WORK ZONE INTRUSION ALERT TECHNOLOGIES: ASSESSMENT AND PRACTICAL GUIDANCE

Final Report

SPR 790

RESEARCH

Oregon Department of Transportation

WORK ZONE INTRUSION ALERT TECHNOLOGIES: ASSESSMENT AND PRACTICAL GUIDANCE

FINAL REPORT

SPR 790

by

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16. Abstract

A work zone intrusion alert technology is a type of safety system that is used in a roadway work zone to alert field workers and secure time for them to escape when errant vehicles intrude into the work zone. Although such technologies have potential to significantly improve the overall safety of construction work zones, previous studies reported mixed findings, resulting in limited application of intrusion alert technologies. In response, the primary goal of this research study is to scientifically assess the effectiveness of currently available work zone intrusion alert technologies, and to provide recommendations for use of the technologies in future ODOT construction and maintenance work zones. To fulfill this goal, the research gathered information about work zone intrusion alert technologies, gained experiential input and advice from ODOT staff and industry practitioners, and tested technologies under controlled conditions and in active work zones. While sample sizes were limited, the findings from the study indicate that aspects of intrusion alarms via visual, audio, and haptic means can be effective warning mechanisms in a work zone. To improve the potential impacts of these technologies, this report identifies recommended minimum standards for each of the aforementioned means of alert. Implementation of the research results is expected to assist ODOT with enhancing the safety of motorists and workers in construction work zones on high-speed roadways.

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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TABLE OF CONTENTS

1.0 INTRODUCTION.. 1

1.1 BACKGROUND 1
1.2 STUDY GOAL AND OBJECTIVES 3
1.3 RESEARCH SCOPE 4
1.4 IMPLEMENTATION 6

2.0 LITERATURE REVIEW 7

2.1 PREVIOUS RESEARCH 7
2.1.1 Work Zone Intrusions..7
2.2 SAFETY TECHNOLOGIES IN HIGHWAY CONSTRUCTION 9
2.3 PREVIOUS INTRUSION ALERT TECHNOLOGIES.. 10
2.4 AVAILABLE TECHNOLOGIES 11
2.5 POINT OF DEPARTURE 14

3.0 SURVEY OF CURRENT PRACTICE.. 15

3.1 SURVEY STRUCTURE 15
3.2 SURVEY ADMINISTRATION.. 15
3.3 SURVEY DISTRIBUTION... 15
3.4 RESULTS 16
3.5 SUMMARY OF CURRENT PRACTICES 22

4.0 PRELIMINARY INVESTIGATION.. 25

4.1 ODOT 14821 TUALATIN RIVER NATIONAL WILDLIFE REFUGE (TRNWR) TURN LANE PROJECT.. 25
4.2 DATA COLLECTION.. 26
4.3 RESULTS AND ANALYSIS.. 27
4.4 SUMMARY OF PRELIMINARY INVESTIGATION 32

5.0 PILOT TESTING OF TECHNOLOGIES... 33

5.1 CATALOG OF TECHNICAL SPECS OF EQUIPMENT TESTED............................ 33
5.2 TYPES OF TESTING ACTIVITIES 33
5.3 CONTROLLED TESTING 34
5.4 PILOT TESTING SCHEDULE.. 35
5.5 PILOT TESTING RESULTS.. 36
5.5.1 Recording False Alarms 36
5.5.2 Measuring Relationship between Sound level and Distance 38
5.5.3 Impact of Orientation of Alarm...42
5.5.4 Sound Level Inside of a Vehicle..48
5.5.5 Impact of Equipment on Sound Level 49
5.5.6 Spectral Analysis to Test Distinctiveness of Audio Alarm 53
5.5.7 Transmission Distance...56
5.5.8 Light Level of Visual Alarm..58
5.6 SUMMARY OF PILOT TESTING 62

6.0 SELECTION OF TECHNOLOGIES FOR LIVE TESTING.................................... 65

6.1 DEMONSTRATION EVENT 65
6.1.1 SonoBlaster® *66*
6.1.2 Intellicone® *69*
6.1.3 Worker Alert System (WAS) *71*
6.1.4 Summary of Technology Demonstration Event Results *74*
6.2 FOCUS GROUPS 74
6.2.1 Methods *74*
6.2.2 Results *75*
6.3 CONCLUSIONS OF TECHNOLOGY SELECTION 84
7.0 IMPLEMENTATION AND TESTING OF SELECTED TECHNOLOGIES 85
7.1 INTRODUCTION 85
7.2 PROJECT IDENTIFICATION 85
7.3 PROPOSED DATA COLLECTION MATRIX 86
7.4 DATA COLLECTION 87
7.4.1 Research Plan *87*
7.4.2 Equipment and Tools *89*
7.4.3 Other Equipment and Tools *91*
7.5 CASE STUDY PROJECT #1: US-30 SWEDETOWN ROAD TO WONDERLY ROAD 91
7.5.1 Project Description *91*
7.5.2 Research Plan *92*
7.6 CASE STUDY PROJECT #2: I-84 CASCADE LOCKS TO HOOD RIVER 96
7.6.1 Project Description *96*
7.6.2 Research Plan *97*
7.7 CASE STUDY PROJECT #3: I-84 MOSIER TO THE DALLES 103
7.7.1 Project Description *103*
7.7.2 Research Plan *104*
7.8 SUMMARY OF TECHNOLOGY IMPLEMENTATION 108
8.0 RESULTS 109
8.1 PRE-LIVE TESTING SURVEY 109
8.2 CRITERIA WEIGHTING 110
8.2.1 SonoBlaster® *111*
8.2.2 Intellicone® *112*
8.2.3 Worker Alert System (WAS) *112*
8.2.4 Summary *113*
8.3 LIVE TESTING ON CASE STUDY PROJECTS 114
8.3.1 Equipment Noise Level Evaluation *114*
8.3.2 Participant Response Rate *116*
8.3.3 Response Rate by Work Role *120*
8.3.4 Reaction Time for each Work Role *122*
8.3.5 Impact of Location on Response Rate (In Front of vs. Behind Paver) *128*
8.4 POST-LIVE TESTING SURVEY 129
8.4.1 Project Level *129*
8.5 SUMMARY OF LIVE TESTING 138
9.0 SPECIFICATION FOR FUTURE PRODUCTS 141
9.1 SOUND LEVEL 141
9.2 TRANSMISSION DISTANCE 142
9.3 HAPTIC ALARMS 143
9.4 VISUAL ALARMS 144

9.5 MOBILITY ... 144
9.6 EASE OF USE ... 145
9.7 TRIGGERING MECHANISM ... 145
9.8 COST ... 145

10.0 CONCLUSIONS AND FUTURE RESEARCH ... 147

10.1 AVAILABILITY AND LEVEL OF AWARENESS OF INTRUSION ALERT TECHNOLOGIES ... 147
10.2 PILOT TEST OF INTRUSION TECHNOLOGIES ALERT ... 147
10.3 FOCUS GROUP DEMONSTRATION AND INPUT ... 149
10.4 LIVE TESTING ... 149
10.5 COST ANALYSIS ... 151
10.5.1 SonoBlaster® ... 152
10.5.2 Intellicone® ... 152
10.5.3 Worker Alert System (WAS) ... 152
10.6 STUDY LIMITATIONS ... 153
10.7 FUTURE RESEARCH ... 153
10.8 OTHER SUPPORTING TECHNOLOGIES AND NEWLY-DEVELOPED INTRUSION ALERT TECHNOLOGIES ... 154
10.8.1 Safe Vest (InZoneAlert Vest) ... 154
10.8.2 Wrong Way Alarm (WWA) ... 155
10.8.3 Directional Audio System ... 155
10.8.4 Proximity Alarm for Visual Alarm ... 155
10.8.5 AWARE System by Oldcastle ... 155
10.8.6 Smart Taper and Safelane by Highway Resource Solutions ... 156
10.8.7 Wireless Sensor Network-Based Intrusion Alarm System ... 156
10.8.8 TMA Mounted LED Panic Lights and Sound ... 156

11.0 REFERENCES ... 157

APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

APPENDIX E

APPENDIX F

APPENDIX G

LIST OF FIGURES

Figure 3.1: Types of Participants' Organizations (n = 111) 16
Figure 3.2: Respondents Distributed by Work Positions (n = 111) 17
Figure 3.3: Years of Experience of Respondents (n = 111) 17
Figure 3.4: Types of Work Zone Safety Technologies Used on Highway Construction Projects 18
Figure 3.5: Effectiveness Rating of PCMS 19
Figure 3.6: Level of Respondent Knowledge of Intrusion Alert Technologies 19
Figure 3.7: Benefits of Work Zone Intrusion Alert Systems (All Technologies Inclusive) 21
Figure 3.8: Barriers to deployment of Work Zone Intrusion Alert Systems (All Technologies Inclusive) 22
Figure 4.1: Project Location (Images from Google Maps 2016) 25
Figure 4.2: Project Layout [Image Excepted from the Project Contract Documents (ODOT 2015c)] 26
Figure 4.3: Grid System for Data Collection 27
Figure 4.4: Daytime and Nighttime Observations 27
Figure 4.5: Sound Level in Close Proximity to Workers 28
Figure 4.6: Sound Level along Grid-Line 1 29
Figure 4.7: Sound Level along Grid-Line 2 29
Figure 4.8: Sound Level in Close Proximity to the Excavator and Regular Vehicle Traffic 30
Figure 4.9: Average Sound Levels based on Distance from Construction Equipment Observed 31
Figure 4.10: Light Intensity along Grid-Line 1 (Nighttime Observation) 32
Figure 5.1: Pilot Testing Location (Aerial image from Google Maps 2016) 35
Figure 5.2: SonoBlaster® Damaged after Simulated Intrusion (Vehicle Striking Cone) 37
Figure 5.3: Distance Markings (in feet) on Roadway 38
Figure 5.4: Sound Measurement at 20 feet 39
Figure 5.5: Ice Accumulation on Nozzle of SonoBlaster® 40
Figure 5.6: Median Sound Level vs. Distance from the Technology 41
Figure 5.7: Median Sound Level of Intellicone® vs. Distance from the Intellicone® 41
Figure 5.8: Median Sound Level of SonoBlaster® vs. Distance from SonoBlaster® 42
Figure 5.9: Median Sound Level of WAS vs. Distance from WAS 42
Figure 5.10: One Speaker Oriented towards Sound Meter 43
Figure 5.11: Two Speakers Oriented towards Sound Meter 44
Figure 5.12: Median Sound Levels of Intellicone® relative to Alarm Orientation 44
Figure 5.13: SonoBlaster® Outlet Facing Downward 45
Figure 5.14: SonoBlaster® Outlet Facing Upward 45
Figure 5.15: Median Sound Levels of SonoBlaster® relative to Alarm Orientation 46
Figure 5.16: WAS Speaker Facing Sound Meter 46
Figure 5.17: WAS Speaker Facing Sideways 47
Figure 5.18: Median Sound Levels of WAS Relative to Alarm Orientation 48
Figure 5.19: Test Setup for Sound Level Measurement inside Vehicle 49
Figure 5.20: Measured Sound Level inside Vehicle 49
Figure 5.21: First Setup for Testing Sound Level Relative to Position of Equipment and Alarm 50
Figure 5.22: Alarm at 50 feet from Equipment 50
Figure 5.23: Alarm at 200 feet from Equipment 51
Figure 5.24: Second Setup for Testing Sound Level Relative to Position of Equipment and Alarm 52
Figure 5.25: Sound Meter 50 feet from Equipment 52
Figure 5.26: Sound Meter 200 feet from Equipment 53
Figure 5.27: Image of Spectral Analysis on Sound produced by Intellicone® 54
Figure 5.28: Image of Spectral Analysis on Sound produced by SonoBlaster® 55
Figure 5.29: Image of Spectral Analysis on Sound produced by WAS 56
Figure 5.30: Transmission Distance of Intellicone® 57
Figure 5.31: Reference Lights at 50 feet away from Intellicone® 59
Figure 5.32: Reference Lights at 50 feet away from WAS 60
Figure 5.33: Intellicone® 500 feet away from Camera 60

Figure 5.34: Light Intensity Measured by Luminance Meter 61
Figure 6.1: Setup for Demonstration 66
Figure 6.2: SonoBlaster® Activated Manually...67
Figure 6.3: Retrival of SonoBlaster® after Impact...67
Figure 6.4: Distribution of Participants' Rating for SonoBlaster® (n = 10)......................................68
Figure 6.5: Intellicone® Activated Manually 69
Figure 6.6: Intellicone® Activated on Impact 70
Figure 6.7: Distribution of Respondents Rating for Intellicone® (n = 10)..70
Figure 6.8: WAS Located 50ft from Equipment while Activated by Intruding Vehicle 72
Figure 6.9: WAS Located on Wheel Loader 72
Figure 6.10: Distribution of Respondent Ratings for WAS (n = 10) 73
Figure 6.11: Mean Ratings of Evaluation Criterion (n = 16)..75
Figure 7.1: Clicker Test Set-Up..90
Figure 7.2: Location of US-30 Swedetown to Wonderly Road Project (Image from Google Maps 2016) 91
Figure 7.3: Demonstration Prior to Live Testing, Case Study Project #1, Day 1 93
Figure 7.4: Site for Live Testing, Case Study Project #1, Day 1 (Image from Google Maps 2016) 94
Figure 7.5: Day 1 Data Collection Setup for Case Study Project #1 94
Figure 7.6: Visualization of Work Zone Leg-Traffic for Day 1 of Case Study Project #1..................95
Figure 7.7: Day 2 Data Collection Setup for Case Study Project #1 96
Figure 7.8: Location of I-84 Cascade Locks - Hood River Project (Image from Google Maps 2016)........................97
Figure 7.9: Demonstration Prior to Live Testing, Day 1 of Case Study Project #2............................99
Figure 7.10: Site for Data Collection, Case Study Project #2, Day 1 (Image from Google Maps 2016) 100
Figure 7.11: Data Collection Setup, Day 1 of Case Study Project #2 100
Figure 7.12: Visualization of Work Zone Leg-Traffic, Day 1 of Case Study Project #2 101
Figure 7.13: Data Collection Setup, Case Study Project #2, Day 2..102
Figure 7.14: Intellicone® triggered 100 feet away from Paver 102
Figure 7.15: Cone in Work Zone Knocked Over...103
Figure 7.16: Location of I-84 Mosier to The Dalles Project (Image from Google Maps 2016)................................104
Figure 7.17: Site for Data Collection, Case Study Project #3 (Image from Google Maps 2016).............................106
Figure 7.18: Data Collection Setup, Case Study Project #3 107
Figure 7.19: Two Workers Indicating Alarm was Heard, Case Study Project #3 107
Figure 8.1: Mean Ratings of Evaluation Criteria (n = 9)...110
Figure 8.2: Mean Ratings of Evaluation Criteria for SonoBlaster®, Intellicone®, and WAS 114
Figure 8.3: Ambient Sound in Work Zone (without Equipment) 115
Figure 8.4: Sound Level 5 feet away from a Paver in Work Zone 115
Figure 8.5: Sound Level 5 feet away from Operational Roller..116
Figure 8.6: Target Worker Locations 117
Figure 8.7: Response Rates for Case Study Projects 1, 2, 3, and Cumulative 120
Figure 8.8: Summary Response Rate for each Worker, All Case Study Projects..............................122
Figure 8.9: Dump person Reaction Time, Case Study Project #3 (SonoBlaster®) 124
Figure 8.10: Dump person, Case Study Project #3 (Intellicone®) 125
Figure 8.11: Dump person Reaction Time, Case Study Project #3 (WAS)......................................125
Figure 8.12: Inspector's Reaction Time, Case Study Project #3 (SonoBlaster®) 126
Figure 8.13: Inspector's Reaction Time, Case Study Project #3 (Intellicone®)................................127
Figure 8.14: Inspector's Reaction Time, Case Study Project #3 (WAS)..127
Figure 8.15: Response Rates when Intellicone® is triggered in Front (Downstream) of and Behind (Upstream of) the Paver (n = 14)...128
Figure 8.16: Combined Paving Crew and Inspector Perception of SonoBlaster® Distinctiveness and Loudness (Case Study Project #1)...130
Figure 8.17: Combined Paving Crew and Inspector Perception of Intellicone® Distinctiveness and Loudness (Case Study Project #1)...130
Figure 8.18: Paving Crew and Inspector Perception of WAS Distinctiveness and Loudness (Case Study Project #1) 131
Figure 8.19: Paving Crew and Inspector Perception of SonoBlaster® Distinctiveness and Loudness (Case Study Project #2)...133

Figure 8.20: Paving Crew and Inspector Perception of Intellicone® Distinctiveness and Loudness (Case Study Project #2) 133
Figure 8.21: Paving Crew and Inspector Perception of WAS Distinctiveness and Loudness (Case Study Project #2) 134
Figure 8.22: Paving Crew and Inspector Perception of SonoBlaster® Distinctiveness and Loudness (Case Study Project #3) 135
Figure 8.23: Paving Crew and Inspector Perception of Intellicone® Distinctiveness and Loudness (Case Study Project #3) 136
Figure 8.24: Paving Crew and Inspector Perception of WAS Distinctiveness and Loudness (Case Study Project #3 136
Figure 8.25: Perception of Intellicone® Distinctiveness and Loudness, All Case Study Projects (n=14) 138
Figure 9.1: Equipment Noise Level Impact on Worker 141
Figure 9.2: Travel Speed and Distance travelled for Different values of "Time to Impact" (TTI = Time to Impact) 142
Figure 9.3: Time taken by Worker to Cover Specific Distance 143

LIST OF TABLES

Table 2.1: Work Zone Safety Technologies used in State DOT's (Adapted from Schrock et al. 2013) 9
Table 2.2: Summary of Intrusion Alarm Technologies (Adapted from Burkett et al. 2009) 11
Table 2.3: Available Intrusion Alert Technologies 12
Table 3.1: Number of Responses by State 18
Table 5.1: Summary of Intrusion Alert Technologies Selected for Pilot Testing 33
Table 5.2: Pilot Testing Schedule 36
Table 5.3: Duration of Sound Alarms (n = 21) 39
Table 5.4: Transmission Range of Intellicone® and WAS* 57
Table 5.5: Recorded Luminance Level of Technologies 62
Table 6.1: Summary Table of Participant Feedback (n = 10) 74
Table 6.2: Recorded Mean Response and Standard Deviation for SonoBlaster® 76
Table 6.3: Recorded Mean Response and Standard Deviation for Intellicone® 79
Table 6.4: Recorded Mean Response and Standard Deviation for WAS 81
Table 7.1: Candidate Projects for Live Testing 85
Table 7.2: Data Collection Matrix 86
Table 7.3: Planned Activities for Mobile Operation 88
Table 7.4: Planned Activities for Stationary Operation 88
Table 7.5: Updated Research Plan for Case Study Project #1 92
Table 7.6: Updated Research Plan, Day 1 of Case Study Project #2 98
Table 7.7: Updated Research Plan, Day 1 of Case Study Project #3 105
Table 7.8: Summary of Activities Conducted for Live Testing 108
Table 8.1: Pre-Live Testing Evaluation Participants 109
Table 8.2: Mean and Standard deviation of Evaluation Criterion Ratings 110
Table 8.3: Recorded Mean Response and Standard Deviation for SonoBlaster® 111
Table 8.4: Recorded Mean Response and Standard Deviation for Intellicone® 112
Table 8.5: Recorded Mean Response and Standard Deviation for WAS 113
Table 8.6: Percentage of Workers who Heard, Felt, or Saw the Alarm, Case Study Project #1 (n = 5) 118
Table 8.7: Percentage of Workers who Heard, Felt, or Saw the Alarm, Case Study Project #2 (n = 4) 118
Table 8.8: Percentage of Workers who Heard, Felt, or Saw the Alarm, Case Study Project #3 (n = 5) 119
Table 8.9: Percent of Workers who heard or saw the Alarm, All Case Study Projects (n = 14) 119
Table 8.10: Worker Response Rate for SonoBlaster®, All Case Study Projects (n = 14) 120
Table 8.11: Worker Response Rate for Intellicone®, All Case Study Projects (n = 14) 121
Table 8.12: Worker Response Rate for WAS, All Case Study Projects (n = 14) 122
Table 10.1: Cumulative Response Rate (n = 14) 149
Table 10.2: Worker Response Rate 150
Table 10.3: Cost for SonoBlaster® 152
Table 10.4: Cost for Intellicone® 152

1.0 INTRODUCTION

A work zone intrusion alert technology is a type of safety system used in a roadway work zone to alert field workers and secure time for them to escape when errant vehicles intrude into the work zone. Although alert technologies have potential to significantly improve the overall safety of construction work zones, previous studies reported mixed findings, resulting in limited application of intrusion alert technologies. After a fatality occurred due to an intrusion on one of its projects, ODOT entered into a contract with the School of Civil and Construction Engineering at Oregon State University (OSU) to scientifically assess the effectiveness of currently available work zone intrusion alert technologies, and to provide recommendations for use of the technologies in future ODOT construction and maintenance work zones. This document is the final report for the study. It describes the study activities undertaken to review previous research, to survey current industry practices, to develop a catalogue of available technologies, and to report the results of a preliminary investigation performed on a case project. In addition, it describes the conduct, analysis, and results of the application of intrusion alert technologies on case study projects. Finally, minimum specifications for audio, visual, and haptic alerts are recommended. The report is intended to provide ODOT with a comprehensive description of the study and recommendations for application of the results in practice.

