are discussed in this concluding chapter.

7.1 Concluding Remarks

Construction sites are characterized by harsh outdoor environments, changing site conditions, and dynamic interactions between resources, including personnel, equipment, and materials. The peculiar nature of the construction environment makes it very hazardous and thus increases the rate of occupational injuries, illnesses, and fatalities recorded in the construction industry (BLS 2016a). Regulatory agencies, such as OSHA, require construction companies to record and report workplace accidents including illnesses, injuries, and fatalities, all of which are categorized as lagging indicators (OSHA 2015). This research has demonstrated that reporting safety leading indicators, such as near misses, allows for worker safety performance measurement without requiring accident data. By collecting and analyzing safety leading indicators such as near misses, potentially hazardous conditions or worker behaviors on construction sites can be identified before an illness, injury, or fatality occurs. Safety managers

and other construction site personnel can then disseminate near miss information and lessons learned through worker safety education and training.

Leveraging technology to collect, analyze, and disseminate safety leading indicator information can be very beneficial to improving worker safety performance on construction sites. This research has also established that the use of wearable technologies for automated collection, analysis, and dissemination of safety leading indicator data of specific hazardous situations can be implemented in construction. Deploying intrusion sensing technologies on highway work zones can provide an additional layer of protection through warning alerts when hazardous conditions exist. By implementing these technologies in construction, real-time information can be provided to construction personnel on safety and health hazards in order to mitigate the potential of having a high rate of illnesses, injuries, or fatalities on construction sites and highway work zones.

Based on the objectives of this research and the hypothesis generated, the conclusions of the research are summarized as follows.

- 1) It is hypothesized that a multitude of minor incidents such as near misses are required for one major incident to occur on a construction site. In this research, a near miss data collection and analysis framework was provided. This framework provides scientific data for managing near miss information and includes strategies for implementation, statistical outlines for analyzing collected data, and recommendations for disseminating useful information and lessons learned. The significance of reporting and analyzing near miss data was validated by the results of this research, which show that near miss reporting decreased OSHA-defined recordable injuries on a construction site.

- 2) This research also provided an evaluation of the features of wearable technology and the resulting safety metrics capable of predicting safety performance and management practices. Potential applications of wearable devices for capturing and monitoring various metrics responsible for the common injuries and fatalities on construction sites were identified. Specifically, wearable sensors for physiological monitoring, environmental sensing, proximity detection, and location tracking were identified and evaluated for continuous monitoring of a wide range of vital signals which can provide early warning signs of safety issues to construction workers.
- 3) Strategies for identifying and selecting intrusion sensing technologies that can be deployed on work zones were developed using an exploratory review of applicable technology systems. Candidate commercially available intrusion sensing technologies were selected based on chosen evaluation metrics and the performance characteristics of the devices. The findings of the experimental evaluation of candidate commercially available technologies indicate that by implementing highway work zone intrusion sensing technologies, pedestrian workers in work zones can be alerted when hazardous situations exist.
- 4) Best practices for collecting and analyzing these near miss data was provided using a near miss data collection and analysis framework. A model for integrating several sensors and systems into construction-specific wearable devices for multi-parameter monitoring was provided. An implementation guide, or a set of best practices associated with implementing and maintaining highway work zone intrusion sensing technology, was provided.

7.2 Contributions and Impacts

Several contributions are identified in this research. These contributions can supplement and enhance existing information in both academic research and in the construction industry concerning the use of safety leading indicators and sensing technologies. The following are the specific contributions of this research:

- A near miss data collection and analysis framework and scientific data for the management of near miss information;
- A scientific evaluation of wearable technology systems for personalized safety monitoring in construction, as well as a model for integrating wearable sensors for multi-parameter safety performance monitoring;
- An evaluation data and experimental methodology for selecting and implementing intrusion sensing technologies to enhance safety in highway work zones;
- A best safety practice for construction management personnel that allows implementing innovative safety technologies as well as the use of collected data and information in operational procedures, safety training, and education.

These contributions have potential to impact the construction industry by improving safety conditions of workers during hazardous situations. Envisioned supplementation impacts include the following: barriers for implementation of safety technologies can be better understood and addressed, research deliverables can be used for education and safety training, and construction safety can be promoted by evaluating and implementing active safety leading indicators, including selected innovative safety technologies.

7.3 Limitations and Future Research

While the use of safety leading indicators such as near misses can identify hazards, and predict potential worker illnesses, injuries, or fatalities, the analysis of the collected data is not done in real-time. Further research in this area includes automated safety observations using sensing technologies such as physiological monitoring devices. By knowing a construction worker's physiological data, such as heart rate, skin temperature, and bending angle, a safety manager can proactively identify an existing hazard before an injury, illness or fatality occurs.

Although this research provides a comprehensive evaluation of applicable wearable technology systems for construction, potential future research includes performing experimental trials with commercially available wearable technologies to determine their effectiveness and applicability in construction. Prototypes of construction-specific wearable devices can also be developed and tested for personalized safety monitoring and trending in construction.

Other than providing real-time alerts for workers in highway work zones, other hazard mitigation efforts resulting from analyzed safety leading indicator data (such as precise hazard location or direction) are not available in real-time. Wearable devices on workers can also be used along with the intrusion sensing technologies for automated collection and analysis of other safety leading indicator data to provide more precise and detailed information to workers when hazardous situations exist in highway work zones.

REFERENCES

- Agent, K. and J. Hibbs. (1996). "Evaluation of SHRP work zone safety devices." *Research Report No. KTC-96-30*, Kentucky Transportation Center, Lexington, KY.
- Ahmadi, A., Rowlands, D., and James, D. A. (2010). "Towards a wearable device for skill assessment and skill acquisition of a tennis player during the first serve." *Sports Engineering*, 2(3-4), 129-136. <https://doi.org/10.1002/jst.112>
- Albert, A., Hallowell, M. and Kleiner, B. (2013). "Enhancing construction hazard recognition and communication with energy-based cognitive mnemonics and safety meeting maturity model: multiple baseline study." *Journal of Construction Engineering and Management*, 140(2), 04013042-1-12.
- Ananthanarayan, S., and Siek, K. A. (2010). "Health Sense: A Gedanken Experiment on Persuasive Wearable Technology for Health Awareness." *Proceedings of the 1st ACM International Health Informatics Symposium*, 400-404. <https://doi.org/http://doi.acm.org/10.1145/1882992.1883051>
- Anastasi, G., Conti, M., Di Francesco, M., and Passarella, A. (2009). "Energy conservation in wireless sensor networks: A survey." *Ad Hoc Networks*, 7(3), 537-568. <https://doi.org/10.1016/j.adhoc.2008.06.003>
- Andrijcic, E., Haimes, Y. Y., and Beatley, T. (2013). "Public policy implications of harmonizing engineering technology with socio-economic modeling: Application to transportation infrastructure management." *Transportation Research Part A: Policy and Practice* 50: 62-73.
- Anliker, U., Ward, J. A., Lukowicz, P., Tröster, G., Dolveck, F., Baer, M., ... Vuskovic, M. (2004). "AMON: A wearable multiparameter medical monitoring and alert system." *IEEE Transactions on Information Technology in Biomedicine*, 8(4), 415-427. <https://doi.org/10.1109/TITB.2004.837888>
- Anzaldo, D. (2015). "Wearable sports technology - Market landscape and compute SoC trends." *ISOCC 2015 - International SoC Design Conference: SoC for Internet of Everything (IoE)*, (November), 1-6. <https://doi.org/10.1109/ISOCC.2015.7401796>
- Astro Optics (2017). "Traffic Guard Worker Alert System." *Astro Optics, LLC*. <http://www.astrooptics.com/products/traffic-guard-worker-alert-system>