1.1 BACKGROUND

Roadway construction and maintenance operations commonly require workers to conduct their work in close proximity to ongoing traffic. Short-term work zones on high speed roadways often involve working adjacent to passing vehicles separated by only a line of tubular markers or drums. This worksite condition presents significant safety risk for both the workers and passing motorists. Inattentive or speeding drivers, careless workers, misplaced drums, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities. Other factors that can cause increased numbers of work zone crashes include: extensive nighttime work; lack of consistency of work zones; distracted drivers (e.g., cell phone use); and greater vehicle miles travelled.

Data from the Bureau of Labor Statistics (BLS) show that 962 workers were killed in road construction work zones from 2003 to 2010 (Pegula 2013). Studies conducted by Bryden and Andrew (1999) and Bryden et al. (2000) reported that work zone intrusion crashes accounted for 10% of all total traffic accidents and 8% of fatal injuries. For the last decade, the fatal injuries in work zones led to over 100 deaths every year, and the trend has been persistent (NHTSA 2014). Approximately 50% of these deaths were attributed to vehicles or mobile equipment striking the worker (Pegula 2013). Based on NYDOT data collected from 2000 to 2005, Ullman et al. (2010) found that approximately 59% of the intrusion crashes occurred in work zones involving lane closures, 44% of which were the result of deliberate driver decisions and actions to enter the work zone (e.g., driver deliberately decides to enter closed lane to reach exit, intersection, or driveway). These studies highlight the importance of establishing an effective safety buffer between moving vehicles and workers in work zones, and any safety measures to prevent intrusion crashes can significantly enhance the overall safety level of work zones (Morgan et al. 2010).

Specific to the state of Oregon, a total of 107 deaths have been reported in road construction work zones from 2003 to 2013 (ODOT 2015). In an effort to develop effective mitigation measures, research has recently been conducted by ODOT to evaluate the impacts of various traffic control devices on high speed roadways (e.g., SPR 751 and SPR 769). These studies have targeted devices aimed at reducing vehicle speeds through work zones. However, the studies did not specifically address errant vehicles crossing the line of cones into the closed lane and entering the active work area. On occasion during the course of these studies, vehicles were seen mistakenly intruding into the work area on their own or while following behind a construction vehicle that was entering the active work area. When interviewed, construction personnel involved in the prior studies also commented that they have witnessed vehicles crossing into the work area. Errant vehicles driving into the work area is a serious safety risk for workers on the roadway and for the driving public.

New technologies are publicly available that alert workers of work area intrusions. A work zone intrusion incident on Interstate 5 in ODOT Region 3 (https://www.youtube.com/watch?v=W2PeRyEr8MU) is an example where technologies could have added to the ability to detect intrusions and alert the workers. The video shows ODOT employees describe their story of a very serious near miss incident where a truck lost its brakes on I-5 and entered into the work zone. Although no one was hurt and there was no serious property damage, the incident was a very scary near miss in which intrusion alert technologies could have helped to further protect the workers. The following are four currently available technologies considered for this project:

SonoBlaster® Dual Alert work zone intrusion alarm, by Transpo Industries: An impact-activated device attached to a barricade, cone, drum, or other traffic control device that emits a loud warning sound to the workers when the traffic control device is struck and knocked over. (http://www.transpo.com; cost approximately $100 each)

"Traffic Guard Worker Alert System" (WAS), by Astro Optics, LLC: Audio alarm and visual alarm wirelessly triggered when a vehicle crosses over a pneumatic hose into the work area. (http://www.astrooptics.com/products/traffic-guard-worker-alert-system; cost approximately $600 each)

IntelliStrobe® AFAD Lane Intrusion Safety System, by IntelliStrobe Safety Systems, LLC: An audio alarm and visual system that is activated when a vehicle crosses over a pneumatic hose into the work area. (http://intellistrobe.com/; cost approximately $25,000 each)

Intellicone®, by Highway Resource Solutions (UK): A lamp-integrated motion sensor attached to a traffic cone that can detect being hit by a vehicle and when vehicles cross between cones. When triggered, the unit signals an audio and visual alarm. An alert is also sent wirelessly to a web portal to enable automated on-line reporting. (http://www.intellicone.co.uk; not yet commercially available in US; cost approximately $2000 each)

There are multiple possible means for protecting workers in work zones, of which intrusion alert technologies are one possible solution. Providing positive protection systems (e.g., concrete barriers) is another. Although positive protection systems such as concrete barriers, a mobile barrier trailer, and truck mounted attenuator (TMA) could be implemented in work zones to protect workers from vehicle impact, the high initial cost of owning and implementing positive protection devices creates an obstacle for implementation on some projects (Brillhart, 2010; Schrock et al., 2014). Intrusion alert technologies, on the other hand, may provide cost-efficient solutions that also provide increased protection for workers. If intrusion alert devices are not easy to implement with current traffic control plans or are overly expensive, however, the devices may not be the best solution to reduce risk and improve safety in work zones. Research is needed to formally evaluate the feasibility and effectiveness of intrusion alert devices.

Prior work zone safety studies conducted by ODOT did not target work zone intrusions and the technologies available to warn of intrusions. Literature is available from the device manufacturers that describe the specifications of each individual technology; however no studies based on research on actual projects have been found that provide a comprehensive review and comparison of the currently available technologies and present recommendations for use, design, and specification of intrusion alert technologies in practice. Objective evaluation is needed that addresses the capabilities and effectiveness of the technologies, ease of use, viable application conditions (e.g., short-term/long-term work zone; stationary/mobile operation; and nighttime/daytime shift), and current cost and feasibility of implementation.

1.2 STUDY GOAL AND OBJECTIVES

The overall goal of the research is to assist ODOT with enhancing the safety of motorists and workers in construction work zones on high-speed roadways. To meet this goal, the proposed research intends to assess the value and capabilities of an engineered control used in work zones. Specifically, the proposed research study is designed to provide ODOT traffic control, construction, and maintenance staff with guidance on the use of an intrusion alert system in work zones. To attain this goal, the research includes the following tasks:

- Document the work zone intrusion alert technologies and practices that are currently available.
- Select and pilot test a sample of intrusion alert technologies for evaluation and testing in ODOT work zones.
- Evaluate each of the selected technologies in active ODOT construction and/or maintenance work zones.
- Prepare documentation for ODOT that describe the capabilities and cost effectiveness of each technology evaluated.
- Provide recommendations for use of intrusion alert technologies on future ODOT construction and maintenance work zones.

The research focuses on technologies developed to alert workers of errant vehicle intrusions in work zones. Only work zone intrusion alert technologies that are currently available to the public are included; the study does not include designing, fabricating, and testing new technologies. Available technologies that alert drivers of their passage into a closed work zone are also considered for inclusion in the study.

In addition, the study does not address the case when a public vehicle intrudes into a work zone when mistakenly following a construction vehicle into the work zone. The study is limited to considering only the case when a public vehicle intrudes into a work zone on its own.

The work zone intrusion technologies included in the study were purchased, leased, and/or borrowed for the study. In addition, as described below, some of the technologies were donated for use in the study.

1.3 RESEARCH SCOPE

The research included multiple tasks aimed at gathering information about work zone intrusion alert technologies, gaining experiential input and advice from ODOT staff and practitioners, and testing technologies under controlled conditions and in active work zones. This section summarizes the tasks that were undertaken to conduct the entire research study. The actual timing and duration of the live testing (Task 5) varied depending on the construction schedule and progress of case study projects selected for this research and the technologies selected for inclusion in the testing. It was however expected that the selected case study projects would be undertaken in the 2016 construction season. All reports are produced in the standard ODOT Research Unit report format unless another format was deemed to be more appropriate as a supplement to the ODOT format.

Task 1: Documentation of Technologies

Literature on currently available technologies and technologies that have high potential for preventing injury due to work zone intrusions was collected and reviewed. To collect the literature, the researchers conducted a comprehensive search of archival publications and the Internet using on-line search engines. All documents found that are germane to the research topic were accessed and reviewed. Task 1 led to the creation of a catalog of the technologies for use during the research and in the future by ODOT. The catalog contains a description of each technology along with associated benefits, limitations to its use, and summaries of findings from prior research on the technology.

Task 2: Survey of Current Practice

Task 2 involved conducting a survey of state DOTs, construction and traffic control contractors, equipment vendors, and automobile manufacturers. The survey aimed at documenting current and recommended practices, barriers, enablers, and impacts associated with work zone intrusion alert technologies. To conduct the survey, a questionnaire was developed that addresses the aims listed above. The TAC was asked to review the questionnaire and provide feedback. The questionnaire was revised to incorporate the TAC’s input, and then distributed by the researchers to the entities listed above. The survey sample was developed based on input from the TAC, the researcher's personal contacts, and the companies and organizations identified in Task 1. Task 2 led to the identification of the status quo of the construction industry and its current best practice in terms of preventing work zone intrusion crashes.

Task 3: Pilot Testing of Technologies

Based on the results of Tasks 1 and 2, and input from the TAC, a sample of feasible technologies was selected for pilot testing. Selection considered technology availability, cost, ease of use, potential for improving safety, and potential for incorporating the technology in typical transportation control plans. Those selected for testing were purchased, leased, borrowed, or if possible, acquired through a donation. Pilot testing was conducted as initial testing of the selected technologies under controlled, off-roadway conditions. Each selected technology was assessed to capture its capabilities, and record how it is implemented. The results of the pilot testing were used to assess feasibility of use, capabilities, and limitations related to each technology under investigation.

Task 4: Selection of Technologies for Live Testing

Following completion of the pilot testing and analysis of the results, Task 4 involved conducting focus group sessions with ODOT personnel and construction contractors to identify and select specific technologies to implement and test in an active work zone. The TAC was asked to recommend focus group participants from within ODOT and construction companies. The researchers planned, scheduled, and conducted the focus groups. Feedback on each of the technologies was solicited from each targeted group. Those technologies that were deemed promising by the focus group participants, and fit within the research budget, were selected. In addition, the researchers worked with ODOT to select construction and/or maintenance projects on which to conduct live testing of the technologies.

Task 5: Implementation and Testing of Selected Technologies

Task 5 involved implementing the selected technologies on each case study project. Depending on the case study projects selected, it was planned to apply the technologies under different work zone conditions (e.g., short-term and long-term, daytime and nighttime, and stationary and mobile). Each selected technology was implemented during actual work operations. The researchers monitored the technology installation, use, and removal. The researchers videotaped the operations and monitored vehicle speeds as needed to assess each technology. The testing results of each technology were evaluated and compared based on a variety of criteria including, but not limited to: ease of implementation and use, ability to detect intrusions, ability to warn of intrusions, sensitivity to false alarms, impact on risk to worker safety, and implementation cost. Upon completion of testing, feedback on each technology was collected directly from the construction and maintenance workers involved in each case study project.

Task 6: Data Analysis

The data collected from the case study projects was analyzed to determine the feasibility, barriers, enablers, and impacts of each technology and develop guidance for future use of the technologies by ODOT. Where appropriate, multi-criteria decision analysis was applied to rank order the cost effectiveness of each technology. Such comparisons were expected to determine the relative benefits provided by each technology in preventing work zone intrusion crashes.

Task 7: Documentation and Dissemination

A draft final research report was prepared and submitted to ODOT for review and comment. The draft report presents the findings of the research and provides recommendations to ODOT for implementation in practice. The draft final research report will be revised based on the comments received from ODOT, and a final research report prepared and submitted to ODOT for publication.

1.4 IMPLEMENTATION

The product of the research will be this report that describes the identification and testing of technologies that are feasible and effective in preventing work zone intrusion crashes, and provides guidelines and recommendations for their use in practice. The results and products of the research will be used by the Statewide Construction and Maintenance Offices for planning construction and maintenance work. Recognizing that technology and tools change over time, this report will correspond the research recommendations into minimum levels of visual, audio, and haptic categories for future technological evaluations. The outputs will also be used by the Transportation Safety Division, and by the Transportation Safety Coordinators in each Region, as a resource for effectively designing work zones and planning construction and maintenance operations.

2.0 LITERATURE REVIEW

The researchers conducted an extensive search of archival literature to uncover information on work zone intrusions and intrusion alert technologies. To perform the literature search, the researchers used a keyword search of Google Scholar and other online resources such as American Society of Civil Engineering's (ASCE) publications, Safety Science, Science Direct, Transportation Research Information Services (TRIS), and Research Direct to locate relevant research articles, reports, and other documents. The literature collected from this activity was reviewed for its relevance and application to the study. This section of the report presents a summary of previous research that addressed issues related to work zone intrusions and intrusion alert technologies.

2.1 PREVIOUS RESEARCH

2.1.1 Work Zone Intrusions

Different types of vehicle crashes occur around roadway work zones. According to research by Ullman et al. (2010) based on the New York DOT highway accident database, the key crash types include:

- Rear end
- Multi-vehicle (not rear-end) collision
- Single vehicles run-off road
- Intrusion impact with workers, equipment, or debris
- Non-intrusion impact with workers, equipment, or debris
- Impacts with truck-mounted attenuators (TMA)

Among the identified crash types, a series of studies conducted by Bryden and Andrew (1999) and Bryden et al. (2000) reported that work zone intrusion crashes accounted for 10% of all total traffic accidents and 8% of fatal injuries. Intrusion accidents can be defined as accidents resulting from the breaching of a work zone or buffer space (defined by channelizing devices) by an errant driver. A persistent trend of work zone accidents has been observed and documented; in the last decade, over 100 deaths have been recorded each year as a result of work zone accidents (NHTSA 2014). Specific to Oregon, work zone fatalities accounted for 2% of all roadway fatalities in 2013. An annual average of 510 work zone related crashes have been recorded over the past 10 years in Oregon, 40% of which occurred in the transition zone prior to the work area. Out of the 2,381 work zone related crashes recorded between 2009 and 2013, 49 fatalities occurred (ODOT 2015b). Similar data was not found for the U.S. as a whole, however other studies have identified high risk areas of work zones based on state-based data in Ohio and Virginia (Garber and Zhao, 2002; Salem et al. 2006).

Bryden et al. (2000) classified accidents caused by work zone intrusions into the following five categories using accident descriptors:

- Full intrusion – a result of a passing vehicle completely intruding into the construction work zone (as defined by channelizing devices)

- Buffer (lateral and longitudinal) intrusion – accidents that occur within the buffer zone. The buffer zone is the boundary between the traffic space and the workspace (FHWA 2009). The vehicles involved in this type of accident do not fully enter the work zone in general. For example, a worker could be struck by an object extended from an oncoming vehicle such as a side mirror (sideswipe contact).

- Moving operation – accidents that occur in mobile work zones that are not demarcated using channelizing devices, but defined by flaggers, work vehicles, etc.

- Access accidents – accidents that occur when a vehicle attempting to join or leave mainstream traffic through the work zone comes in contact with a worker, construction equipment/vehicle, or another errant driver.

- Debris intrusion – accidents that occur when a construction equipment/vehicle or worker is hit by debris or traffic control devices thrown into the work zone by drivers of passing vehicles.

Based on 290 intrusion accidents that occurred between 1993 and 1998, Bryden et al. (2000) reported that 196 of the accidents (68%) involved full intrusions into the work zones. Other common characteristics of intrusion accidents included: moving operations (19%), lack of buffer (8%), and access issues (3%). Another research study by Ullman et al. (2011) collected and analyzed information on 249 intrusion crashes that occurred in New York. The study found that the majority of intrusions (58.7%) occurred during a lane closure. Intrusions occurred to a much less extent when there was work on the shoulder or median (8.9%), traffic control setup and removal activities (7.7%), mobile operations (6.5%), and activities involving flaggers (6.5%).

Previous studies (Bryden et al. 2000; Cole 2013; Ullman et al. 2011) also identified the following culprits of drivers and driving behavior as factors that contribute to work zone intrusions:

- Speed

- Distraction (such as texting)

- Alcohol

- Drugs

- Confusion (e.g., faulty work zone traffic control set up, ineligible signs, etc.)

- Sleep

Specific to Oregon, mechanical failure of vehicles has been mentioned as a possible source of work zone intrusion. For instance, in 2013, a mechanical failure of a vehicle caused a work zone intrusion that led to fatality on Interstate 5 during a paving project in Glendale, Oregon. In addition, a near miss occurred on Interstate 5, along the downward slope of the Siskiyou Summit in 2010. A tractor-trailer heading downhill broke through the work zone barriers as a result of a failed brake (ODOT 2015b). Although there was considerable damage to ODOT equipment, no fatality or major injury was recorded.

2.2 SAFETY TECHNOLOGIES IN HIGHWAY CONSTRUCTION

Various safety technologies have been introduced in response to the growing safety concern in highway construction. According to the Center for Construction Research and Training (CPWR 2012), 2,707 fatalities were linked with highway construction between 1992 and 2010, with work zone accidents accounting for 26.1% (210) of the total fatalities in 2010. Data from the Bureau of Labor Statistics (BLS) also show that 962 construction workers were killed in highway work zones from 2003 to 2010 (Pegula 2013). The high fatality rate is largely due to the unavoidable need for workers to work adjacent to live traffic during highway construction and maintenance operations.

In response, previous research efforts have aimed at assessing effective means of reducing the fatalities connected to highway work zones. For example, state Department of Transportation agencies (state DOT's) across the US have assessed the effectiveness of various traffic control devices that contribute to work zone safety (Agent and Hibbs 1996). Safety technologies used by state DOT's to improve work zone safety are listed in Table 2.1.

Table 2.1: Work Zone Safety Technologies used in State DOT's (Adapted from Schrock et al. 2013)

Safety Technologies	State DOTs that use the Technology
Portable highway advisory radio	DE, FL, IN, MN, NC, NJ, OH, VA, and WA
Portable changeable message signs (truck-mounted signs)	AZ, CT, DE, FL, GA, IA, IN, KY, MA, MN, MO, MS, NC, NE, NJ, NY, OH, OK, OR, TN, TX, VA, WA, and WV
Portable speed display trailer	AZ, CT, DE, FL, GA, IN, KY, MA, MN, MO, NE, NY, OK, TN, TX, VA, WA, and WV
Automated flagger assistance device (AFAD)	AL, CO, IN, MN, NY, OR, SC, UT, VA, and WA
Drone Radar Speed Reduction	IN, MA, NC, NE, NY, TX, VA, and WA
Portable rumble strip (PRS)	AZ, FL, MD, MS, MN, NC, NJ, VA, WA, and WV
Intrusion devices	CT, IN, KS, MD, NJ, TX, VA, WA, and WV
CB wizard alert system	IN, MO, NE, OH, OK, TX, and WA
Smart work zone (e.g., Intelligent Transport System)	AR, GA, IL, MI, MN, NJ, NM, NY, OR, TX, and WA

Depending on the constraints of a highway construction project, different combinations of safety technologies can be used to improve the safety of construction workers within work zones. Among the available safety technologies, the present study is focused on intrusion alert technologies that help secure much needed extra time for construction workers to evade errant vehicles when intrusions occur.

2.3 PREVIOUS INTRUSION ALERT TECHNOLOGIES

An extensive literature search revealed that a number of intrusion technologies have been developed and tested to determine their effectiveness in work zones. Some of these technologies are no longer commercially available. It was identified that previously available intrusion alert technologies were based on different alarm triggering mechanisms such as infrared beams, microwave, and pneumatic pressured tubes (Hatzi 1997). These technologies were mostly developed by safety device manufacturers as a result of a research study initiated by the Strategic Highway Research Program (SHRP). This section presents a summary of previous alert technologies and results of pilot testing where DOTs tested the target technologies to ascertain their usefulness and effectiveness on live projects.

Infrared Intrusion Alert (IIA) system

This intrusion alarm is comprised of a transmitter and receiver in the shape of a cone that can be placed on the roadway. The transmitter, which is typically placed at the beginning of the taper, is used to pick up any intrusion into the work zone by errant drivers. The receiver can be placed up to 1,000 feet away from workers. If an intrusion occurs, the dual transmitted beams would be obstructed, causing the receiver to activate the 147-decibel air horn to alert workers. IIA was evaluated for 30 hours over eight days by a maintenance group within the Arizona DOT. The test was considered successful because only three false alarms occurred and the crews involved in the testing liked the unit. The Iowa DOT also tested the unit on a 3-hour maintenance operation to verify if ambient radio signals could trigger false alarms. No false alarm was recorded (Wang et. al. 2011).

Microwave Intrusion Alert System

Similar to the IIA system, the microwave intrusion alert technology consists of transmitting and receiver units to create a wireless barrier. The units are attached to a drum (barrel), tubular marker, or other roadway device at regular spacing in the work zone, and aligned so that they can remain in continuous communication. When an errant vehicle intrudes into the work zone, the line of sight of both components is disrupted, automatically triggering an alarm. The Iowa DOT tested this technology on several projects to determine its effectiveness, yet rejected the use of the technology due to the lengthy set-up time required for deployment. Additional issues related to difficulty in keeping the device aligned, excessive amount of false alarms, and inaudible alarm were reported by the Alabama DOT, Pennsylvania DOT, and Colorado DOT, respectively, leading to the discontinuation of the technology (Hatzi 1997; Trout and Ullman 1997; Wang et al. 2011).

Pneumatic Hose Intrusion Alert System

This intrusion alert technology consists of a pneumatic tube and switch. The tube is placed on the ground around the channelized perimeter of a work zone. When an errant vehicle runs over the tube, a warning signal is sent to a siren device located close to the workers. When an errant vehicle puts pressure on the tube, an alarm goes off immediately. The Virginia, Washington, Florida, and Iowa DOTs found the use of this technology to be challenging and ineffective. Issues found during testing include: (1) pneumatic tubes were easily punctured by heavy equipment, (2) it did not provide enough warning time for workers to respond, (3) it required excessive set-up time, and (4) persistent false alarms were caused by work vehicles (Burkett et al. 2009; Hatzi 1997).

Table 2.2 indicates the availability of work zone intrusion alert technologies that have been developed to date. As seen in Table 2.2, Burkett et al. (2009) reported that most previous work zone intrusion alert technologies have been decommissioned for a number of reasons, including low demand (small market), persistent false alarms, high cost, difficulty to deploy, and limited range of alarm.

Table 2.2: Summary of Intrusion Alarm Technologies (Adapted from Burkett et al. 2009)

System	Status
Infrared intrusion alarm	Decommissioned
Microwave intrusion alarm	Decommissioned
Pneumatic tube and radio	Decommissioned
Pneumatic tube safety alarm	Decommissioned
Watch Dog perimeter work zone intrusion alarm	Decommissioned
Safety Line SL-D12	Decommissioned
Wireless warning systems	Decommissioned
SonoBlaster®	Available
Worker Alert System (Traffic Guard)	Available
Intellicone®	Available
IntelliStrobe®	Available

Despite the mixed results from previous studies, a recent study in Kansas (Novosel 2014) reported promising findings. The study aimed at evaluating the effectiveness of the SonoBlaster® and Intellicone®, both of which are currently available. Four case studies were carried out on different projects to investigate the perception of construction workers and to measure how the devices respond to different project conditions. The study results highlighted that although the sounds produced by both technologies were effective only within limited distances, the two technologies can significantly contribute to improving the safety of workers in work zones.

2.4 AVAILABLE TECHNOLOGIES

The literature search described above along with an extensive search of the Internet using Google revealed a limited number of instruction alert technologies that are currently available to the public. The four intrusion alert technologies that were identified as available are presented in Table 2.3 along with in-depth details about the operation and performance of each technology. An extended version of Table 2.3 is provided in Appendix A that provides additional detailed information about each technology.

Table 2.3: Available Intrusion Alert Technologies

	SonoBlaster®	Intellicone®	Worker Alert System	IntelliStrobe
Manufacturer	Transpo Industries	Highway Resource Solution	Astro Optics, LLC	IntelliStrobe Safety Systems
Website	www.transpo.com	www.intellicone.co.uk	www.astrooptics.com	www.flaggersafety.com
Price Estimate	$100 each	$2,000 each	$600 each	$25,000 each
Components	SonoBlaster® Alarm	Strobe lights, sentry, Portable Site Alarm	Pneumatic hose, Flashing Alarm light, personal vibrating and audio alert device	Flagger - W1-AG and Remote Control Radio- FC 401-1
Suggested Application	Low speed roads, Warehouse blind spots, flagger protection, and offloading space (Wang et al. 2011; ELWC 2015).	To secure construction site access points, and for small and medium temporary work sites (Highway Resource Solution 2015).	No suggested application found	To secure work zone on a single-lane, two direction road
Alert Mechanism	Impact-tilt activated alarm system	Impact-tilt, wireless sensor activated alarm system	Pressured trigger pneumatic tube alarm system	Pressured trigger pneumatic tube alarm system
Type of Alarm	Audio	Audio and visual	Audio, visual, and haptic	Audio
Deployment	Attach device to channelizer along taper Channelizers with SonoBlaster® Work zone	Install device on channelizer along taper and work zone Channelizers with strobes Audio and visual alarm device	Place tube at the beginning of taper. WAS pneumatic tubes Audio and visual alarm device	Place tube at the beginning of taper. IntelliStrobe® with pneumatic tubes

Table 2.3: Available Intrusion Alert Technologies (continued)

	SonoBlaster®	Intellicone®	Worker Alert System	IntelliStrobe®
Audio Alarm Level	125 decibels at 6 feet (Transpo Industries Inc. 2015a)	80 decibels at 50 feet (Novosel 2014)	68 decibels at 50 feet	125 decibels (IntelliStrobe® 2015)
Limitation Reported in Previous Studies*	Alarm range, false alarms, and set up time (Krupa 2010)	Inaudible over long distance (Novosel 2014)	False alarm, short reaction time, extended deployment time, and limited work zone coverage (Wang et al. 2011)	False alarm, short reaction time, extended deployment time, and limited work zone coverage (Wang et al. 2011)
YouTube Link	https://www.youtube.com/watch?v=WRFjerUnNVo	https://www.youtube.com/watch?v=othcn5eMhW4	https://www.youtube.com/watch?v=tXB93yH4mmA	No YouTube video available

*General limitation associated with pneumatic tube systems used for intrusion alert.

2.5 POINT OF DEPARTURE

In short, previous studies that attempted to test work zone intrusion alert technologies were performed in various project conditions or controlled testing environments, making it difficult to draw conclusive results. In response, the present study aims to address the capabilities and effectiveness of the available technologies by applying them to viable, real project condition scenarios on actual ongoing projects (case studies), aimed at yielding meaningful, conclusive findings in a comprehensive manner. The project condition scenarios that are considered for this study include, but are not limited to:

- New construction/maintenance
- Short-term/long-term work zones
- Stationary/mobile operations
- Nighttime/daytime shifts

In particular, more scientific research is needed to test alert technologies for intrusion accidents associated with mobile operations (Bryden 2000), as well as nighttime operations given that approximately 30% of intrusion crashes happen after dusk (Ullman et al. 2010). The lack of pilot testing during mobile operations and/or nighttime operations is concerning, which can be addressed by this study.

3.0 SURVEY OF CURRENT PRACTICE

Task 2 aimed to perform an online survey of the construction industry to gather information on the current practice with respect to work zone intrusion alert system. The survey was intended to improve the chances of obtaining data from a greater geographical spread and at a higher response rate. A draft questionnaire was first developed for the TAC's review, and then revised to incorporate the TAC's input. The draft survey was reviewed and subsequently approved by the Institutional Review Board (IRB) at OSU. The IRB approval letter is provided in Appendix B.

3.1 SURVEY STRUCTURE

The survey contained three sections, consisting of a total of 15 questions. The sections were as follows:

- Part 1 focused on gathering basic background information of participants' background such as job title and experience.
- Part 2 focused on collecting data related to perception on the effectiveness of work zone safety technologies that they have used on past projects.
- Part 3 asked for information about deployments, benefits, and barriers related to the implementation of one specific intrusion alert technology that each participant is most familiar with.

The survey ended with a web link to a separate webpage where participants could provide their contact email address, if they chose to do so. Appendix C shows the survey questionnaire.

3.2 SURVEY ADMINISTRATION

The online survey was hosted and administrated through the Qualtrics survey system supported by OSU (http://main.oregonstate.edu/qualtrics). A separate survey was set up to collect contact email addresses of participants who were willing to make themselves available for further inquiries. The separation was required by the IRB so that survey responses could not be associated with specific respondents.

3.3 SURVEY DISTRIBUTION

Industry practitioners in highway construction were targeted for survey distribution. The contacts used for the survey distribution was obtained from the following sources:

- The alumni contact list of the School of Civil and Construction Engineering (CCE) at OSU;
- Listservs from the Associated General Contractors (AGC) Oregon-Colombia Chapter Highway Construction Committee; and

- AASHTO construction group members.

A web-link to the online survey was distributed to potential participants via email, using the collected contacts and email lists. Additionally, the web-link was posted on official blogs of the Associated General Contractors (AGC) Chapters in Oregon as well as other states. Furthermore, the web-link was distributed to the research department of other state DOT's by ODOT Research personnel. In total, 296 contacts consisting of 30 OSU alumni, 100 AASHTO members, and 166 AGC members were emailed directly. It should be noted that the "request to participate" email asked receivers to forward the message to other professionals involved in highway construction. However, not all 296 emails reached the intended target population due to some unresponsive email addresses. The survey was available online between November 9 and December 30, 2015.

3.4 RESULTS

A total of 144 highway construction professionals took part in the survey. Completed questionnaires were received from 102 out of the 144 responses received. Nevertheless, 111 respondents provided feedback to the first five questions. Of the 111 participants that indicated their company affiliations, 30% of the responses came from general contractors while 51% was received from owner agencies (DOTs) (Figure 3.1). This distribution percentage is representative of the population that was sampled by the researchers. The target sample was intentionally chosen to represent the population that would likely have some knowledge of work zone intrusion alert systems.

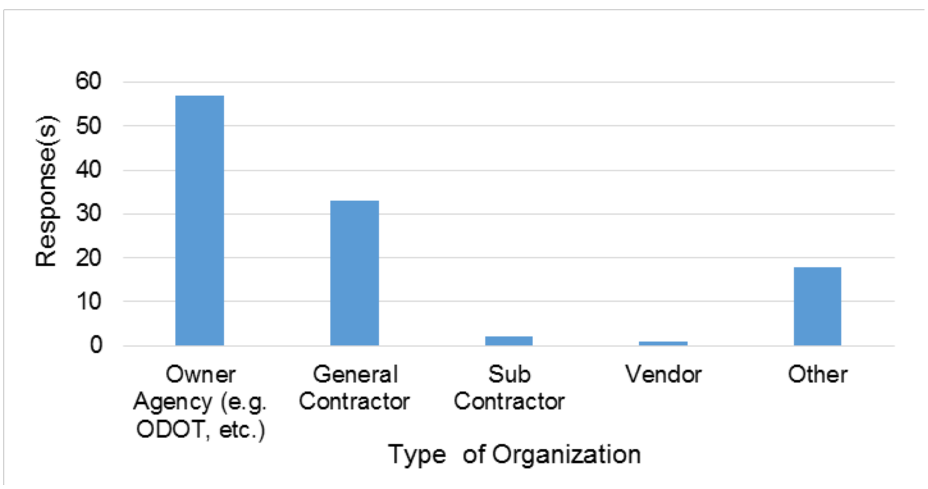

Figure 3.1: Types of Participants' Organizations (n = 111)

Responses were received from different categories of professionals involved in highway construction industry. As seen in Figure 3.2, 10% of the responses came from traffic control designers, while upper-management-level employees (operation, construction, transportation, project, and general) provided 46% of the responses.

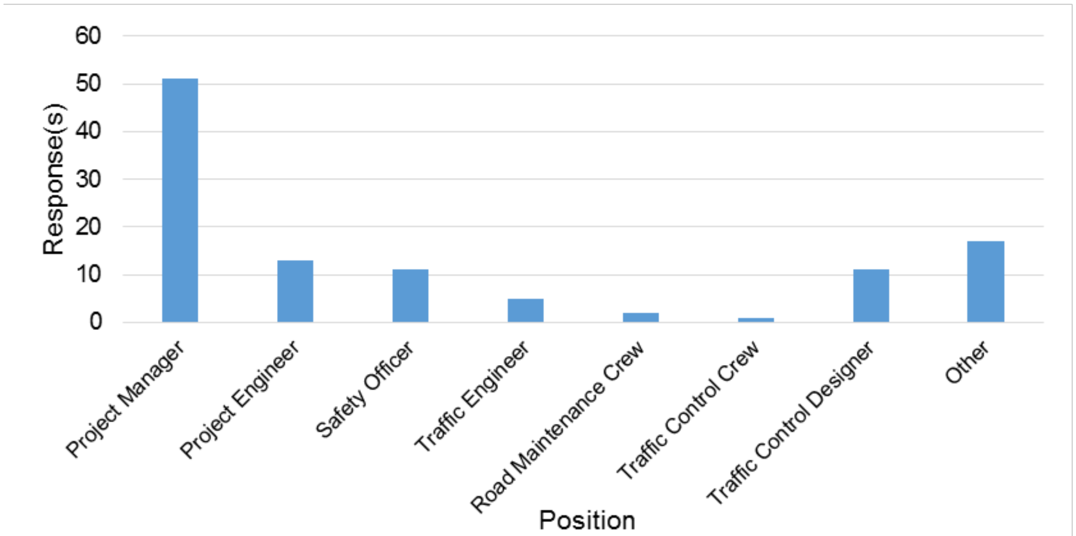

Figure 3.2: Respondents Distributed by Work Positions (n = 111)

Since upper management employees represent a considerable number of the respondents, it is comprehensible that 60% of the respondents have over 20 years of construction experience. Figure 3.3 shows that all of the respondents have more than five years of industry experience with the exception of four participants.

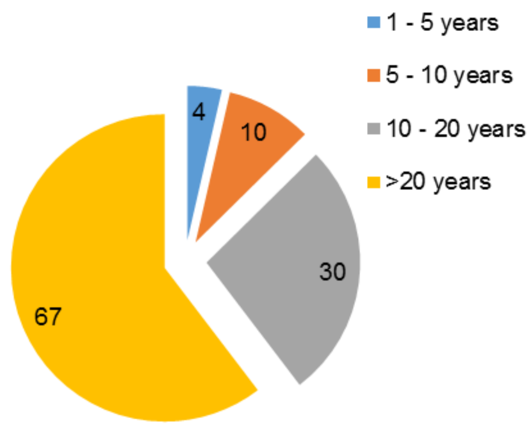

Figure 3.3: Years of Experience of Respondents (n = 111)

A study carried out by Wang et al. (2011) reported that most state DOTs implement different work zone safety technologies as part of traffic control protocols. The study included a survey distributed to state DOT's to ensure that adequate feedback was received from a wide spread of possible users of work zone intrusion alert systems. A total of 32 states from the U.S. and two provinces in Canada (Table 3.1) participated in the survey. Oregon provided 24 responses, which represents 22% of the total responses received. Thirty-three responses were received from

Canada: 32 from British Colombia and one from Saskatchewan. The relatively high number of participants from British Colombia could be a result of a significant interest in work zone safety in British Columbia.

Table 3.1: Number of Responses by State

Number of Responses	States
1	AL, CA, CN, DC, DE, FL, HI, IN, KS, MI, MT, NH, NV, OK, PA, SC, SD, UT, VA, VT, WA, WV, and SK (Canada)
2	AK, IA, MN, MS, NJ, and WY
6	OH
24	OR
32	BC (Canada)

To determine a list of commonly-used work zone safety technologies in the highway construction industry, participants were asked to indicate technologies that were frequently used on their projects. Ninety-four of the 111 participants (85%) reported that Portable Changeable Message Signs (PCMS) are used on their projects while work zone intrusion alert systems were indicated as being used by only 2% of the respondents (Figure 3.4).