- Awolusi, I. G. and Marks, E. D. (2016). "Safety Activity Analysis Framework to Evaluate Safety Performance in Construction." *Journal of Construction Engineering and Management*, 143(3), 05016022-1-05016022-12
- Awolusi, I., Marks, E., and Hallowell, M. (2016). "Physiological Data Collection and Monitoring of Construction Equipment Operators." *Construction Research Congress 2016*, 1136–1145.
- Bansal, V. K. (2011). "Application of geographic information systems in construction safety planning." *International Journal of Project Management*, 29(1), 66–77.
<http://doi.org/10.1016/j.ijproman.2010.01.007>
- Bathula, M., Ramezanali, M., Pradhan, I., Patel, N., Gotschal, J., and Sridhar, N. (2009). "A sensor network system for measuring traffic in short-term construction work zones." *Distributed Computing in Sensor Systems, Volume 5516 of the series Lecture Notes in Computer Science*, 216-230.
- Beecham Research (2016). "Wearable Technology Application Chart." *Beecham Research*, <http://www.beechamresearch.com/article.aspx?id=20>
- Belchior, R., Junior, D., and Monteiro, A. (2013). "ANT+ Medical Health Kit for Older Adults." *Institute for Computer Sciences, Social Informatics and Telecommunications Engineering 2013*, 20–29.
- Benekohal, R., Kaja-Mohideen, A. and Chitturi, M. (2004). "Methodology for estimating operating speed and capacity in work zones." *Transportation Research Record: Journal of the Transportation Research Board*, 1883(1), 103-111.
- Bianchi, F., Redmond, S. J., Narayanan, M. R., Cerutti, S., and Lovell, N. H. (2010). "Barometric pressure and triaxial accelerometry-based falls event detection." *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, (18)619-627
- Bonato, P. (2009). "Advances in wearable technology for rehabilitation." *Studies in Health Technology and Informatics*, 145, 145–159. <https://doi.org/10.3233/978-1-60750-018-6-145>
- Bonato, P. (2010). "Advances in wearable technology and its medical applications." *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC'10, 2021–2024*. <https://doi.org/10.1109/IEMBS.2010.5628037>
- Bonato, P., Mork, P. J., Sherrill, D. M., and Westgaard, R. H. (2003). "Data Mining of Motor Patterns Recorded with Wearable Technology." *IEEE Engineering in Medicine and Biology Magazine*, 22(3), 110–119. <https://doi.org/10.1109/MEMB.2003.1213634>
- Bosch Sensortec (2017). "Environmental Sensing." *Bosch Sensortec*, https://www.bosch-sensortec.com/bst/products/environmental/overview_environmental

- Bourke, A. K., van de Ven, P. W., Chaya, A. E., OLaighin, G. M., and Nelson, J. (2008). "Testing of a long-term fall detection system incorporated into a custom vest for the elderly." *Conf Proc IEEE Eng Med Biol Soc 2008*, 2844-2847.
- Briand, D., Oprea, A., Courbat, J., and Bârsan, N. (2011). "Making environmental sensors on plastic foil." *Materials Today*, 14(9), 416–423. [https://doi.org/10.1016/S1369-7021\(11\)70186-9](https://doi.org/10.1016/S1369-7021(11)70186-9)
- Bryden, J. and Mace, D. (2002). "Guidelines for design and operation of nighttime traffic control for highway maintenance and construction." *NCHRP Report 476, Transportation Research Board*. Washington, D.C.
- Bureau of Labor Statistics (BLS). (2012). "Non-fatal occupational injuries and illnesses requiring days away from work, 2011." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, <http://www.bls.gov/news.release/osh2.nr0.htm> (Oct. 10, 2013).
- Bureau of Labor Statistics (BLS). (2013a). "Industry at a glance: Construction." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, <http://www.bls.gov/iag/tgs/iag23.htm> (Oct. 16, 2014).
- Bureau of Labor Statistics (BLS). (2013b). "Accident/Incident investigation." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, http://www.osha.gov/SLTC/etools/safetyhealth/mod4_factsheets_accinvest.html (Oct. 5, 2013).
- Bureau of Labor Statistics (BLS). (2015a). "Employer-Reported Workplace Injuries and Illnesses – 2014." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, http://www.bls.gov/news.release/archives/osh_10292015.pdf (June 12, 2016)
- Bureau of Labor Statistics (BLS). (2015b). "Employer-Reported Workplace Injuries and Illnesses – 2014." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, http://www.bls.gov/news.release/archives/osh_10292015.pdf (June 12, 2016).
- Bureau of Labor Statistics (BLS). (2016a). "2014 Census of Fatal Occupational Injuries (revised data) – industry by event or exposure, 2014." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, Retrieved from <http://www.bls.gov/iif/oshwc/foi/cftb0286.pdf> (June 12, 2016)
- Bureau of Labor Statistics (BLS). (2016b). "Census of Fatal Occupational Injuries (revised data) – All charts, census of Fatal Occupational Injuries, 2014." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, <http://www.bls.gov/iif/oshwc/foi/cfch0013.pdf> (June 12, 2016)
- Bureau of Labor Statistics (BLS). (2016c). "Injuries, Illnesses, and Fatalities - Revisions to the 2014 Census of Fatal Occupational Injuries (CFOI)." *U.S. Bureau of Labor Statistics, U.S. Department of Labor*, http://www.bls.gov/iif/foi_revised14.htm (June 12, 2016)

- Burkett, G. and Her, V. (2009). "Development of new kinds of mobile safety barriers." *AHMCT Research Center*, California Department of Transportation, Davis, California.
- Callum, J., Kaplan, H., Merkley, L., Pinkerton, P., Fastman, B., Romans, R., Coovadia, A., and Reis, M. (2001). "Reporting of near-miss events for transfusion medicine: Improving transfusion safety." *Transfusion Practice*, 41(1), 1204-1211.
- Cambralia, F., Saurin, T., and Formoso, C. (2010). "Identification, analysis and dissemination of information on near misses: A case study in the construction industry." *Safety Science*, 48(1), 91-99.
- Carlson, P., Fontaine, M. and Hawkins, H. (2000). "Evaluation of traffic control devices for rural high-speed maintenance work zones." *Texas Transportation Institute*, The Texas A&M University System, College Station, Texas.
- Caterpillar (2013). "Object detection system." *Caterpillar*. <http://www.cat.com/detect> (Oct. 10, 2016).
- Center for Disease Control and Prevention (CDC). (2006). "NIOSH fatal occupational injury cost fact sheet: construction." *National Institute of Occupational Safety and Health Publications and Products*, 153.
- Chae, S., and Yoshida, T. (2010). "Automation in Construction Application of RFID technology to prevention of collision accident with heavy equipment." *Automation in Construction*, 19(3), 368–374. <https://doi.org/10.1016/j.autcon.2009.12.008>
- Chambless, J., Ghadiali, A., Lindly, J. and McFadden, J. (2002). "Multistate work-zone crash characteristics." *Institute of Transportation Engineers*. 72(5), 46.
- Cheng, P. T., Tsai, L. M., Lu, L. W., and Yang, D. L. (2004). "The design of PDA-based biomedical data processing and analysis for intelligent wearable health monitoring systems." *Computer and Information Technology, 2004. CIT '04. The Fourth International Conference on*, 879–884. <https://doi.org/10.1109/CIT.2004.1357306>
- Cheng, T., Migliaccio, G. C., Teizer, J., and Gatti, U. C. (2012). "Data fusion of Real-time Location Sensing and Physiological Status Monitoring for Ergonomics Analysis of Construction Workers." *Journal of Computing in Civil Engineering*, 27(3), 320–335. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000222](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000222).
- Cheng, T., Venugopal, M., Teizer, J., and Vela, P. A. (2011). "Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments." *Automation in Construction*, 20(8), 1173–1184. <https://doi.org/10.1016/j.autcon.2011.05.001>
- Cho, Y. K., Youn, J. H., and Martinez, D. (2010). "Error modeling for an untethered ultra-wideband system for construction indoor asset tracking." *Automation in Construction*, 19(1), 43–54. <https://doi.org/10.1016/j.autcon.2009.08.001>

- Choe, S., Leite, F., Seedah, D., and Caldas, C. (2014). "Evaluation of sensing technology for the prevention of backover accidents in construction work zones." *Journal of Information Technology in Construction*, 19, 1–19.
- Choudhry, R. M., Fang, D., and Mohamed, S. (2007). "The nature of safety culture: A survey of the state-of-the-art." *Safety Science*, 45(10), 993–1012.
- Civil Aviation Authority (CAA). (2013). "Safety Management: Incident Reporting and Investigation." *Civil Aviation Authority*.
<http://www.caa.co.uk/default.aspx?catid=1779&pageid=9864> (Oct. 10, 2016).
- Cleaver, L. (2016). "Oldcastle Materials Creates AWARE to Save Lives." *Oldcastle Materials*, <<http://www.forconstructionpros.com/article/12181842/oldcastle-materials-creates-aware-to-save-lives>> (Feb. 8, 2017).
- ConocoPhillips (2004). "Occupational Health and Industrial Hygiene." *ConocoPhillips*.
<http://www.conocophillips.com/sustainable-development/safety-health/Pages/occupational-health-and-industrial-hygiene.aspx> (Oct. 10, 2016)
- Construction Industry Institute (CII). (2012). "Measuring Safety Performance with Active Safety Leading Indicators." *Construction Industry Institute*, Austin, Texas.
- Dağdeviren, M., Yüksel, I., and Kurt, M. (2008). "A fuzzy analytic network process (ANP) model to identify faulty behavior risk (FBR) in work system." *Safety Science*, 46(5), 771–783. <http://doi.org/10.1016/j.ssci.2007.02.002>
- Darwish, A., and Hassanien, A. E. (2011). "Wearable and implantable wireless sensor network solutions for healthcare monitoring." *Sensors*, 11(6), 5561–5595.
<https://doi.org/10.3390/s110605561>
- Demirkesen, S., and Arditi, D. (2015). "Construction safety personnel's perceptions of safety training practices." *International Journal of Project Management*, 33(5), 1160–1169.
<https://doi.org/10.1016/j.ijproman.2015.01.007>
- Donovan, T. (2011). "U.S. Nuclear Power Plants 2010: UCS Report." *Huffington Post*.
http://www.huffingtonpost.com/2011/03/17/us-nuclear-power-near-misses-2010_n_837176.html#s254851&title=HB_Robinson (May 16, 2013).
- Duranton, G. and Turner, M. (2012). "Urban growth and transportation." *The Review of Economic Studies*, 79(4), 1407-1440.
- Fabiano, B. and Curro, F. (2012). "From a survey on accidents in the downstream oil industry to the development of a detailed near-miss reporting system." *Process Safety and Environmental Protection*, 90(5), 357-367.
- Fahn, C. S., and Sun, H. (2010). "Development of a fingertip glove equipped with magnetic tracking sensors." *Sensors*, 10(2), 1119–1140. <https://doi.org/10.3390/s100201119>

- Fang, Y., Cho, Y. K., Zhang, S., and Perez, E. (2016). “Case Study of BIM and Cloud-Enabled Real-Time RFID Indoor Localization for Construction Management Applications.” *Journal of Construction Engineering and Management*, 142(7), 1–12. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001125](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001125).
- Fearnley, J., and Nair, S. R. (2009). “Determining process safety performance indicators for major accident hazards using process hazard information.” *IChemE Symposium*, (155), 221–225.
- Federal Highway Administration (FHWA). (2015). “Manual on Uniform Traffic Control Devices.” *U.S. Department of Transportation. Federal Highway Administration*, <<http://mutcd.fhwa.dot.gov>> (Oct. 10, 2016).
- Federal Highway Administration (FHWA). (2016). “NCHRP Report 350: Devices in Work Zones.” *U.S. Department of Transportation*, <https://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/nchrp_350/> (Feb. 8, 2017).
- Federal Highway Administration (FHWA). (2016). Facts and Statistics – Work Zone Safety. *U.S. Department of Transportation. Federal Highway Administration*, http://www.ops.fhwa.dot.gov/wz/resources/facts_stats/safety.htm (Oct. 10, 2016)
- Finley, M., Ullman, G., and Dudek, C. (2001). “Sequential Warning-Light System for Work-Zone Lane Closures.” *Transportation Research Record*, 1745(1), 39–45. <http://doi.org/10.3141/1745-05>
- Flin, R., Mearns, K., O'Connor, P., and Bryden, R. (2000). “Measuring safety climate: identifying the common features.” *Safety Science*, 34(1), 177-192.
- Friedman, E. (2015a). “Using Wearable Tech for Workplace Safety.” *BrainXchange LLC*. <https://brainxchange.events/blog/using-wearable-tech-for-workplace-safety/> (June 12, 2016)
- Friedman, E (2015b). “Wearable Technology by Industry Series: Vol. 5 – Construction.” *BrainXchange LLC*. <https://brainxchange.events/blog/wearable-technology-industry-series-construction/>
- Friedman, E (2015c). “Wearable Technology by Industry Series: Vol. 4 – Public Safety & Security.” *BrainXchange LLC*. <https://brainxchange.events/blog/wearable-technology-industry-series-public-safety-security/>
- Fullerton, C. E., Allread, B. S., and Teizer, J. (2009). “Pro-Active-Real-Time Personnel Warning System.” *Construction Research Congress 2009*, 31–40.
- Fyhrie, P. (2016). “Work zone intrusion alarms for highway workers: Preliminary investigation.” *Caltrans Division of Research, Innovation and System Information*. California Department of Transportation.