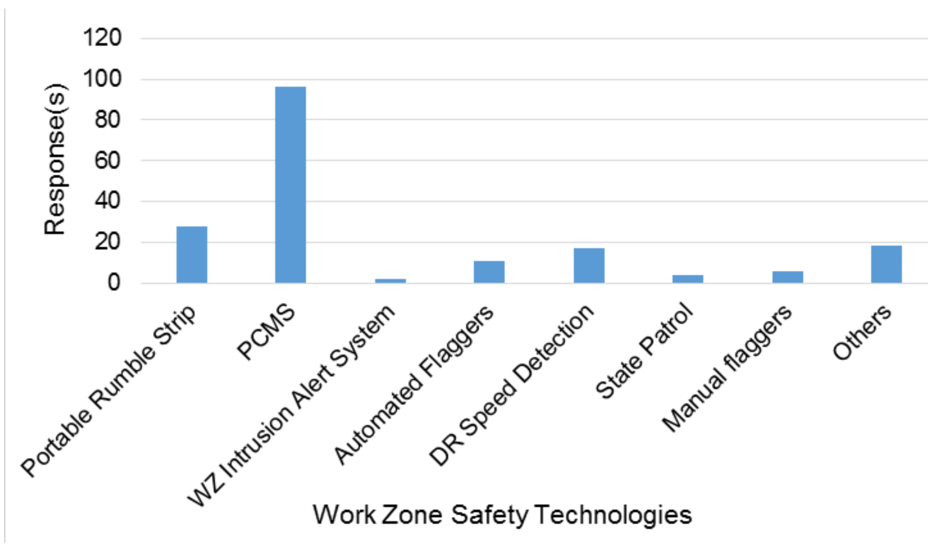

Figure 3.4: Types of Work Zone Safety Technologies Used on Highway Construction Projects

The effectiveness of some work zone safety technologies to prevent accidents has been questioned in past studies (Ullman et al. 2011). The survey results show that a PCMS was considered to be the most effective work zone safety device in terms of accident prevention. As seen in Figure 3.5, 47 participants indicated that a PCMS has an effectiveness rating of at least 4 on a scale of 1 to 5, where 1 represents minimally effective while 5 represents highly effective.

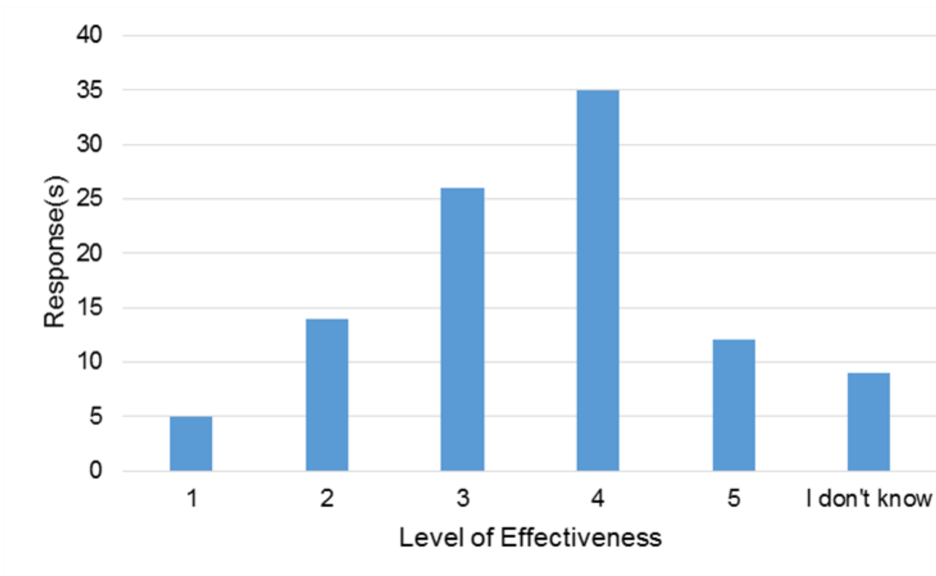

Figure 3.5: Effectiveness Rating of PCMS

The existing literature suggests that work zone intrusion alert systems are not currently widely used in the construction industry (Wang et al. 2011). To validate this finding, the survey participants were asked if they had used or are using work zone intrusion alert technologies on any project. The responses show that 90% were neither using nor planning to use work zone intrusion alert systems.

Although 11 respondents indicated that they are familiar with work zone intrusion alert systems, only nine participants answered questions related to such systems. Five out of the nine participants indicated that they have some knowledge of intrusion alert technologies (Figure 3.6).

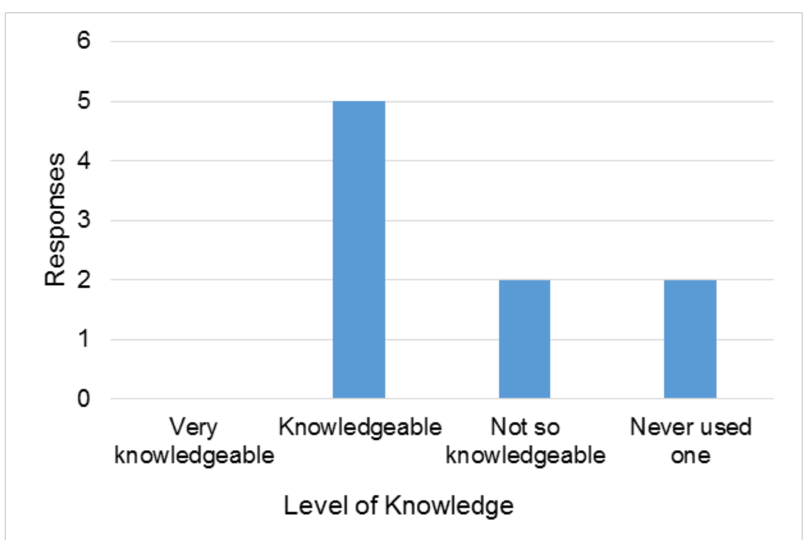

Figure 3.6: Level of Respondent Knowledge of Intrusion Alert Technologies

Six participants indicated that they were familiar with infrared beam intrusion alert systems, while no respondent indicated having prior knowledge of microwave intrusion alert systems. A previous study of Burkett et al. (2009) indicated that the use of microwave technology as an intrusion alert system was discontinued due to several issues such as inconsistent alarm, difficulty with deployment, and inadequate coverage. This could be a major reason why participants have little or no knowledge of the work zone intrusion alert systems. When asked how beneficial work zone intrusion alert systems were to work zone safety, all nine responses indicated that intrusion alert systems had some benefits, while some participants had some reservations. Highlighted below are some comments from the participants about intrusion alert technologies:

- *"Never used one or even heard of them in our Province. Definitely want to know more."*
- *"The current ones we use are difficult to cover a large work zone and with [strong] wind cones are knocked over constantly so the SonoBlaster® is a "CRY WOLF" product."*
- *"The current systems are better than nothing, but will improve as time goes on."*
- *"I believe that any attempt to alert workers of intrusion is beneficial to WZ safety."*
- *"I have seen [automated flagger assistance devices] AFADs equipped with intrusion alarms, both pneumatic and flagger activated, successfully stop drivers of dump trailers from accessing one lane two way operations illegally."*
- *"Not much luck with SonoBlaster® type catching intruders or setting up quickly."*

As previously mentioned, all participants attested to the potential benefits from the deployment of work zone intrusion alert systems. Figure 3.7 shows that all five participants who have knowledge about intrusion alert systems believe that the systems can provide extra reaction time for construction workers.

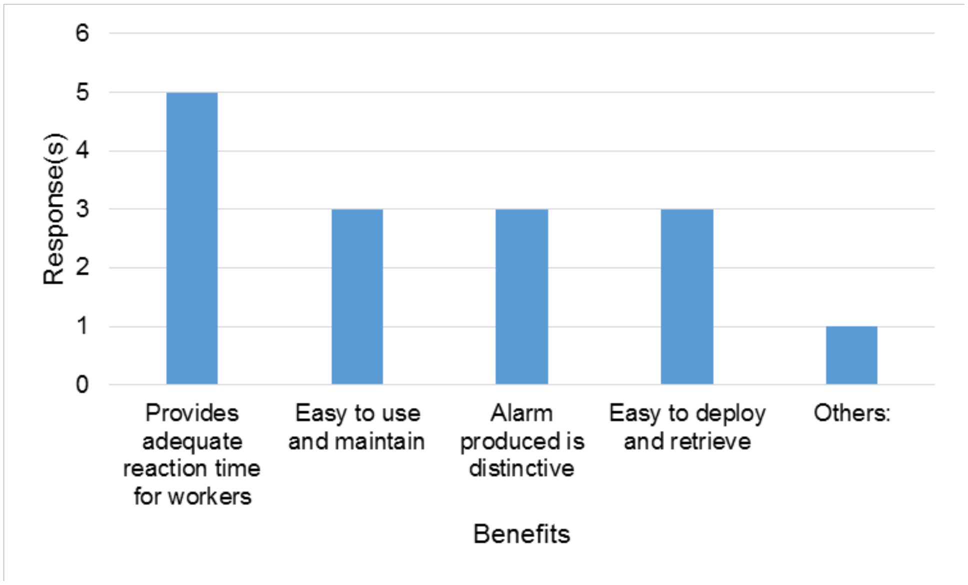

Figure 3.7: Benefits of Work Zone Intrusion Alert Systems (All Technologies Inclusive)

The highlighted benefits shown in Figure 3.7 appear to concur with the previous studies. It is interesting to note that one participant mentioned that in addition to these benefits, a pneumatic tube alert system "Can also be activated by the flagger if intruder comes around a tube".

In terms of barriers, multiple previous studies highlighted that work zone intrusion alert systems are susceptible to various operational shortfalls (Burkett 2009; Novosel 2014; Ullman et al. 2010). In the same regard, the survey asked to identify barriers that hamper the use of work zone intrusion alert systems. As seen in Figure 3.8, the top three barriers were identified as inaccurate alarm (false-positive and false-negative), inadequate work zone coverage, and difficulty to operate and maintain. This assertion is supported by Wang et al. (2011) that reported inconsistent alarms and lack of proper coverage as factors and impede the extensive use of work zone intrusion alert systems. No response indicated that the quality of the alarm sound was a shortcoming of intrusion alert systems. Rather, one participant indicated a possible issue related to the coverage of pneumatic tube alert systems, saying "Typically only located at one lane, two way AFAD applications".

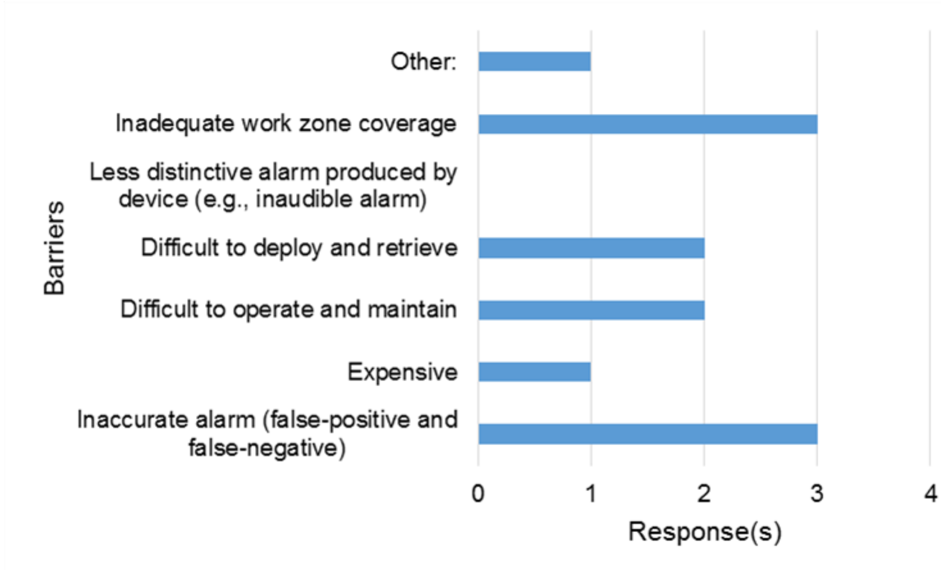

Figure 3.8: Barriers to deployment of Work Zone Intrusion Alert Systems (All Technologies Inclusive)

A total of 41 participants, representing approximately 40% of the total respondents, provided contact information in the separate survey, which was linked to the end of the main survey. As stated earlier, this was done to keep the responses anonymous.

3.5 SUMMARY OF CURRENT PRACTICES

The survey performed for Task 2 was designed to determine how knowledgeable highway construction professionals are about work zone intrusion alert systems. The survey also targeted determining the level of acceptance of the systems, their barriers and benefits, and to receive feedback on how these technologies could be improved. The survey results suggest that notwithstanding the possible benefits from the use of work zone alert systems, the application of such systems on live projects has been limited. It was also found that only a small percentage of participants are familiar with work zone intrusion alert systems. In general, the acceptance of work zone intrusion systems as a useful addition to other work zone safety technologies has been stagnant although the technologies have been available for the last decade. Listed below are some comments from the survey participants that are aligned with these survey findings:

- “A needed technology, if one life is saved it is worth it”.
- “In the past, WZI alarms have not been used extensively due to false positives. [A company] is developing an intrusion system that seems to solve this problem.”
- “It is difficult to adequately cover some WZ's on a freeway because some closures are 1 mile long”
- “We tried the SonoBlaster® type units by giving several maintenance sections about 6 units and some instruction for implementing. Received some negative comments about

setup time/traffic exposure for workers and did not have instances of intrusions to evaluate adequately”.

The findings and comments from the survey were incorporated into Task 4 of the research study, in which a focus group was formed to evaluate the results of the pilot testing conducted in Task 3. Task 4 is described in detail below.

4.0 PRELIMINARY INVESTIGATION

During the project kick-off meeting in July 2015, a need for a preliminary investigation was raised and discussed, although it was not part of the original Work Plan. The goal of the investigation was to collect sound and light data from a highway work zone which could serve as a baseline for the study. During the meeting, one of the TAC members suggested the ODOT 14821 Turn Lane Project for the Tualatin River National Wildlife Refuge (TRNWR) as a candidate project for the investigation. Subsequently, the research team closely coordinated with the contractor's project manager for setting the dates for data collection. As a result, the data collection occurred on September 9 and 17, 2015 with the daytime observation of the excavation operation and nighttime paving operation, respectively. This section presents a description of the project, the data collection process, and analysis results.

4.1 ODOT 14821 TUALATIN RIVER NATIONAL WILDLIFE REFUGE (TRNWR) TURN LANE PROJECT

The Tualatin River National Wildlife Refuge (TRNWR) is located on OR-99W between King City and Sherwood (Figure 4.1). As a result of vehicles making a right turn directly from OR-99W (55 mph) to access the adjacent refuge, the traffic needed to slow down in the travel lane. This safety concern led to joint efforts among ODOT, Western Federal Land Highway Division, and TRNWR to create a dedicated right turn lane.

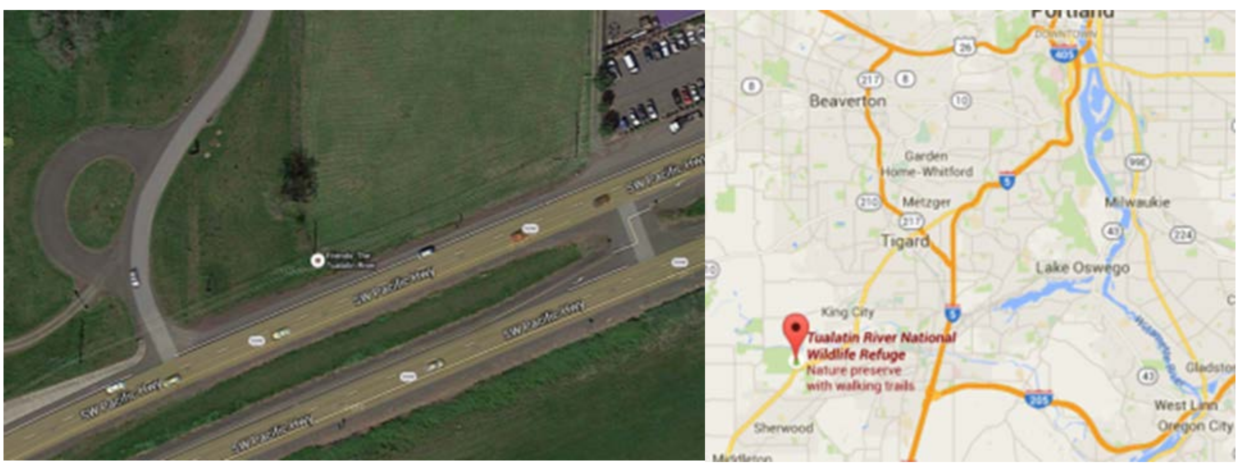

Figure 4.1: Project Location (Images from Google Maps 2016)

Figure 4.2 shows the project layout. The construction site began immediately after the pocket between Stations 335+00 and 340+00 and had a length of approximately 460 feet.

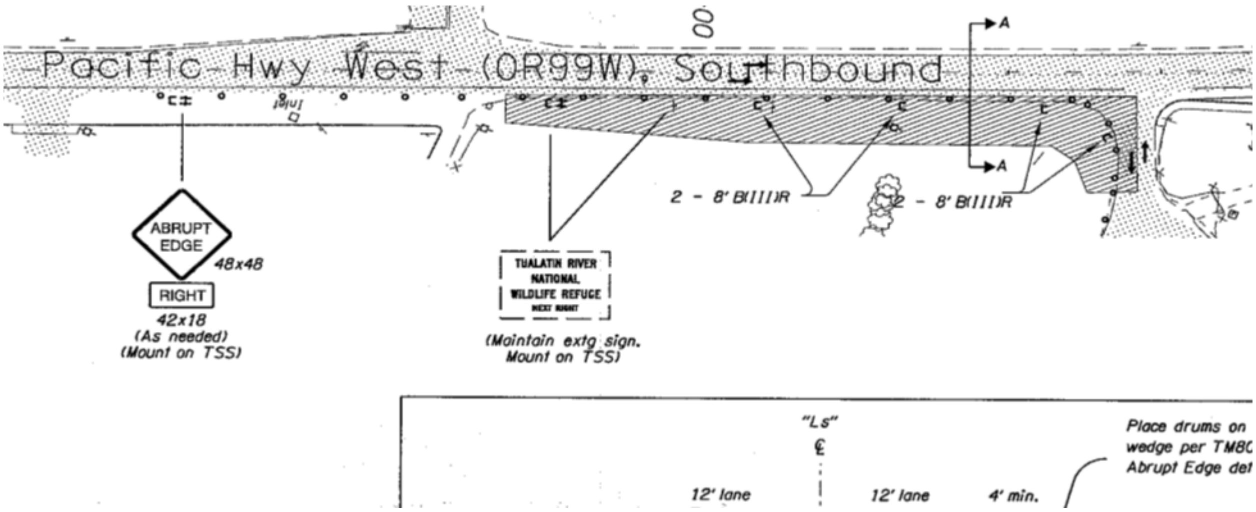

Figure 4.2: Project Layout [Image Excepted from the Project Contract Documents (ODOT 2015c)]

4.2 DATA COLLECTION

For the data collection, sound and light meters were used by the research team, including two dosimeters, one data logging light meter, and one data logging sound meter. The detailed descriptions of the devices used are provided in Appendix D.