- Gambatese, J. and Lee, H. (2016). “Work zone intrusion alert technologies: Assessment and practical guidance.” *SPR Research Program Second-Stage Problem Statement FY 2016. ODOT Research Unit*. Oregon Department of Transportation.
- Gambatese, J., and Hinze, J. (1999). “Addressing construction worker safety in the design phase: designing for construction worker safety.” *Automation in Construction*, 8(6), 643-649.
- Gatti, U., Migliaccio, G., and Schneider, S. (2011). “Wearable Physiological Status Monitors for Measuring and Evaluating Worker’s Physical Strain: Preliminary Validation.” *Computing in Civil Engineering 2011*, 2000(413), 194–201. [https://doi.org/10.1061/41182\(416\)94](https://doi.org/10.1061/41182(416)94)
- Givechi, M. (2015). “Cones sound a warning of work zone intrusion.” *Kansas LTAP Newsletter*, Kansas University Transportation Center.
- Goldenhar, L., Moran, S. and Colligan, M. (2001). “Health and safety training in a sample of open-shop construction companies.” *Journal of Safety Research*, 32(2), 237-252.
- Goodrum, P. M., McLaren, M. A., and Durfee, A. (2006). “The application of active radio frequency identification technology for tool tracking on construction job sites.” *Automation in Construction*, 15(3), 292–302. <http://doi.org/10.1016/j.autcon.2005.06.004>
- Grabowski, M., Ayyalasomayajula, P., Merrick, J., Harrald, J. R., and Roberts, K. (2007). “Leading indicators of safety in virtual organizations.” *Safety Science*, 45(10), 1013–1043. <http://doi.org/10.1016/j.ssci.2006.09.007>
- Guta, M. (2014). “The Impact of Wearable Tech in Sports.” *Wearable Tech World*. <http://www.wearabletechworld.com/topics/wearable-tech/articles/376634-impact-wearable-tech-sports.htm> (July 4, 2015)
- Hagan, M. (2004). “Work-zone safety ITS: technical analysis and system proposal.” *Transportation Research Institute (UMTRI)*. University of Michigan, Ann Arbor, MI.
- Hallowell, M. R. (2012). “Safety-Knowledge Management in American Construction Organizations.” *American Society of Civil Engineers*, 28(2), 203–211. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479](https://doi.org/10.1061/(ASCE)ME.1943-5479)
- Hallowell, M. R., Hinze, J. W., Baud, K. C., and Wehle, A. (2013). “Proactive Construction Safety Control: Measuring, Monitoring, and Responding to Safety Leading Indicators.” *Journal of Construction Engineering and Management*, 139(10), 1–8. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000730](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000730).
- Hallowell, M. R., Teizer, J., and Blaney, W. (2010). “Application of Sensing Technology to Safety Management.” *Construction Research Congress 2010*, (2006), 31–40.
- Hallowell, M., Hinze, J., Baud, K., and Wehle, A. (2013). “Pro-Active construction safety control: Measuring, monitoring, and responding to safety leading indicators.” *Journal of Construction Engineering and Management*, 139(10).

- Hamshar, C. (2014). "FitLinxx Announces AmpStrip Wearable Heart & Activity Monitor." *Wearable Tech World*. <http://www.wearabletechworld.com/topics/wearable-tech/articles/394220-fitlinxx-announces-ampstrip-wearable-heart-activity-monitor.htm> (July 4, 2015)
- Hanscom, F., Graham, J. and Stout, D. (1993). "Highway evaluation of maintenance work zone safety devices." *Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents Conference*, Federal Highway Administration, Hague, Netherlands.
- Health and Safety Executive (HSE). (2006). "Developing process safety indicators: A step-by-step guide for chemical and major hazard industries." *Health and Safety Executive*.
- Health and Safety Executive (HSE). (2014). "Health and safety in construction in Great Britain, 2014." *Health and Safety Executive*. <http://www.hse.gov.uk/statistics/industry/construction/construction.pdf> (Oct. 10, 2016)
- Hecker, S., Gambatese, J., and Weinstein, M. (2005). "Designing for worker safety: Moving the construction safety process upstream." *Professional Safety*, 50(9), 32-44.
- Hinze, J. and Godfrey, R. (2003). "An Evaluation of Safety Performance Measures for Construction Projects." *Journal of Construction Research*, 4(1)5-15.
- Hinze, J. and Wilson, G. (2000). "Moving toward a zero-injury objective." *Journal of Construction Engineering and Management*, 126(5), 399-403.
- Hinze, J. (2002). "Safety plus: Making zero accidents a reality." *Construction Industry Institute*, 160-11, The University of Texas at Austin.
- Hinze, J. (2005). "A Paradigm Shift: Leading to Safety." *Proceedings of 4th Triennial International Conference Rethinking and Revitalizing Construction Safety, Health, Environment and Quality, Port Elizabeth, South Africa, 17-20 May 2005*, 1-11.
- Hinze, J., Madariaga, M., and Pizarro, D. (2006). "Target safety: programs focused on preventing specific hazards." *Construction Industry Institute*, 216-11, The University of Texas at Austin.
- Hinze, J., Thurman, S., and Wehle, A. (2013). "Leading indicators of construction safety performance." *Safety Science*, 51(1), 23-28. <https://doi.org/10.1016/j.ssci.2012.05.016>
- Ho, C. and Dzeng, R. (2010). "Construction safety training via E-Learning: Learning effectiveness and user satisfaction." *Computers & Education*, 55(1), 858-867.
- Hong Kong Occupational Safety and Health (HKOSH). (2013). "Occupational Safety and Health Statistics 2013." *Labor Department, The Government of the Hong Kong Special Administrative Region*. http://www.labour.gov.hk/eng/osh/pdf/archive/statistics/OSH_Statistics_2012.pdf (July 2, 2015)

- Hourdos, J. (2012). "Portable, Non-Intrusive Advance Warning Devices for Work Zones with or without Flag Operators." *Final Report. Minnesota Department of Transportation Research Services*. Minnesota Department of Transportation.
- Huang, X. and Hinze, J. (2006). "Owner's role in construction safety." *Journal of Construction Engineering and Management*, 132(2), 164-173.
- Intellicone (2016). "About." *Intellicone*, <<http://www.intellicone.co.uk/about>> (Feb. 7, 2017).
- IntelliStrobe (2016). "W1-AG automated flagger assistance device." *IntelliStrobe Safety Systems*, <<http://flaggersafety.com/home.html>> (Feb. 7, 2017).
- International Association of Fire Chiefs (IAFC). (2015). "Fire Near Miss." *International Association of Fire Chiefs*. Retrieved Feb 28, 2015, from www.fire.nationalnearmiss.org
- International Labor Organization (ILO). (2003). "Safety in numbers." *International Labor Organizations*, Report Number 61, Switzerland.
- Jovanov, E., Milenkovic, A., Otto, C., and de Groen, P. C. (2005). "A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation." *Journal of Neuroengineering and Rehabilitation*, 2, 6. <https://doi.org/10.1186/1743-0003-2-6>
- Kallie (2016). "Wearable Technology in Construction." *Ryvit*. <https://ryvit.com/wearable-tech-construction/>
- Khan, A. (2007). "Microsimulation of traffic in highway work zones for testing ITS-based traffic management measures." *11th World Conference on Transport Research*, Elsevier, Shanghai, China.
- Khattak, A., Khattak, A. and Council, F. (2002). "Effects of work zone presence on injury and non-injury crashes." *Accident Analysis & Prevention*, 34(1), 19-29.
- Khoury, H. M., and Kamat, V. R. (2009). "Evaluation of position tracking technologies for user localization in indoor construction environments." *Automation in Construction*, 18(4), 444-457. <https://doi.org/10.1016/j.autcon.2008.10.011>
- Kochevar, K. (2008). "Intrusion Devices - New and Emerging Technology in Worker Safety." *Federal Highway Administration*, <http://ops.fhwa.dot.gov/wz/workshops/accessible/Kochevar_ID.htm> (Feb. 7, 2017).
- Krause, T., Groover, D. and Martin, D. (2010) "Preventing incidents and fatalities: Eight questions every senior leader should ask." *Professional Safety*, 55(6), 46-53.
- Krupa, C. (2010). "Work Zone Intrusion Alarm Effectiveness." *Report NJ-2010-004*, New Jersey Department of Transportation.

- Lancaster, J., Alali, K., and Casali, J. (2007). "Interaction of vehicle speed and auditory detection of backup alarms AKA: can the construction worker get out of the way?" *Proceedings of Human Factors and Ergonomics Society Annual Meeting, Sage Publications*, 51(20), 1421-1424.
- Lander, L., Eisen, E., Stentz, T., Spanjer, K., Wendland, B. and Perry, M. (2011). "Near-miss reporting system as an occupational injury preventive intervention in manufacturing." *American Journal of Industrial Medicine*, 54(1), 40-48.
- Lee, H., Lee, K., and Park, M. (2012). "RFID-based Real-Time Locating System for Construction Safety Management." *Journal of Computing in Civil Engineering*, 26(3), 366–378. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000144](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000144)
- Leigh, P. (2011). "Economic burden of occupational injury and illness in the United States." *Milbank Quarterly*, 89(4), 728-772.
- Leo Near Miss (2017). "Report Library." *Leo Near Miss*, <https://www.leonearmiss.org/reports/>
- Lewis, G. K., Langer, M. D., Henderson, C. R., and Ortiz, R. (2013). "Design and evaluation of a wearable self-applied therapeutic ultrasound device for chronic myofascial pain." *Ultrasound in Medicine and Biology*, 39(8), 1429–1439.
- Li, J., Carr, J., and Jobes, C. (2012). "A shell-based magnetic field model for magnetic proximity detection systems." *Safety Science*, 50(3), 463–471. <https://doi.org/10.1016/j.ssci.2011.10.007>
- Li, P., Wen, Y., Liu, P., Li, X., and Jia, C. (2010). "A magnetoelectric energy harvester and management circuit for wireless sensor network." *Sensors and Actuators, A: Physical*, 157(1), 100–106. <https://doi.org/10.1016/j.sna.2009.11.007>
- Li, Y. and Bai, Y. (2008). "Development of crash-severity-index models for the measurement of work zone risk levels." *Accident Analysis & Prevention*, 40(5), 1724-1731.
- Lin, P., Kang, K. and Chang, G. (2004). "Exploring the effectiveness of variable speed limit controls on highway work-zone operations." *Intelligent Transportation Systems*, 8(3), 155-168.
- Lindsay, F. (1992). Successful health and safety management: The contribution of management audit. *Safety Science*, 15(1), 387-402.
- Liu, H. and Yieh-lin Tsai, Y. (2012). "A fuzzy risk assessment approach for occupational hazards in the construction industry." *Safety Science*, 50(4), 1067-1078.
- Liu, T., Inoue, Y., and Shibata, K. (2010). "A wearable force plate system designed using small triaxial force sensors and inertial sensors." *Lecture Notes in Electrical Engineering*, 55 *LNEE*, 61–73. https://doi.org/10.1007/978-3-642-05167-8_5

- Liu, Y., Li, C., He, Y., Wu, J. and Xiong, Z. (2007). "A perimeter intrusion detection system using dual-mode wireless sensor networks." *Communications and Networking in China*, IEEE, 861-865.
- Lu, W., Huang, G. Q., and Li, H. (2011). "Scenarios for applying RFID technology in construction project management." *Automation in Construction*, 20(2), 101–106. <https://doi.org/10.1016/j.autcon.2010.09.007>
- Maddox, T. (2014). "Wearables: An emerging trend with staying power." *ZDNet*. <http://www.zdnet.com/article/wearables-an-emerging-trend-with-staying-power/> (July 4, 2015)
- Marks, E., and Teizer, J. (2012). "Proximity Sensing and Warning Technology for Heavy Construction Equipment Operation." *Proceedings of Construction Research Congress 2012, ASCE, West Lafayette, Indiana, May 21-23, 2012, 981–990*.
- Marks, E., and Teizer, J. (2013). "Method for Testing Proximity Detection and Warning Technology for Construction Equipment Operation." *Journal of Construction Management and Economics*, 31(6), 636-646.
- Martin, J., Rozas, A. and Araujo, A. (2016). "A WSN-Based intrusion alarm system to improve safety in road work zones." *Journal of Sensors*, MDPI.
- Martin, S., Etchegaray, J., Simmons, D., Belt, W., and Clark, K. (2005). "Development and Implementation of The University of Texas Close Call Reporting System." *Information for the Defense Community*, 1-13.
- McDonald, M. A., Lipscomb, H. J., Bondy, J., and Glazner, J. (2009). "Safety is everyone's job: The key to safety on a large university construction site." *Journal of Safety Research*, 40(1), 53–61. <https://doi.org/10.1016/j.jsr.2008.12.005>
- Mckay, B. (2013). "Measures of effect: Near miss reporting and construction site injuries." *Masters Practicum Thesis*. Retrieved February 2015, from Scholarworks@UA: <http://hdl.handle.net/11122/4828>. (February 23, 2015)
- Mehmood, N. Q., and Culmone, R. (2016). "A Data Acquisition and Document Oriented Storage Methodology for ANT+ Protocol Sensors in Real-Time Web." *2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA)*, 312–318. <https://doi.org/10.1109/WAINA.2016.49>
- Meng, F. and Spence, C. (2015). "Tactile warning signals for in-vehicle systems." *Accident Analysis and Prevention*, 75 (2015) 333–346
- Mohan, S. and Gautam, P. (2002). "Cost of highway work zone injuries." *Practice Periodical on Structural Design and Construction*, 7(2), 68-73.