In order to perform a spatial analysis related to the impact of sound and light emitted in/around the work zone on a field worker, data was collected based on a 20 feet by 25 feet grid system spread across the work zone (Figure 4.3). The first data point had an offset of approximately two feet into the work zone (Station 1), and the grid system was developed based on the first point. Figure 4.3 illustrates 21 data points (hereinafter, stations) created along Grid-Line 1 on the southbound lane and Grid-Line 2 on the north side of the work zone. The two grid lines were to cover the width of the work zone, yet due to site constraints within the work zone, only 13 stations were located along Grid-Line 2. As part of the observation process, two field workers were asked to wear the dosimeter to collect the level of sound each worker was exposed to during the construction activities.

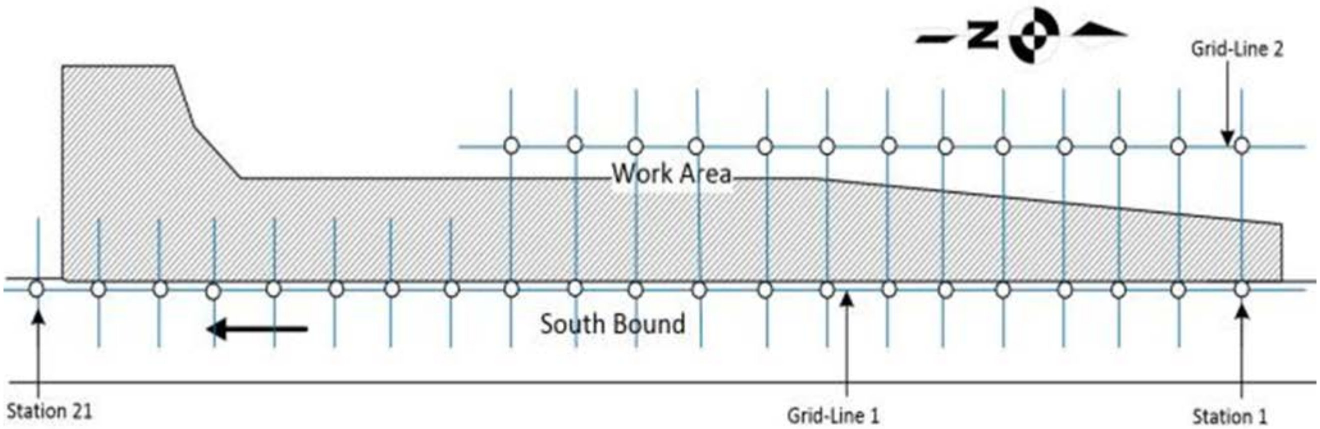

Figure 4.3: Grid System for Data Collection

At each station, sound and light measurements were recorded irrespective of the activity going on. To ensure adequate representation of the noise and light level within the work zone, data was measured and recorded three times at each station at different intervals. In addition, photos and videos were taken for the purpose of record keeping.

A two-phased data collection approach involving data gathering of daytime and nighttime operations was developed and used to ensure that the study would account for a broad range of project constraints and operational factors (Figure 4.4).

Figure 4.4: Daytime and Nighttime Observations

4.3 RESULTS AND ANALYSIS

The research team arrived at the construction site at approximately 7:00am on September 9. The weather was clear with a temperature of about 52oF. Excavation and soil compaction were scheduled to take place between 7:30am and 2:30pm. These activities were carried out by one field worker and a foreman under the supervision of the project manager. The foreman and field worker took turns operating the 135G John Deere Excavator, compactor, and 1,500 gallon water truck. The foreman started excavating at about 7:30am while the dosimeters for both worker and foreman were activated at approximately 8:04 am. It is important to note that each worker within close proximity of the excavator wore hearing protection. At approximately 10:45am, the field worker began compacting the soil using the roller. Prior to operating the roller, the worker operated the water truck and excavator. The research team set up a video camera close to the taper and another camera on the north side of the work zone to capture the whole operation. The data logging grid system was created using a laser distance measure to determine 25 feet by 20 feet offsets. Spray paint was used to create reference points for each station. The measurements along Grid-Line 1 were approximately four feet away from the actual construction area (but within the work zone). Data recording along the grid-lines began at about 8:25am and was concluded at approximately 11:30am. Figure 4.5 shows the noise level to which each worker was exposed between 8:04am and 11:06am. Both workers maintained close proximity to the equipment at all times except between 9:20am to 9:40am when the foreman left the work zone. The peak noise level recorded during the observation was between 10:40am and 11:02am when the field worker was using the roller. Figure 4.5 also shows the maximum noise level permitted by OSHA without hearing protection (85 decibels).

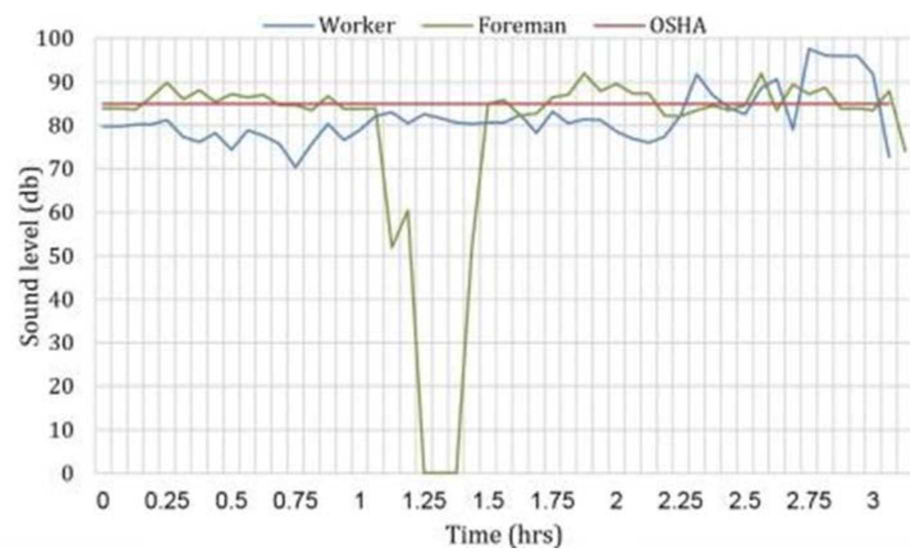

Figure 4.5: Sound Level in Close Proximity to Workers

The noise level around the work zone was recorded at the 21 stations using the locations identified on the grid system. Sound level measurements were taken three times (rounds). Each round of measurements was captured at each station to provide a range for noise level per station. Figure 4.6 shows that all of the measurements were observed to be below 85 decibels. Stations 13, 17, and 19 indicate the maximum noise level of each round of data collection. It was found that the peaks recorded resulted from the close proximity of the excavator to the station being observed.

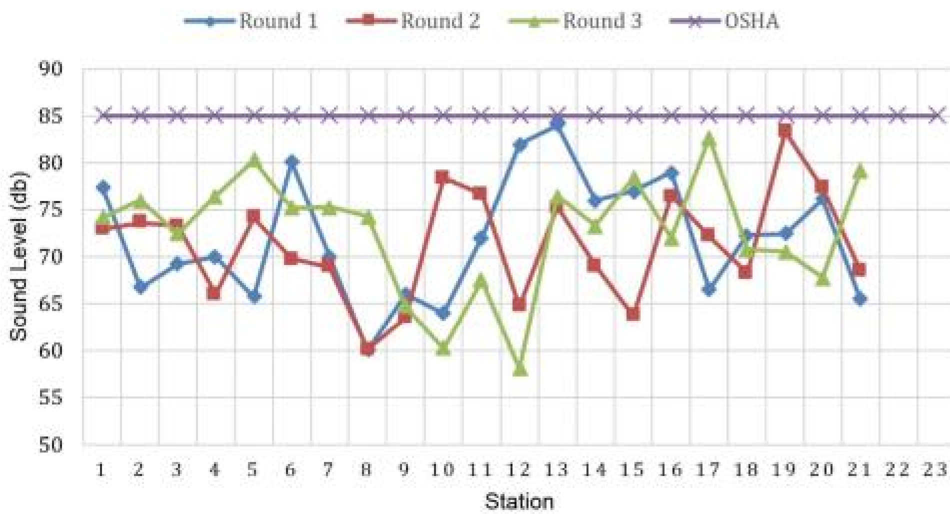

Figure 4.6: Sound Level along Grid-Line 1

Sound and light levels were also measured along Grid-Line 2. Generally, there was less ambient noise due to the distance between the sources of noise and the recording location. The effect of noise emanating from running equipment was only recorded during the second round of data collection as evidenced in the peak at Station 7, as seen in Figure 4.7. There is some consistency with the level of sound produced by the roller. Findings from the dosimeter showed that the roller produced more noise than the other equipment used.

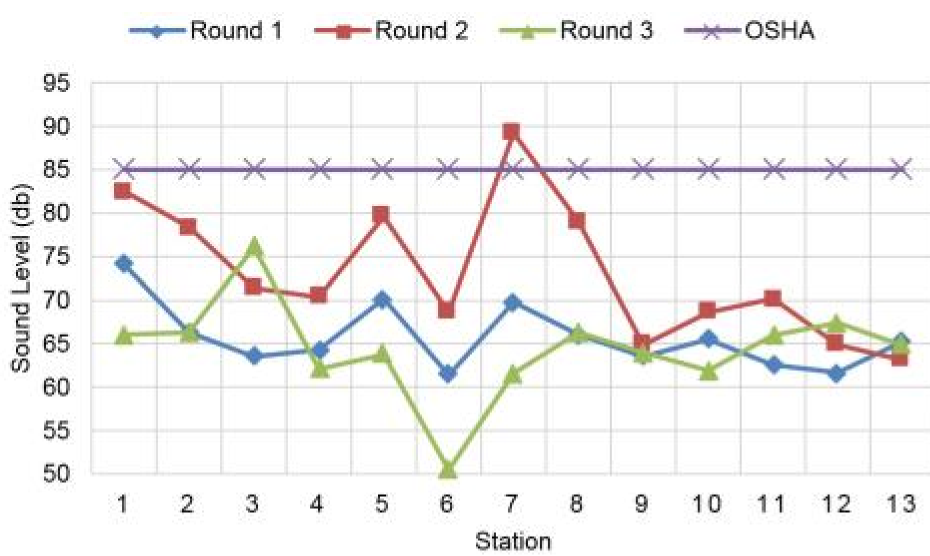

Figure 4.7: Sound Level along Grid-Line 2

Figure 4.8 shows a seven-minute recording of sound level close to the excavator and vehicle traffic. Although both noise levels have similar peaks, the noise level around the equipment was relatively consistent over the seven minutes. The median noise level around the excavator and vehicle traffic was recorded as 75 and 71 decibels, respectively.

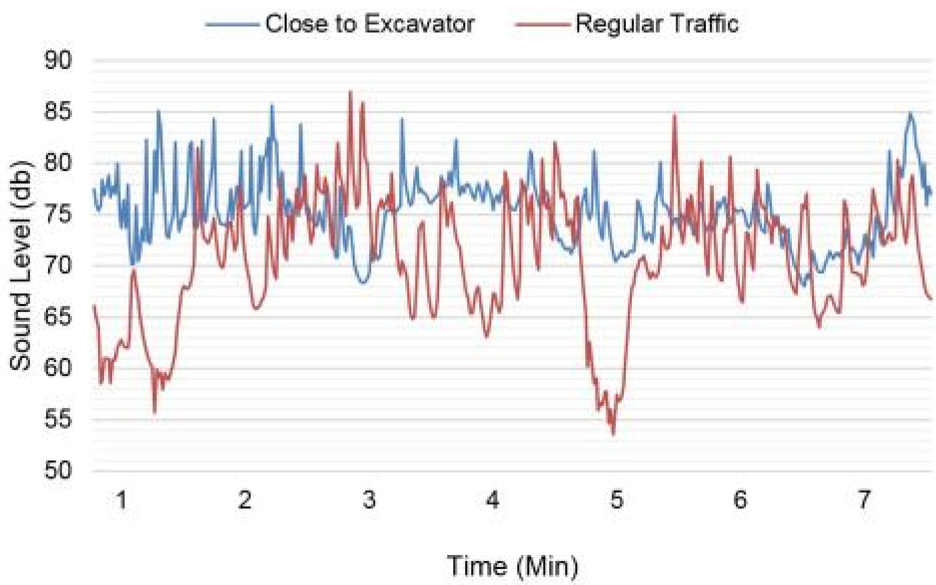

Figure 4.8: Sound Level in Close Proximity to the Excavator and Regular Vehicle Traffic

The data collection process used during the daytime observation was repeated during a nighttime operation on September 17. The research team observed a paving operation between 7:00pm and 10:00pm. The operation fleet consisted of two rollers (Caterpillar CB54 and extra-wide Caterpillar CB54XW), a paver (CAT AP1055F), and asphalt dump trucks. Approximately 6 to 8 people were stationed within close proximity to the paver at any given time. Gridlines and stations had to be recreated because some of them were destroyed after the first observation (additional observation results from the nighttime along the gridlines can be found in Appendix E). One dosimeter was assigned to a worker operating the big roller and the other to the paver operator. Figure 4.9 shows the average maximum noise level recorded across a distance of 120 feet during the three observations along Grid-Line 1. During the operation, 84.5, 90.1, and 88.1 decibels were recorded as the peak noise level for the paver, roller, and asphalt truck, respectively. Note: These measurements were based on the relative distance from each piece of equipment on both sides of the equipment, and the station being observed. Therefore, there are multiple zero points along the horizontal axis.

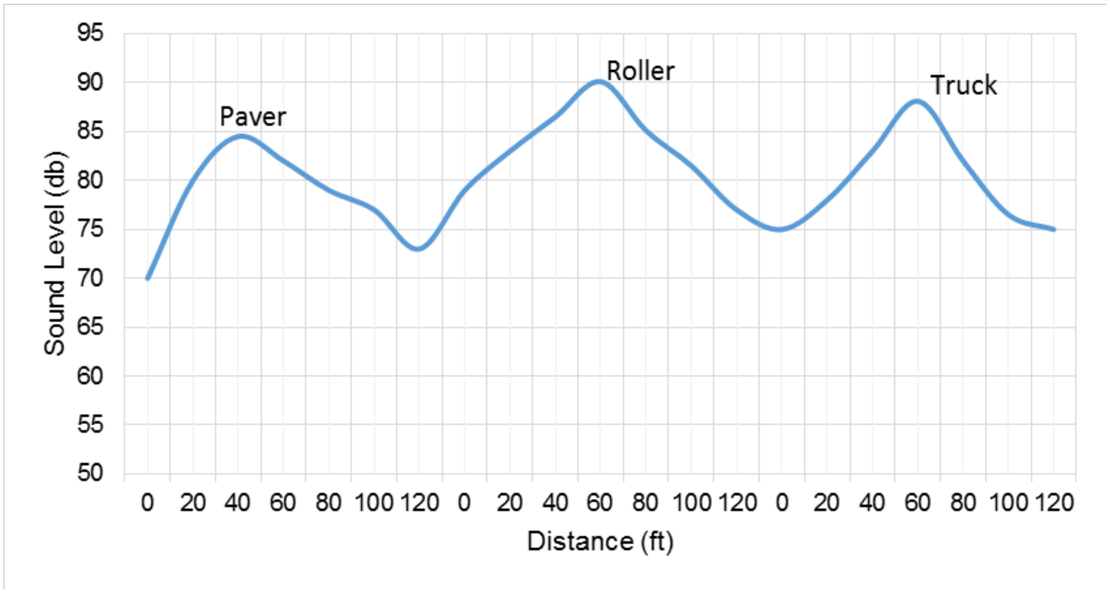

Figure 4.9: Average Sound Levels based on Distance from Construction Equipment Observed

The amount of light in an area is typically measured in foot-candles or lux. A foot-candle can be defined as the illuminance on a uniform surface one foot away from the light of one candle. One foot-candle (Fc) equals 1 lumen/ft2 and one lux is equal to 1 lumen/m2 (Gambatese and Rajendran 2011). For safe construction operations, multiple studies (Bryden and Mace 2002b; Ellis and Amos 1996; Hanna 1996) recommended three different levels of illuminance:

- Level I – a minimum of 5.0 Fc is recommended for general illumination in the work zone for areas which crew movement takes place
- Level II - a minimum of 10 Fc is recommended for illumination on and around maintenance and construction equipment.
- Level III - Illumination above 20 Fc is recommended for tasks that require increased attention.

Figure 4.10 shows the level of light for different stations within the work zone, collected at specific times from the nighttime observation. While recording the first round of measurements along Grid-Line 1, Station 6 recorded 38.2 Fc—the highest level of light intensity logged. The high values recorded were a result of the close proximity of the paver to Station 6. The second and third round of measurements peaked at Stations 21 and 19, respectively, due to the presence of the paver and roller. The observations indicate that most stations recorded light levels below the 5.0 Fc minimum illuminance level for a work zone. However, it should be noted that the field workers clustered around the paver most of the time.

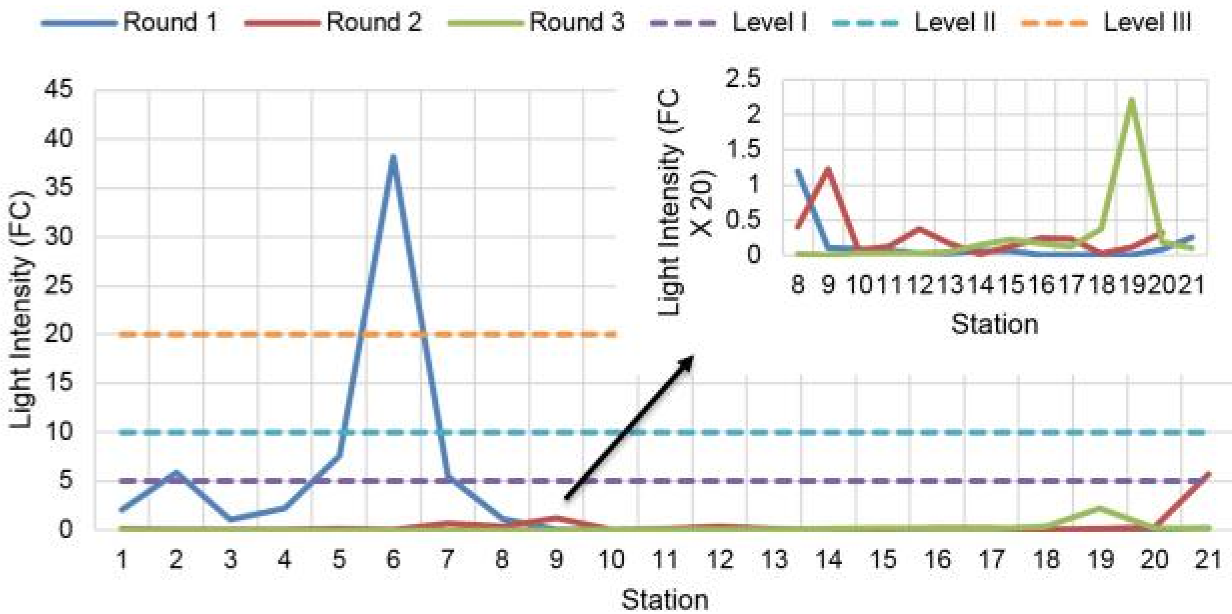

Figure 4.10: Light Intensity along Grid-Line 1 (Nighttime Observation)

4.4 SUMMARY OF PRELIMINARY INVESTIGATION

Previous studies reported that in the last decade, over 100 deaths have been reported every year due to work zone accidents, and the trend has been persistent (NHTSA 2014). On average, between 2010 and 2014, 13 serious injuries and seven fatal crashes were recorded annually in Oregon. In particular, work zone intrusion crashes accounted for 10% of all traffic accidents and 8% of all fatal injuries (Bryden and Andrew 1999; 2000). In response to the growing safety concern in roadway construction, a wide variety of safety technologies have been tested and implemented to improve the overall safety of field workers in work zones. Among the available technologies, the present study is focused on work zone intrusion alert technologies that are designed to alert field workers in work zones and secure much-needed time for them to evade errant vehicles when intrusions occur.

A number of previous studies have been identified where the effectiveness of work zone intrusion alert technologies were evaluated. The types of the alarm triggering mechanism tested in the previous studies include infrared intrusion alert, microwave intrusion alert, and pneumatic hose intrusion. However, the studies reported mixed results, which resulted in limited application of work zone intrusion alert technologies. In response, the objective of this research study is to scientifically assess the effectiveness of currently available work zone intrusion alert technologies, and to provide recommendations for use of the technologies on future ODOT construction and maintenance work zones. To achieve the study objective, the research aims to gather information about work zone intrusion alert technologies, gain experiential input and advice from ODOT staff and practitioners, and test technologies under controlled conditions and in active work zones. Findings discussed in Section 4 provide important base-line information that informed the planning, designing, and execution of the succeeding pilot test protocols.

5.0 PILOT TESTING OF TECHNOLOGIES

Task 3 pilot testing was conducted as an initial testing of the selected technologies under controlled, off-roadway conditions. Each selected technology was assessed to capture its capabilities and limitations, and document how it is implemented. The results of the pilot testing contribute to assessing feasibility of use, capabilities, and limitations related to each technology, and to establish recommended minimum standards for audio, visual, and possibly haptic forms of alerts. The research team developed operation-specific processes and adapted recommendations from past research to verify the functionality of the work zone intrusion alert technologies. Section 5.1 summarizes the basic information of the technologies selected for the pilot testing.

5.1 CATALOG OF TECHNICAL SPECS OF EQUIPMENT TESTED

Four work zone intrusion alert technologies were determined to be currently available in the construction industry through an extensive search by the research team. Task 1 of this research study highlighted all four technologies, providing an overview of the specifications cost, application, and features. As a result of project constraints, the IntelliStrobe® technology was excluded from the testing, leaving the research team to focus on three technologies. Table 5.1 provides a high-level summary of the three intrusion alert technologies selected for the study (See Table 2.3 and Appendix A for more information).

Table 5.1: Summary of Intrusion Alert Technologies Selected for Pilot Testing

	SonoBlaster®	Intellicone®	Worker Alert System
Manufacturer	Transpo Industries	Highway Resource Solution	Astro Optics, LLC
Website	www.transpo.com	www.intellicone.co.uk	www.astrooptics.com
Price Estimate	$100 each	$2,000 each	$600 each
Components	SonoBlaster® Alarm	Strobe lights, sentry, Portable Site Alarm	Pneumatic hose, flashing alarm light, personal vibrating and audio alert device
Alert Mechanism	Impact-tilt activated alarm system	Impact-tilt, wireless sensor activated alarm system	Pressured trigger pneumatic tube alarm system
Type of Alarm	Audio	Audio and visual	Audio, visual, and haptic
Accessories	Single alarm unit	Lamps, motion detector, and portable site alarm	Pneumatic hose, flashing alarm light, personal vibrating and audio alert

5.2 TYPES OF TESTING ACTIVITIES

Different tests were carried out to provide quantitative data to enhance the understanding of the capabilities and limitations of each technology. It was also important to determine if these intrusion alert technologies work better than past intrusion alert devices that previous research showed contain significant limitations (Ullman et al. 2010).

Based on a literature review, the following tests were determined to be needed to better understand the technologies:

1.) Recording false alarms

2.) Measuring the relationship between sound level and distance

    2.1.) Measuring the impact of alarm direction

3.) Measuring the sound level inside a vehicle

4.) Measuring the impact of other nearby equipment on sound quality

5.) Performing a spectral analysis to test the distinctiveness of alarms

6.) Measuring transmission distances

7.) Measuring the light level of visual alarms

5.3 CONTROLLED TESTING

According to a Strategic Highway Research Program (SHRP) study conducted by Agent and Hibbs (1996), it is important to select a location that can be controlled, yet have the capacity to mimic real life operation for closed testing. The research team identified a section of asphalt roadway located at the Corvallis airport as an appropriate location for testing the work zone intrusion technologies. As seen in Figure 5.1, the location provides a stretch of approximately 24 feet wide by 1,600 feet long paved road, containing two lanes (one in each direction), that is predominantly devoid of heavy vehicular and human traffic, making it a safe and ideal location for closed testing. It is important to note that in addition to the limited vehicular traffic within the controlled location, some air traffic was observed by the research team.

Figure 5.1: Pilot Testing Location (Aerial image from Google Maps 2016)

5.4 PILOT TESTING SCHEDULE

Pilot testing was spread across seven days over a period of six weeks. On each day, the research team spent approximately three hours evaluating each technology. Table 5.2 presents a summary schedule of the dates, weather, types of tests carried out, and duration of the pilot testing.

Table 5.2: Pilot Testing Schedule

Date	Weather (Temp/Rain/Wind)	Duration (Hours)	Start Time	Type of test
10/23/2015	44°F/ 0.00 in/ 3 mph	3.5	2:00pm	• Sound level relative to distance • False alarm
11/2/2015	47°F/ 0.1 in/ 6 mph	2	3:00pm	• Sound level relative to distance • Transmission distance • False alarm
11/6/2015	49°F/ 0.00 in/ 2 mph	4	1:00pm	• Sound level inside vehicle • Transmission distance • Sound level relative to distance • Directional testing • False alarm
11/20/2015	41°F/ 0.00 in/ 5 mph	3	2:00pm	• Sound level inside vehicle • Directional testing • False alarm
12/4/2015	46°F/ 0.2 in/ 7 mph	6	9:00am	• Measuring impact of equipment on sound level (two different setups) • Spectral analysis • False alarm
2/6/2015	44°F/ 0.00 in/ 2 mph	2.5	8:00pm	• Visual testing (night time)
2/8/2015	Indoor	2	9:00am	• Visual testing (day time, using luminance meter)

The research team tried to ensure that similar tests were conducted for each technology on a given day to reduce the variability associated with external factors. To further improve the quality of data collection, the research team stopped testing activities once the weather became poor enough to interfere with intended data collection. As seen in Table 5.2, the test carried out on November 2nd was discontinued after 2 hours due to rain and strong wind. This was the only day a test was repeated on a different technology on a different day. The research team monitored the weather and took note of skewed data from both days. Although the weather condition on December 4th was comparable to that of November 2nd, data collection was completed. The pilot testing for December 4th focused on replicating the constraints associated with construction environment.

5.5 PILOT TESTING RESULTS

Sections 5.5.1 through 5.5.7 describe the findings from each of the seven testing activities that were conducted.

5.5.1 Recording False Alarms

Results from past research stated that a key barrier to the implementation and acceptance of work zone intrusion alert technologies in the construction industry was a relatively high probability of having a false alarm (Burkett 2009). Therefore, a controlled experiment which consisted of triggering each work zone intrusion alert technology multiple times was carried out independently. Considering the difficulty of developing a process to test false positive situations (the device sounding an alarm without it being triggered), the research focused more on assessing the frequency of false negatives (the device not sounding an alarm when it is triggered). Nevertheless, while other tests were conducted, the research team took note of any false positives that occurred.

5.5.1.1 False Negative Alarms

Alarms were triggered by the research team one at a time to record any possible false negatives. Results from this test showed that after more than 20 triggers, none of the technologies had a false negative alarm. That is, each intrusion alert system produced the expected alarm once triggered; in no cases was the alert triggered but the alarm not produced. Notwithstanding the success rate of the technologies, six false negatives were recorded when a SonoBlaster® device was used more than once (following changing of cartridge). The research team believes that the SonoBlaster® is not designed for reuse after impact. In fact, in real operations, it is anticipated that once a SonoBlaster® unit has been triggered by an intrusion, it will likely be discarded due to severe damage occurring to the unit (see Figure 5.2), thereby making the false negatives recorded during the testing more or less understandable and likely not present in practice.

Figure 5.2: SonoBlaster® Damaged after Simulated Intrusion (Vehicle Striking Cone)

5.5.1.2 False Positive Alarms

A false positive alarm in this research study is defined as a situation where an alarm is produced from a device due to unintentional triggering of the technology. During the testing, the SonoBlaster® recorded zero false-positives. This could be attributed to the design of the SonoBlaster® technology. The SonoBlaster® has a lock mechanism that disarms the alarm if not in use. This prevented the occurrence of any false positives. For tests that required moving the trigger mechanism of the Intellicone® (sensor lamp) and WAS (pneumatic tube), false positives were recorded as a result of mishandling of the units during placement (operator error). This could be prevented by deactivating the WAS transmission before handling the unit by either shutting off the pneumatic tube control or the alarm unit itself. For the Intellicone®, the audio alarm could be deactivated before handling the unit by either muting the audio capability or shutting off the command unit.

5.5.2 Measuring Relationship between Sound level and Distance

The sound level which a worker is exposed to relative to his/her distance from each intrusion alert technology was measured. The level of sound was recorded between 5 feet and 500 feet in terms of distance between the technology and the sound meter, to provide sufficient information over an appreciable range of distances. Distance (in feet) starting from 0 feet was marked on the roadway using a spray marker and a 300 feet tape measure (Figure 5.3). For the Intellicone® and WAS, the source of alarm was placed at the 0 feet station facing a pre-determined position while the trigger mechanism was within transmission range. For the SonoBlaster®, the technology was attached to a cone and remained stationary on the 0 feet mark. Sound level measurements were then taken along the pavement striping marked for distances after each alarm was activated (Figure 5.4). The sound meter was positioned approximately 3 feet above the ground when recording sound levels.

Figure 5.3: Distance Markings (in feet) on Roadway

Figure 5.4: Sound Measurement at 20 feet

The sound level recording exercise captured the duration of alarm sounds produced by each technology. It was observed that while the duration of alarm produced by the Intellicone® and WAS technology remained constant over multiple attempts, the alarm produced by the SonoBlaster® varied considerably (Table 5.3). It is important to note that the research team opted to report the median sound level instead of the mean in order to reduce the impact a recorded outlier could have on the reported findings.

Table 5.3: Duration of Sound Alarms (n = 21)

Technology	Duration of Alarm (in seconds)			
	Median	Maximum	Minimum	Standard Dev.
Intellicone®	32	32	32	0
SonoBlaster®	14	41	7	10.89
WAS	6	6	6	0

The inconsistency in the duration of sound produced by the SonoBlaster® appears to be largely due to its use of CO2 cartridges as an alarm-creating mechanism. The CO2 cartridge is required to be changed after every use. It was observed that after the SonoBlaster® was triggered once, subsequent uses of the SonoBlaster® with new cartridges produced shorter bursts of sound. Novosel (2015) pointed out that cold or wet weather could be a possible cause for this phenomenon (note that the pilot testing was conducted during the winter season). Also, accumulated ice was noticed on the nozzle after triggering the SonoBlaster®, especially in cold weather. The ice was caused by a reaction of the metallic nozzle to the pressurized CO2 being pushed through it. The accumulated ice made the cartridge changing process challenging because the ice made the cartridge stick to the nozzle, and replacing the cartridge was delayed until the ice melted (see Figure 5.5).

Figure 5.5: Ice Accumulation on Nozzle of SonoBlaster®

The test results show that despite the variable nature of the alarm duration of the SonoBlaster®, it consistently had a higher sound level than the Intellicone® and WAS. Figure 5.6 shows the median sound level measured at various distances from the device for each technology. The figure shows a declining slope across all three technologies. This result is due to the continuous reduction in sound level as distance from the intrusion alert technology increases. It is important to note that the markers on each line in Figure 5.6 (and following figures) represent the median sound level measured at that given distance.

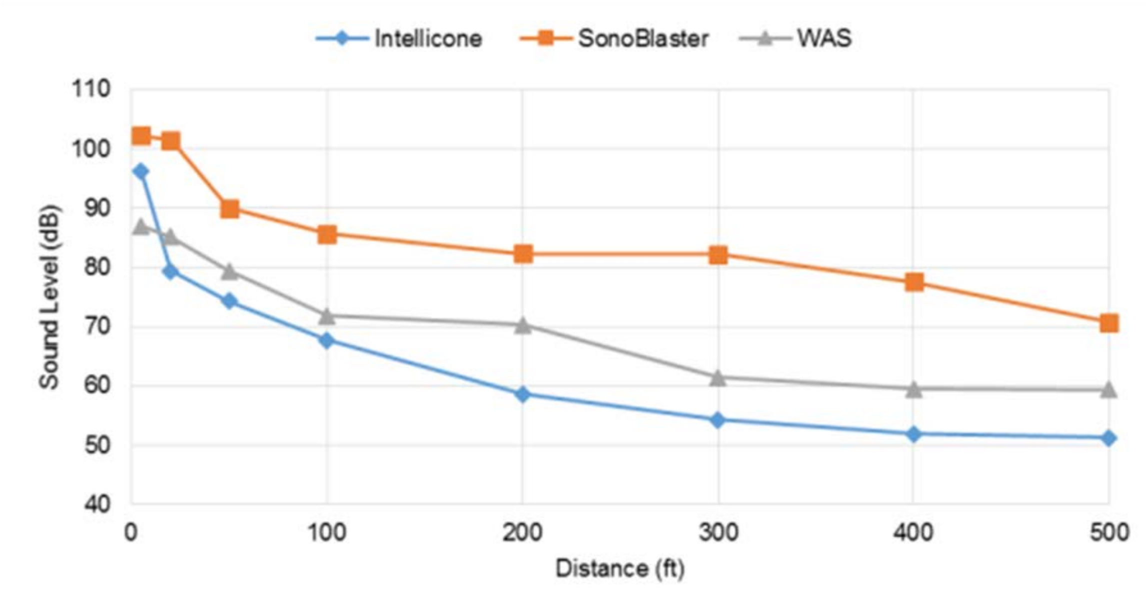

Figure 5.6: Median Sound Level vs. Distance from the Technology

Figures 5.7, 5.8, and 5.9 show the median sound level vs. distance curves along with the error bars at each data point for the Intellicone®, SonoBlaster®, and WAS, respectively. The error bars represent the maximum and minimum sound level recorded for the devices. These figures show that the Intellicone® produces a relatively consistent sound level compared to the SonoBlaster® and WAS.

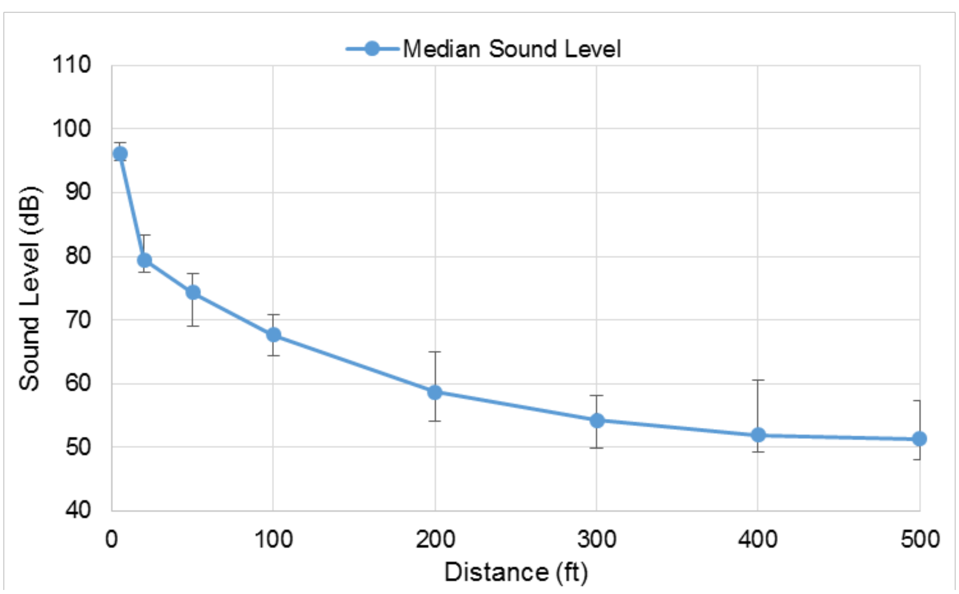

Figure 5.7: Median Sound Level of Intellicone® vs. Distance from the Intellicone®

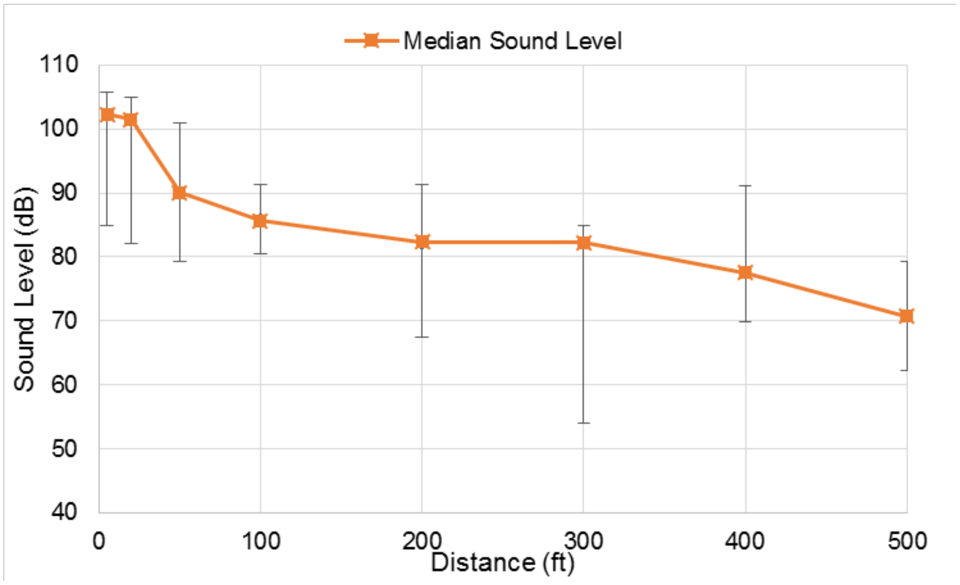

Figure 5.8: Median Sound Level of SonoBlaster® vs. Distance from SonoBlaster®

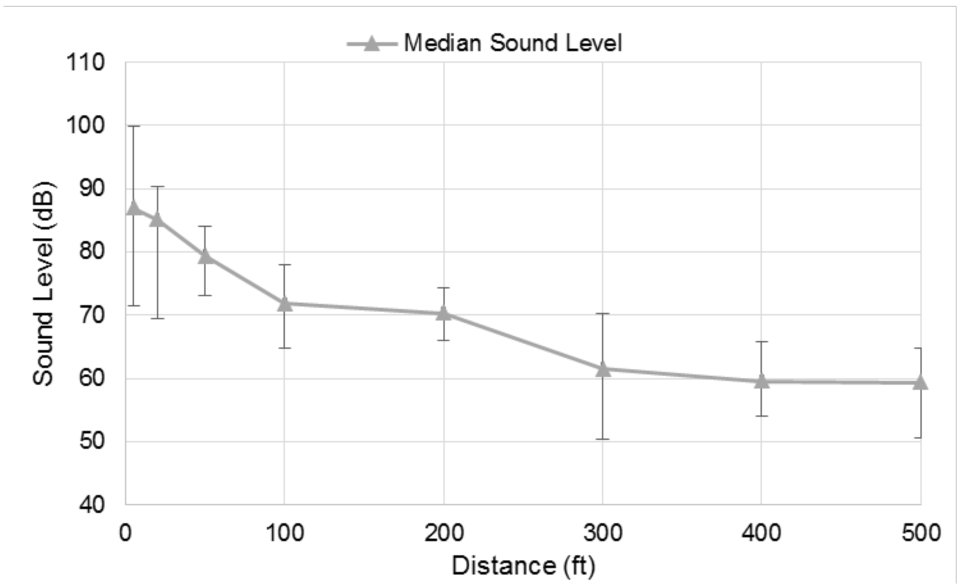

Figure 5.9: Median Sound Level of WAS vs. Distance from WAS

It is noteworthy that when the power level in the battery of the main alarm unit of the WAS is low, the unit loses audio transmission capabilities and produces a weaker visual alarm.