- Moon, Y.J., Lee, J., and Park, Y. (2003). "System Integration and Field Tests for Developing In-Vehicle Dilemma Zone Warning System." *Transportation Research Record*, 1826(1), 53–59. <http://doi.org/10.3141/1826-08>
- Moynihan, G. P., Batson, R. G., and Jaiswal, V. (2000). "Aviation Safety and Analysis Data Requirements Study." *Office of System Safety Administration, Washington, D.C.*
- National Safety Council (NSC). (2008). "Injury facts, 2008 edition." *National Safety Council*, <<https://www.usw12775.org/uploads/InjuryFacts08Ed.pdf>> (Oct. 10, 2016).
- National Work Zone Safety Information Clearinghouse (NWZSIC). (2016). "Fatalities in Motor Vehicle Traffic Crashes by State and Work Zone (2014)." *U.S. Department of Transportation Federal Highway Administration*, <<https://www.workzonesafety.org/crash-information/workzone-fatalities/workzone-fatalitiesmotor-vehicle-traffic-crashes-2014/>> (February 3, 2017).
- Navon, R. (2005). "Automated project performance control of construction projects." *Automation in Construction*, 14(4), 467–476. <https://doi.org/10.1016/j.autcon.2004.09.006>
- Navon, R., and Kolton, O. (2006). "Model for automated monitoring of fall hazards in building construction." *Journal of Construction Engineering and Management*, 132(7), 733-740.
- Navon, R., and Sacks, R. (2007). "Assessing research issues in Automated Project Performance Control (APPC)." *Automation in Construction*, 16(4), 474–484. <https://doi.org/10.1016/j.autcon.2006.08.001>
- Novosel, C. (2014). "Evaluation of advanced safety perimeter systems for Kansas temporary work zones." *MS. Thesis*, Civil, Environmental, and Architectural Engineering, University of Kansas, Lawrenceville, KS.
- Noyce, D. and Smith, C. (2003). "Driving simulators for evaluation of novel traffic-control devices: Protected-permissive left-turn signal display analysis." *Transportation Research Record: Journal of the Transportation Research Board*, 1844(1), 25-34.
- Occupational Safety and Health Administration (OSHA) (2016). "Commonly Used Statistics." *U.S. Department of Labor*, <https://www.osha.gov/oshstats/commonstats.html> (June 12, 2016)
- Occupational Safety and Health Administration (OSHA) (2017). "Worker Safety Series: Construction." *U.S. Department of Labor*, <https://www.osha.gov/Publications/OSHA3252/3252.html>
- Occupational Safety and Health Administration (OSHA). (2002). "Signs, signals, and barricades." *U.S. Department of Labor*, <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGI STER&p_id=17390&p_text_version=FALSE> (Oct. 10, 2016).

- Occupational Safety and Health Administration (OSHA). (2004). “Standard interpretations.” *U.S. Department of Labor*, <https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=24799> (Oct. 10, 2016).
- Occupational Safety and Health Administration (OSHA). (2007). “Preventing backovers: OSHA standard interpretations.” *U.S. Department of Labor*, <<https://www.osha.gov/doc/topics/backover/standard.html>> (Oct. 10, 2016)
- Occupational Safety and Health Administration (OSHA). (2011). “OSHA injury and illness recordkeeping and reporting requirements.” *U.S. Bureau of Labor Statistics*, <https://www.osha.gov/recordkeeping> (Oct. 14, 2013).
- Occupational Safety and Health Administration (OSHA). (2013). Commonly used statistics. *U.S. Bureau of Labor Statistics*, <http://www.osha.gov/oshstats/commonstats.html> (Sep. 3, 2014).
- Occupational Safety and Health Administration (OSHA). (2015). “Accident/Incident investigation.” *U.S. Department of Labor*, https://www.osha.gov/dte/IncInvGuide4Empl_Dec2015.pdf (Oct. 10, 2016).
- Øien, K., Utne, I. B., Tinmannsvik, R. K., and Massaiu, S. (2011). “Building Safety indicators: Part 2 - Application, practices and results.” *Safety Science*, 49(2), 162–171. <http://doi.org/10.1016/j.ssci.2010.05.015>
- Oloufa, A. A., Ikeda, M., and Oda, H. (2003). “Situational awareness of construction equipment using GPS, wireless and web technologies.” *Automation in Construction*, 12, 737–748. [https://doi.org/10.1016/S0926-5805\(03\)00057-8](https://doi.org/10.1016/S0926-5805(03)00057-8)
- Organisation for Economic Co-operation and Development (OECD). (2003). “Guidance on safety performance indicators. Guidance for industry, public authorities and communities for developing SPI programmes related to chemical accident prevention, preparedness and response.” *OECD Environment, Health and Safety Publications. Series on Chemical Accidents No. 11*.
- Ozbay, K., Bartin, B., Yang, H. and Chien, S. (2012). “Traffic control and work zone safety for high volume roads: Final report.” *Center for Advanced Infrastructure and Transportation (CAIT) Rutgers*, The State University of New Jersey. New Jersey Department of Transportation.
- Papapostolou, A., and Chaouchi, H. (2011). “RFID-assisted indoor localization and the impact of interference on its performance.” *Journal of Network and Computer Applications*, 34(3), 902–913. <https://doi.org/10.1016/j.jnca.2010.04.009>
- Park, J., Kim, K., and Cho, Y. (2016). “A Framework of Automated Construction Safety Monitoring using Cloud-enabled BIM and BLE Mobile Tracking Sensors.” *Journal of Construction Engineering and Management*, 143(2), 1–12. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001223](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001223)

- Patel, S., Park, H., Bonato, P., Chan, L., and Rodgers, M. (2012). "A review of wearable sensors and systems with application in rehabilitation." *Journal of NeuroEngineering and Rehabilitation*, 9(1), 21. <https://doi.org/10.1186/1743-0003-9-21>
- Phanomchoeng, G., Rajamani, R. and Hourdos, J. (2010). "Directional sound for long-distance auditory warnings from a highway construction work zone." *IEEE Transactions on Vehicular Technology*, 59(5), 2266-2276.
- Phimister, J., Oktem, U., Kleindorfer, P. and Kunreuther, H. (2003). "Near-Miss Incident Management in the Chemical Process Industry." *Risk Analysis*, 23(1), 445-459.
- Phimister, J., Oktem, U., Kleindorfer, P., and Kunreuther, H. (2000). "Near-Miss System Analysis: Phase I." *Wharton School, Center for Risk Management and Decision Processes*, University of Pennsylvania.
- Pradhananga, N., and Teizer, J. (2013). "Automatic spatio-temporal analysis of construction site equipment operations using GPS data." *Automation in Construction*, 29, 107–122. <http://doi.org/10.1016/j.autcon.2012.09.004>
- Pratt, S., Fosbroke, D. and Marsh, S. (2001). "Building safer highway work zones: Measures to prevent worker injuries from vehicles and equipment." *No. DHHS (NIOSH) Publication*, Center for Disease Control.
- Qiao, F., Jia, J., Yu, L., Li, Q. and Zhia, D. (2014). "Drivers' smart assistance system based on radio frequency identification: Enhanced safety and reduced emissions in work zones." *Transportation Research Record Report 2458. Journal of the Transportation Research Board*, 37-46.
- Rebolj, D., Babič, N. Č., Magdič, A., Podbreznik, P., and Pšunder, M. (2008). "Automated construction activity monitoring system." *Advanced Engineering Informatics*, 22(4), 493–503. <https://doi.org/10.1016/j.aei.2008.06.002>
- Reiman, T., and Pietikäinen, E. (2012). "Leading indicators of system safety - Monitoring and driving the organizational safety potential." *Safety Science*, 50(10), 1993–2000. <http://doi.org/10.1016/j.ssci.2011.07.015>
- Roberts, C. M. (2006). "Radio frequency identification (RFID)." *Computers and Security*, 25(1), 18–26. <https://doi.org/10.1016/j.cose.2005.12.003>
- Rozenfeld, O., Sacks, R., Rosenfeld, Y., and Baum, H. (2010). Construction job safety analysis. *Safety Science*, 48(4), 491-498.
- Ruff, T. (2006). "Evaluation of a radar-based proximity warning system for off-highway dump trucks." *Accident Analysis and Prevention*, 38(1), 92–98. <https://doi.org/10.1016/j.aap.2005.07.006>

- Ruff, T. M., and Hession-Kunz, D. (2001). "Application of radio-frequency identification systems to collision avoidance in metal/nonmetal mines." *IEEE Transactions on Industry Applications*, 37(1), 112–116. <https://doi.org/10.1109/28.903133>
- Ruff, T. M., and Holden, T. P. (2003). "Preventing collisions involving surface mining equipment: A GPS-based approach." *Journal of Safety Research*, 34(2), 175–181. [https://doi.org/10.1016/S0022-4375\(02\)00074-9](https://doi.org/10.1016/S0022-4375(02)00074-9)
- Ruxton, G. (2006). "The unequal variance t-test is an underused alternative to Student's t-test and the Mann–Whitney U test." *Behavioral Ecology*, 17(4), 688–690.
- Sacks, R., Rozenfeld, O. and Rosenfeld, Y. (2009). "Spatial and temporal exposure to safety hazards in construction." *Journal of Construction Engineering and Management*, 135(8), 726–736.
- Saidi, K. S., Teizer, J., Franaszek, M., and Lytle, A. M. (2011). "Static and dynamic performance evaluation of a commercially-available ultra wideband tracking system." *Automation in Construction*, 20(5), 519–530. <https://doi.org/10.1016/j.autcon.2010.11.018>
- Schaaf, T. and Kanse, L. (2004). "Biases in incident reporting databases: An empirical study in the chemical process industry." *Safety Science, Elsevier*, 42(1) 57–67.
- Schiffbauer, W. and Mowrey, G. (2001). "An environmentally robust proximity warning system for hazardous areas." *Proceedings of ISA Emerging Technologies Conference, Research Triangle Park, NC, 16 July 2001, 1-10.*
- Sen, P. (1968). "Estimates of the regression coefficient based on Kendall's tau." *Journal of the American Statistical Association*, 63(324), 1379–1389.
- Sensirion (2017). "Environmental Sensors." *Sensirion*.
<https://www.sensirion.com/en/environmental-sensors/>
- Seo, J., Han, S., Lee, S., and Kim, H. (2015). "Computer vision techniques for construction safety and health monitoring." *Advanced Engineering Informatics*, 29(2), 239–251. <https://doi.org/10.1016/j.aei.2015.02.001>
- Shahi, A., Aryan, A., West, J. S., Haas, C. T., and Haas, R. C. G. (2012). "Deterioration of UWB positioning during construction." *Automation in Construction*, 24, 72–80. <https://doi.org/10.1016/j.autcon.2012.02.009>
- Shen, X., Awolusi, I., and Marks, E. (2017). "Construction Equipment Operator Physiological Data Assessment and Tracking." *Practice Periodical on Structural Design and Construction*, 22(4), 04017006-1-7. [http://dx.doi.org/10.1061/\(ASCE\)SC.1943-5576.0000329#sthash.8vk1J1ly.dpuf](http://dx.doi.org/10.1061/(ASCE)SC.1943-5576.0000329#sthash.8vk1J1ly.dpuf)
- Silverstein, E. (2014). "FitLinxx Illustrates Continuing Promise of Wearable Technology, Wellness Applications." *Wearable Tech World*.
<http://www.wearabletechworld.com/topics/wearable-tech/articles/370836-fitlinxx->

- illustrates-continuing-promise-wearable-technology-wellness-application.htm (July 4, 2015)
- Sullivan, J. (2005). "Work-zone safety ITS: smart barrel for an adaptive queue-warning system." *Transportation Research Institute (UMTRI)*. University of Michigan, Ann Arbor, MI.
- Sultan, N. (2015). "Reflective thoughts on the potential and challenges of wearable technology for healthcare provision and medical education." *International Journal of Information Management*, 35(5), 521–526. <https://doi.org/10.1016/j.ijinfomgt.2015.04.010>
- Sun, B., Osborne, L., Xiao, Y. and Guizani, S. (2007). "Intrusion detection techniques in mobile ad hoc and wireless sensor networks." *IEEE Wireless Communications*, 14(5), 56-63.
- Sung, M., Marci, C., and Pentland, A. (2005). "Wearable feedback systems for rehabilitation." *Journal of Neuroengineering and Rehabilitation*, 2(17), 1–12. <https://doi.org/10.1186/1743-Received>
- Swan, M. (2012). "Sensor Mania! The Internet of Things, Wearable Computing, Objective Metrics, and the Quantified Self 2.0." *Journal of Sensor and Actuator Networks*, 1(3), 217–253. <https://doi.org/10.3390/jsan1030217>
- Teizer, J., Allread, B. S., Fullerton, C. E., and Hinze, J. (2010). "Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system." *Automation in Construction*, 19(5), 630–640. <https://doi.org/10.1016/j.autcon.2010.02.009>
- Teizer, J., and Vela, P. A. (2009). "Personnel tracking on construction sites using video cameras." *Advanced Engineering Informatics*, 23(4), 452–462. <https://doi.org/10.1016/j.aei.2009.06.011>
- Teizer, J., Caldas, C. H., and Haas, C. T. (2007). "Real-Time Three-Dimensional Occupancy Grid Modeling for the Detection and Tracking of Construction Resources." *Journal of Construction Engineering and Management*, 133(11), 880–888. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2007\)133:11\(880\)](https://doi.org/10.1061/(ASCE)0733-9364(2007)133:11(880))
- Tesoriero, R., Tebar, R., Gallud, J. A., Lozano, M. D., and Penichet, V. M. R. (2010). "Improving location awareness in indoor spaces using RFID technology." *Expert Systems with Applications*, 37(1), 894–898. <https://doi.org/10.1016/j.eswa.2009.05.062>
- Toellner, J. (2001). "Improving safety and health performance: Identifying and measuring leading indicators." *Professional Safety*, 46(9), 42.
- Toole, M. and Gambatese, J. (2008). "The trajectories of prevention through design in construction." *Journal of Safety Research*, 39(2), 225-230.
- Torrent, D. G., and Caldas, C. H. (2009). "Methodology for Automating the Identification and Localization of Construction Components on Industrial Projects." *Journal of Computing*