5.5.3 Impact of Orientation of Alarm

Since the level of alarm sound can be significantly affected by the direction of the alarm (i.e., the direction in which the sound is emitted relative to the sound meter), the tests included altering the sound-alarm direction of each technology relative to the sound meter. This procedure was carried out to determine if there is a considerable difference in sound level a worker is exposed to depending on the orientation of the alert technology.

5.5.3.1 Intellicone®

The Portable Site Alarm (PSA) of the Intellicone® has three speakers: one on the front of the unit, and two others each of which is located at 120 degrees from the front speaker (Figures 5.10 and 5.11). Two series of tests were carried out. The first test was conducted with the PSA facing forward to the sound meter (one speaker facing forward directly; Figure 5.10). The second test was conducted with the PSA facing backward (the two side speakers facing forward with 60 degree angles; shown in Figure 5.11).

Figure 5.10: One Speaker Oriented towards Sound Meter

Figure 5.11: Two Speakers Oriented towards Sound Meter

The data collected show that a higher level of alarm sound was produced from the PSA when two speakers were oriented towards the sound meter (Figure 5.12). However, a higher sound level was recorded for the single speaker orientation at the 500 feet station. The research team noted that ambient noise, caused mainly by wind, could be a reason for this observation. Measurements taken at 500 feet tend to be slightly inconsistent (skewed) considering the sound level produced by the 6 mph wind on November 2, 2016. In short, the abnormality appears largely due to varying testing conditions.

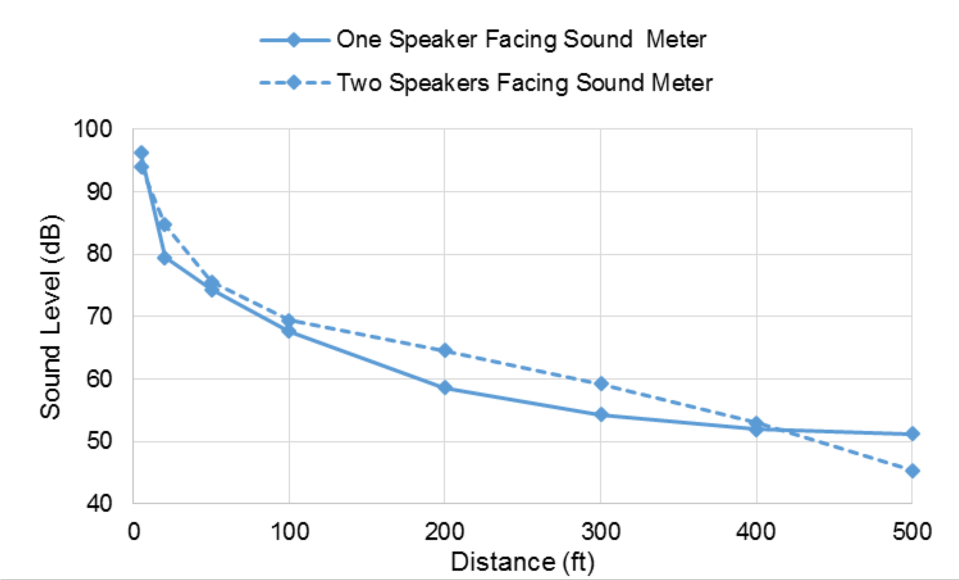

Figure 5.12: Median Sound Levels of Intellicone® relative to Alarm Orientation

5.5.3.2 SonoBlaster®

The first series of tests was carried out orienting the outlet of the sound alarm face down when tilted, as seen in Figure 5.13. Since videos and documentation on the SonoBlaster® did not explicitly state a preferred direction for facing the technology in a work zone, and since a cone may be impacted in any direction by an intruding vehicle depending on the orientation of the cone to the oncoming traffic, the reverse direction (facing upward) was tested as well (see Figure 5.14).

Figure 5.13: SonoBlaster® Outlet Facing Downward

Figure 5.14: SonoBlaster® Outlet Facing Upward

Figure 5.15 shows that although both directions result in a similar trend in sound level, the sound produced was higher when the outlet faced down. This pattern was consistent for all distances except for the measurements acquired 5 feet and 500 feet away from the device. These abnormalities may also be due to varying testing conditions, as noted above.

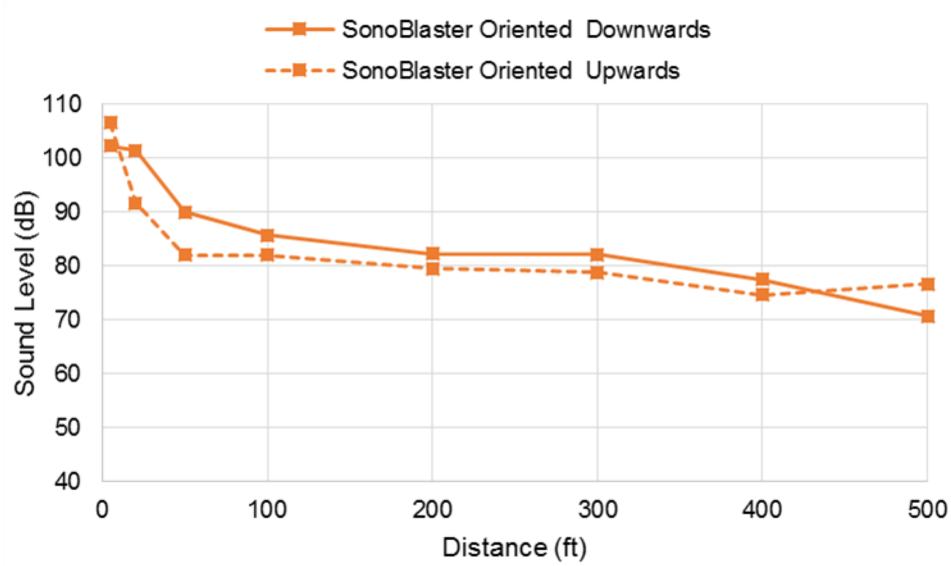

Figure 5.15: Median Sound Levels of SonoBlaster® relative to Alarm Orientation

5.5.3.3 Worker Alert System

The orientation of the WAS was changed as well to provide additional information on effective placement directions. First, the speaker was positioned to face toward the sound meter (Figure 5.16), and then it was rotated 90 degrees to the side for another measurement (Figure 5.17).

Figure 5.16: WAS Speaker Facing Sound Meter

Figure 5.17: WAS Speaker Facing Sideways

As shown in Figure 5.18, the results show that a higher level of sound was recorded by the WAS when the sound outlet was oriented towards the sound meter. An abnormality was recorded when measurements were taken at the 5 feet station. It is speculated that this inconsistency could be a result of the proximity of the sound meter to the technology.

It is important to note that the WAS has a magnetic bottom, which allows it to be mounted on the side or top of equipment. However, such scenarios were not included in the pilot testing. Nevertheless, the research team assumes that the relative difference in sound level of facing forward vs. facing sideways will not be affected by the equipment noise, and will be comparable to that shown in Figure 5.18.

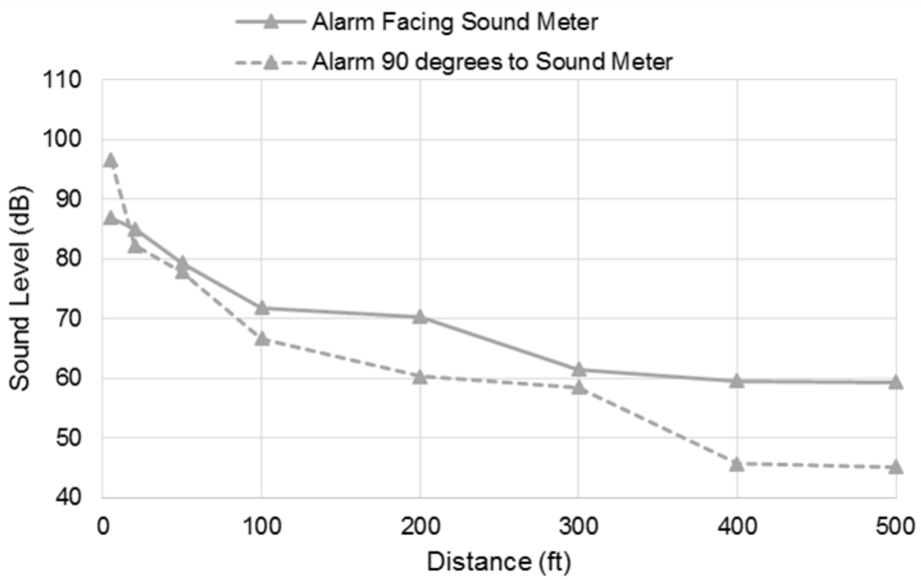

Figure 5.18: Median Sound Levels of WAS Relative to Alarm Orientation

5.5.4 Sound Level Inside of a Vehicle

Most tests carried out focused on how the alarm impacts construction workers. However, the research team also wanted to measure its impact on vehicle occupants, as it may also be important to determine how the occupants will react to sound alarms. To assess the sound level a vehicle occupant could be exposed to when an alarm is triggered, the sound level was measured from the driver's seat of a 2015 Honda Odyssey, a distance of 15 feet from the alarm, with windows fully closed (Figure 5.19). The test results show that despite the relatively low sound level within the vehicle, the relative sound levels emitted by each technology remained constant. Also, it should be noted that the sound levels were higher when the car moved faster, which shows the impact of engine and wind noise in a moving vehicle. Overall, the test yielded findings comparable to Figure 2.5; that is, the sound alarm of the SonoBlaster® was heard the most while that of the Intellicone® was heard the least (Figure 5.20). However, in general, the results of this testing activity did not produce a conclusive finding. Although inconclusive, the research team believes a similar test should be considered when assessing newer intrusion technologies to ensure that impacts of technologies on drivers are also accounted for.

Figure 5.19: Test Setup for Sound Level Measurement inside Vehicle

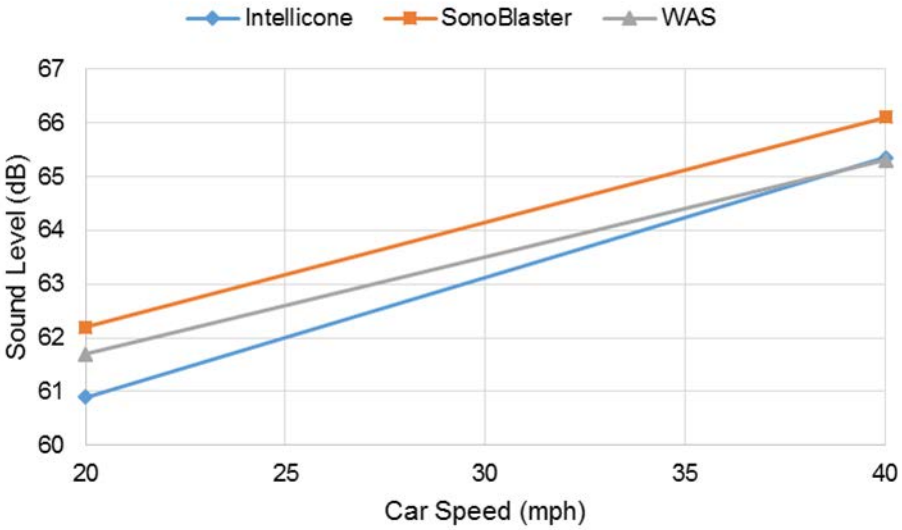

Figure 5.20: Measured Sound Level inside Vehicle

5.5.5 Impact of Equipment on Sound Level

Two types of testing procedures were established to provide an adequate representation of possible varying deployment positions of alert technologies within a work zone. The first setup involved placing each intrusion alert technology between the equipment (excavator and dump truck) and the sound meter that represents the position of a worker (see Figure 5.21). The intrusion alert technology was placed 50 feet away from the excavator while sound level was measured using the sound meter an additional 50 feet away (i.e., 100 feet from the equipment). Two more measurements were taken by moving the sound meter further along the line, at 100 feet (150 feet station) and 200 feet (250 feet station) away from the intrusion technology. After recording sound levels at 200 feet away, the technology was moved 100 feet away from the equipment (see Figure 5.21). After taking three sound measurements at 50 feet (150 feet station), 100 feet (200 feet station), and 200 feet (300 feet station) away from each intrusion alert technology, the process was repeated one more time starting at the 250 feet station.

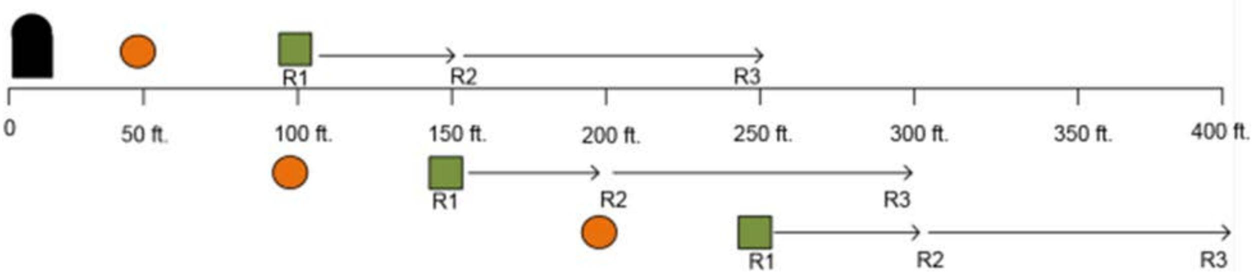

Figure 5.21: First Setup for Testing Sound Level Relative to Position of Equipment and Alarm

This process was repeated with the alert technologies at 200 feet away from the equipment. Figure 5.22 shows a summary of the sound level when the intrusion alert technology is 50 feet away from the equipment, while Figure 5.23 highlights the sound level when the technologies are 200 feet away from the equipment.

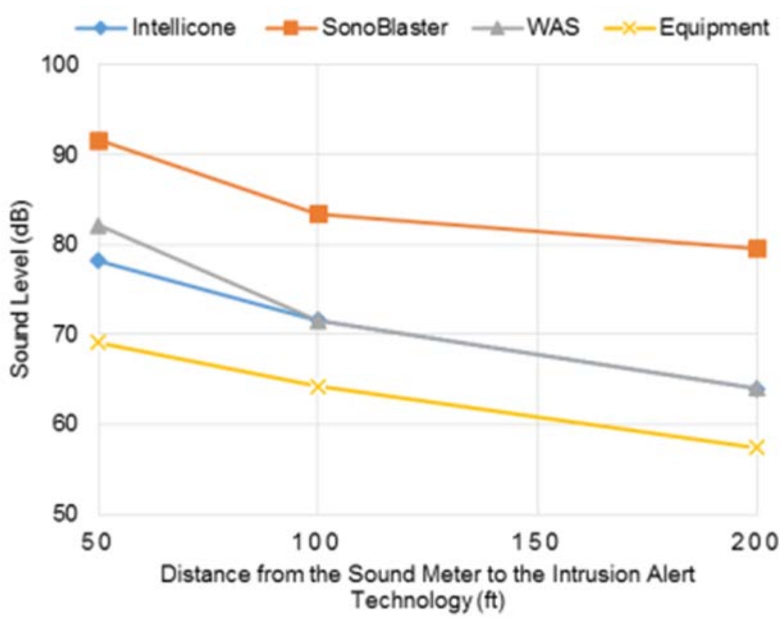

Figure 5.22: Alarm at 50 feet from Equipment

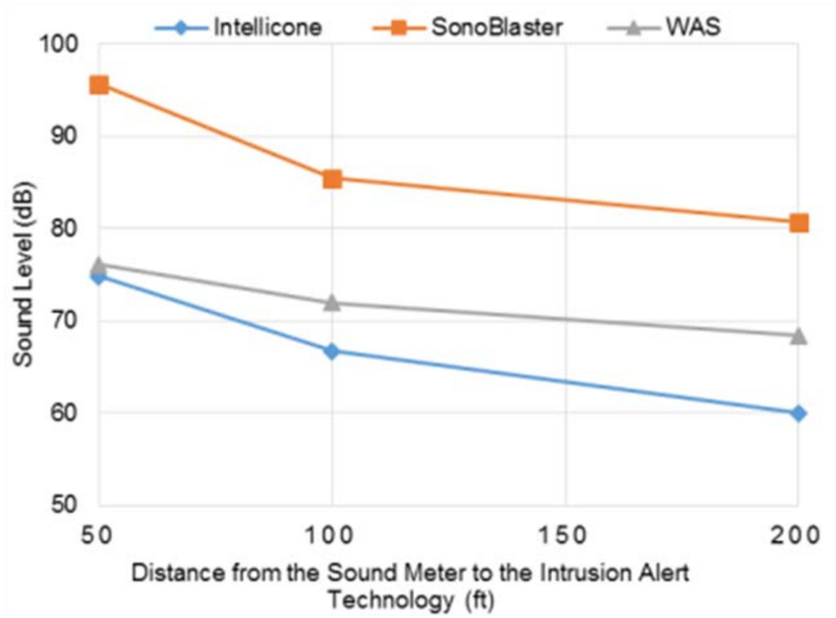

Figure 5.23: Alarm at 200 feet from Equipment

Figure 5.22 shows that the sound produced by an idle excavator and loader was lower than those from the three technologies at any distance. However, the research team believes that the presence of construction equipment could have an impact on the noise level a worker is exposed to because incremental differences in sound level between the equipment and the technologies ranged only from 10 decibels to 20 decibels. A comparison of Figure 5.22 to Figure 5.6 shows that when measurements are taken at 50 feet away from the alert technology, the median values of the Intellicone®, SonoBlaster®, and WAS increased by 4, 1, and 3 decibels, respectively. A similar increase in sound level was observed 100 feet and 200 feet away from the technologies as well.