- in Civil Engineering*, 23(1), 3–13. [https://doi.org/10.1061/\(ASCE\)0887-3801\(2009\)23:1\(3\)](https://doi.org/10.1061/(ASCE)0887-3801(2009)23:1(3))
- Trans Canada Traffic Inc. (2016). “Intellicone Traffic Management Unit.” *Intellicone*, <<http://www.transcanadatrafic.ca/Intellicone-WorksitePack.html#>> (Feb. 4, 2017).
- Transpo (2010). “SonoBlaster Work Zone Intrusion Alarm.” *Transpo Industries Inc.*, <<http://www.transpo.com/SonoBlaster.html>> (Feb. 4, 2017).
- Treacy, M. (2013). “10 environmental sensors that go along with you.” *Treehugger*. <https://www.treehugger.com/clean-technology/environmental-sensors.html>
- Trout, N. and Ullman, G. (1997). “Devices and technology to improve flagger/worker safety.” *Research Report 2963-1F*. Texas Transportation Institute, College Station, Texas.
- Tsai, Y. (2011). “Development of a sensing methodology for intelligent and reliable work-zone hazard awareness. *Final Report for Highway IDEA Project 139*. Transportation Research Board of the National Academics. Washington, D.C.
- Tsai, Y., Wang, C. and Wu, Y. (2011). “A vision-based approach to study driver behavior in work zone areas.” *International Conference on Road Safety and Simulation*, Indianapolis, IN.
- Ullman, G., Finley, M., Bryden, J., Srinivasan, R. and Council, F. (2008). “Traffic safety evaluation of nighttime and daytime work zones.” *Project. 17-30 Report*, Transportation Research Board, Washington, D.C.
- United States Department of Defense (U.S. DoD) (2008). “Global Positioning System Standard Positioning Service Performance Standard.” *United States Department of Defense*.
- Van der Schaaf, T. W. (1992). “Near miss reporting in the chemical process industry.” *Ph.D. Thesis*. Eindhoven, The Netherlands: Eindhoven University of Technology.
- Wagenaar, R. C., Sapir, I., Zhang, Y., Markovic, S., Vaina, L. M., and Little, T. D. C. (2011). “Continuous monitoring of functional activities using wearable, wireless gyroscope and accelerometer technology.” *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, 4844–4847. <https://doi.org/10.1109/IEMBS.2011.6091200>
- Wagner, L., Capezuti, E., and Ouslander, J. (2006). “Reporting near-miss events in nursing homes.” *Nursing Outlook*, 54(1) 85-93.
- Wang, J., and Razavi, S. N. (2016). “Low False Alarm Rate Model for Unsafe-Proximity Detection in Construction.” *Journal of Computing in Civil Engineering*, 30(2), 1–13. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000470](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000470).
- Wang, M. (2011). “Evaluation of innovative traffic safety devices at short-term work zones.” *Report No. K-TRAN: KU-09-5*, Kansas Department of Transportation.

- Wang, M., Schrock, S., Bai, Y. and Rescot, R. A. (2011). "Evaluation of innovative traffic safety devices at short-term work zones." *Bureau of Materials and Research, Kansas Department of Transportation*.
- Wearable Technologies Innovation World Cup (WTIWC). (2015). "Information for participants." *Wearable Technologies Innovation World Cup*. http://www.varta-microbattery.com/fileadmin/user_upload/mb_data/cms_data/news_data/1090f_WT_IWC_2014_2015_ParticipantBrochure.pdf (July 4, 2015)
- Wu, W., Huanjia, Y., Chew, D., Yang, S., Gibb, A., and Li, Q. (2010). "Towards an Autonomous Real-Time Tracking System of Near-Miss Accidents on Construction Sites." *Automation in Construction*, Elsevier 19(1), 134-141.
- Yang, J., Cheng, T., Teizer, J., Vela, P. A., and Shi, Z. K. (2011). "A performance evaluation of vision and radio frequency tracking methods for interacting workforce." *Advanced Engineering Informatics*, 25(4), 736–747. <https://doi.org/10.1016/j.aei.2011.04.001>
- Yavuz, G., Kocak, M., Ergun, G., Alemdar, H. O., Yalcin, H., Incel, O. D., and Ersoy, C. (2010). "A smart phone based fall detector with online location support." *International Workshop on Sensing for App Phones; Zurich, Switzerland 2010*, 31-35
- Yin, S. Y. L., Tserng, H. P., Wang, J. C., and Tsai, S. C. (2009). "Developing a precast production management system using RFID technology." *Automation in Construction*, 18(5), 677–691. <https://doi.org/10.1016/j.autcon.2009.02.004>
- Zhang, M., and Sawchuk, A. A. (2012). "USC-HAD: A Daily Activity Dataset for Ubiquitous Activity Recognition Using Wearable Sensors." *Proceedings of the 2012 ACM Conference on Ubiquitous Computing - UbiComp '12*, 1036. <https://doi.org/10.1145/2370216.2370438>
- Zhang, Y., Sapir, I., Markovic, S., Wagenaar, R., and Little, T. (2011). "Continuous Functional Activity Monitoring Based on Wearable Tri-axial Accelerometer and Gyroscope." *Proceedings of the 5th International ICST Conference on Pervasive Computing Technologies for Healthcare*, 370–373. <https://doi.org/10.4108/icst.pervasivehealth.2011.245966>
- Zhu, X., Mukhopadhyay, S. K., and Kurata, H. (2012). "A review of RFID technology and its managerial applications in different industries." *Journal of Engineering and Technology Management*, 29(1), 152–167. <https://doi.org/10.1016/j.jengtecman.2011.09.011>
- Zito, D., Pepe, D., Neri, B., Zito, F., De Rossi, D., and Lanatà, A. (2008). "Feasibility study and design of a wearable system-on-a-chip pulse radar for contactless cardiopulmonary monitoring." *International Journal of Telemedicine and Applications*, 2008. <https://doi.org/10.1155/2008/328597>