The second setup was to examine the sound level a construction worker is exposed to if the worker is positioned between the equipment and the alert technology (see Figure 5.24). The same measurements of the first setup were repeated for the second setup to ensure a basis for comparison.

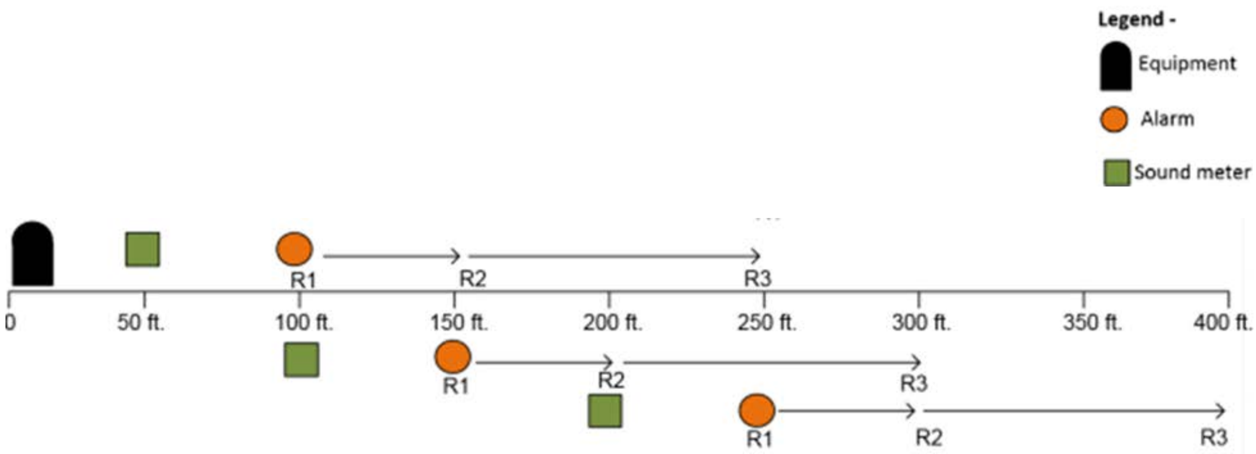

Figure 5.24: Second Setup for Testing Sound Level Relative to Position of Equipment and Alarm

Figures 5.25 and 5.26 depict the median sound levels measured against the distance between the worker (position of the sound meter), the equipment, and the intrusion alert technology at 50 feet and 200 feet, respectively.

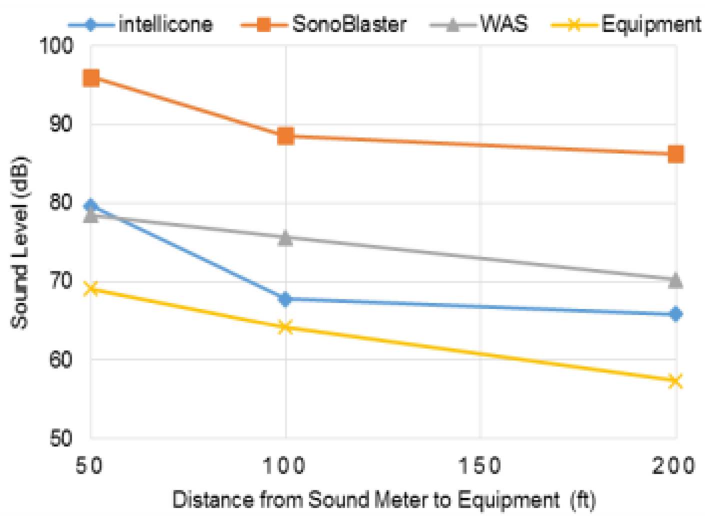

Figure 5.25: Sound Meter 50 feet from Equipment

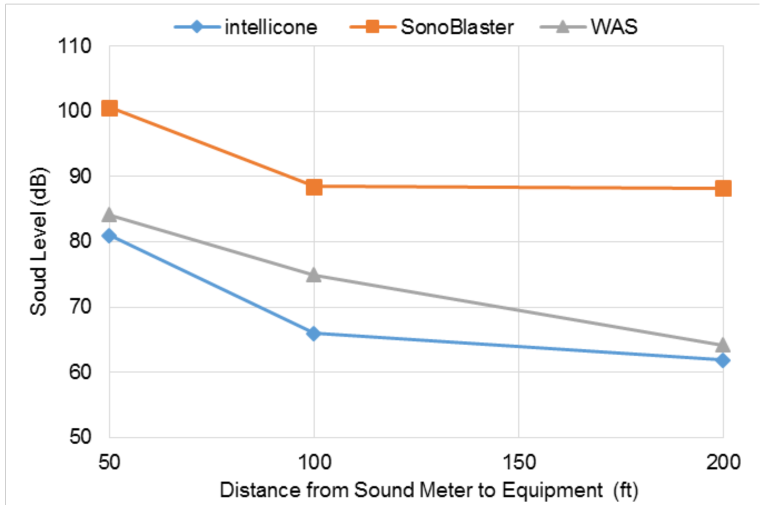

Figure 5.26: Sound Meter 200 feet from Equipment

Data depicted in Figures 5.25 and 5.26 were analyzed to determine the impact of the second setup (including equipment) on a construction worker. When the sound meter is placed at 50 feet away from the alert technologies, the sound level was at least 5 decibels higher for each alert technology with the exception of the WAS which recorded a 1 decibel increase. The sound level recorded for both setups at 100 feet and 200 feet away from the equipment shows a similar trend (higher sound level recorded in first setup). Similar to Figure 5.22, Figure 5.25 indicates that the sound level from the equipment is constantly lower than those from the technologies, yet the difference in the second setup is not as much as the first setup. Therefore, it is concluded that the level of alarm that workers are exposed to can be more subject to the ambient noise produced by equipment when the workers are situated between the equipment and the alarm.

Close observation of Figure 5.23 and Figure 5.26 shows that, similar to the findings when comparing Figure 5.22 and Figure 5.25, the sound level a worker is exposed to tends to be higher when stationed between the equipment and the intrusion alarm technology. When the sound level is measured at 200 feet away from the equipment (see Figure 5.23 and Figure 5.26), it is interesting to note that all three technologies produce a higher decibel reading at 50 feet away from the intrusion alarm using the second setup. The testing results suggest that the location of the intrusion alert technology within the work zone should be carefully considered. A project that requires most workers to be clustered around loud equipment (e.g., paving operation) should consider placing the alarm units of the alert technologies (Intellicone® and WAS) as close to the cluster as possible. The findings from this pilot testing are further validated during live testing planned for Task 5.

5.5.6 Spectral Analysis to Test Distinctiveness of Audio Alarm

A spectral analysis was performed on the audio output of each alert technology to provide a basis to determine the level of distinctiveness (sound quality) of the sound the alarm produces vis-a-vis ambient noise. Spectral analysis is the study of sound frequency using a spectrogram, a representation of a time versus frequency plot where frequency is epitomized by a spectrum

(Daintith 2004; Brown et al. 2015). A Tascom DR-05 linear PCM recorder was used to capture the sound produced by each intrusion alert technology. An idle excavator was used to mimic the sound variations expected in a construction operation. The length of the audio recording varied depending on the duration of the alarm. Each technology was placed 50 feet away from the equipment while the recording was carried out 50 feet away from the technology in the opposite direction (similar as the first setup shown in Figure 5.21). Sonic Visualizer, a sound analyzing freeware (http://www.sonicvisualiser.org) used in a previous work zone alert study (Brown et al. 2015) was used to analyze the audio recording of each technology. Figures 5.27, 5.28, and 5.29 depict the output of the spectral analysis produced by the Sonic Visualizer for the Intellicone®, SonoBlaster®, and WAS, respectively. It should be noted that the figures do not represent an absolute scale. The different colors represent diverse sound energy (intensity) levels with blue representing the least intensity and red indicating the highest energy. According to Nave (2010), sound quality (also known as Timbre) is the characteristics of sound which enables the ear to distinguish between different sounds that could possibly have similar loudness and pitch. Although loudness could be a good indicator of sound quality, loudness is said to be a subjective quality of sound while sound intensity is a preferable quality indicator since it is considered an objective property (Huckvale 2010).

Figure 5.27 depicts the result of a spectral analysis performed on a 38-second MP3 file capturing the audio alarm of the Intellicone®. Figure 5.7 shows that the Intellicone® produces a relatively consistent sound level during the entire duration of the alarm. The findings from the spectral analysis were consistent with the audio pattern of the Intellicone®. The highest sound intensity was recorded at approximately 2 kHz, and a consistent cluster was observed within 1.9 kHz and 3 kHz. The presence of the red and yellow lines indicates that the Intellicone® produces some distinctive sound that could be heard by workers within the measured distance. The green color represents the ambient sound, equipment sound, and the basic sound produced by the Intellicone®.

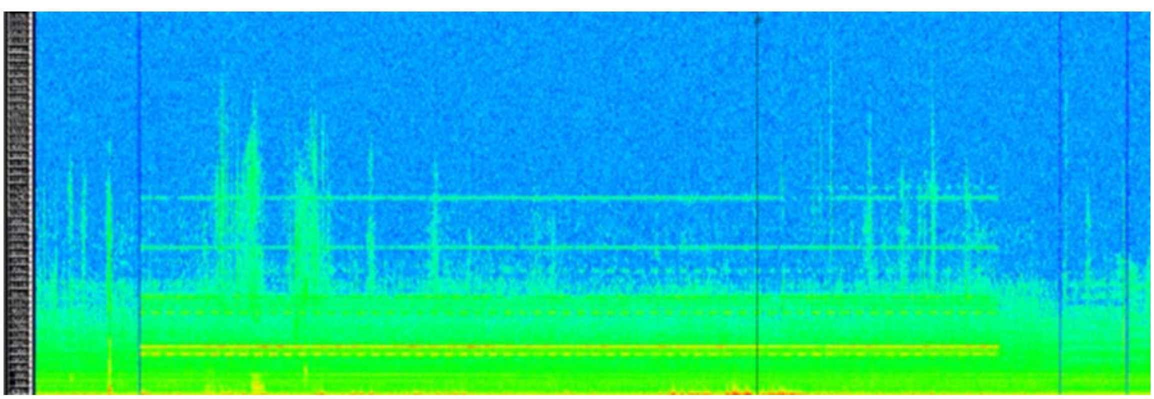

Figure 5.27: Image of Spectral Analysis on Sound produced by Intellicone®

Figure 5.28 shows a spectrogram of the sound alarm produced by the SonoBlaster®. The spectral analysis was based on a 28-second audio recording. Consistent with the findings of past research, the sound produced by the SonoBlaster® produced a wide range of pitch and frequency ranging from 500 Hz to 20 KHz. The frequency produced encapsulated most of the ambient noise onsite

(Novosel 2015). Contrary to the Intellicone®, several strips of high energy sound produced by the SonoBlaster® can be observed in Figure 5.28. High sound energy is observed to be between 500 Hz and 6 KHz. This could be a result of the way CO2 is gradually dispensed from the cartridge and horn, thereby producing different levels of sound intensity.

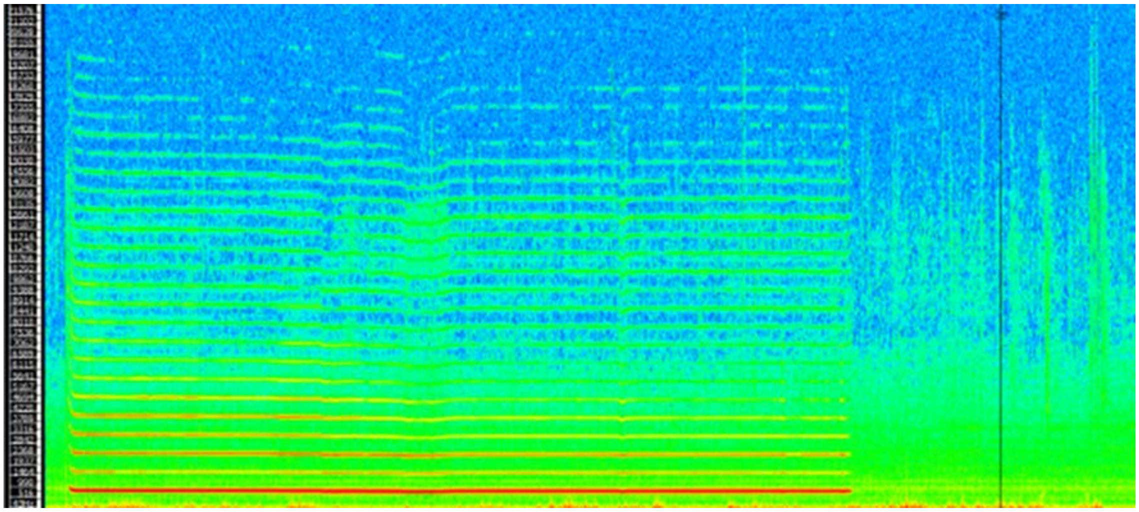

Figure 5.28: Image of Spectral Analysis on Sound produced by SonoBlaster®

The result of the spectral analysis of the WAS is depicted in Figure 5.29. The audio clip lasted for eight seconds, two seconds longer than the alarm duration of the technology. The sound intensity was mainly clustered between 2 and 4 KHz. The sound bins represent the pattern of sound produced by the WAS. Unlike the continuous sound produced by the Intellicone® and SonoBlaster®, the sound emitted from the WAS oscillates at extremes, producing short bursts of high frequency sounds, which can make the alarm sound more distinctive.

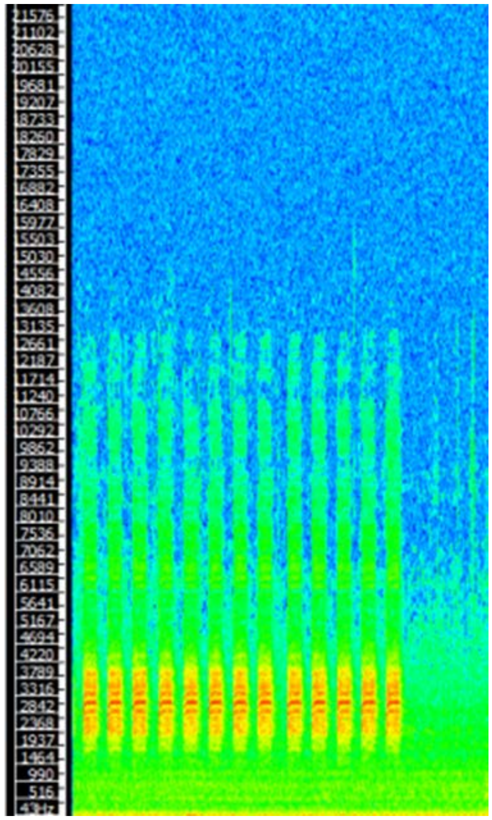

Figure 5.29: Image of Spectral Analysis on Sound produced by WAS

5.5.7 Transmission Distance

Although literature on estimated transmission range of the Intellicone® and WAS was provided by past research and the manufacturers, the research team opted to verify the maximum coverage of each technology that required wireless transmission for alarm triggering. To this end, the transmission distances of the WAS and Intellicone® were tested based on incremental distances (note that the SonoBlaster® is not a wireless device). Each transmission test was performed by activating the trigger mechanism at a given distance from the alert technology. Each technology was triggered three times at every pre-determined distance until the transmission was deemed to be less than 100%. As highlighted previously, the Intellicone® uses a wireless transmission network that remotely sends a message to the command post (PSA) once a sensor is tripped or tilted. The network configuration is based on the wireless connection between different sensors that, when connected, act as an extended perimeter. This gives the Intellicone® a capability to cover a stretch of roadway in case of a lengthy work zone. As seen in Table 5.4, the Intellicone® recorded a 100% transmission rate up to 250 feet, while 33% (1 out of 3) was recorded at 300 feet, and beyond which there was no transmission. This observation does not agree with the findings from Novosel (2015) that reported incomplete transmission from 400 feet. An additional sensor was added to the network to evaluate the extended transmission range owing to a network of multiple sensors along a work zone (see Figure 5.30). The first sensor was placed 250 feet (the farthest distance that shows 100% transmission) away from the PSA while the second sensor was placed 300 feet away from the PSA (i.e., 50 feet away from the first sensor). One hundred percent transmission was recorded at 300 feet using the new configuration. The transmission was tested after every 50 feet increment.

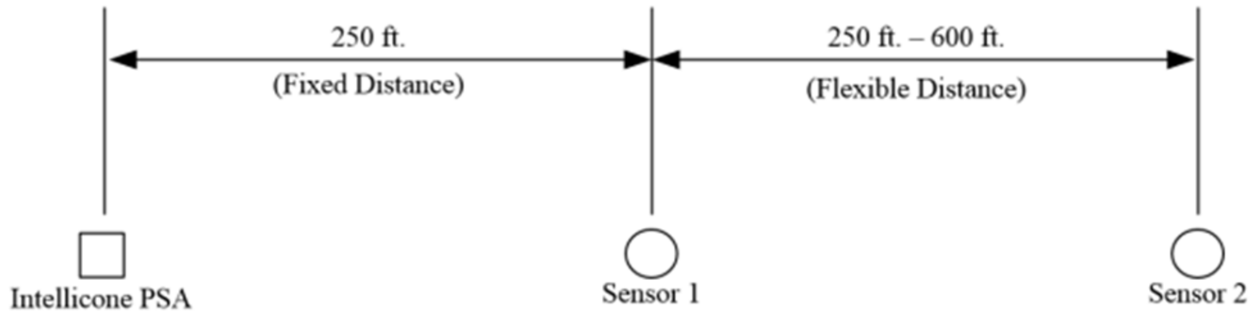

Figure 5.30: Transmission Distance of Intellicone®

At 650 feet, transmission reduced from 100% to 67% (2 out of 3) and total transmission was lost at 700 feet (Table 5.4). It was noted again that the transmission of the Intellicone® was lost at the same distance, i.e., after 300 feet

Table 5.4: Transmission Range of Intellicone® and WAS*

Distance (ft)	Intellicone® (Audio/Visual)	WAS			
		(Audio/Visual)	PSD 1	PSD 2	PSD 3
5	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
10	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
20	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
50	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓✓
100	✓✓✓	✓✓✓			
150	✓✓✓	✓✓✓			
200	✓✓✓	✓✓✓			
250	✓✓✓	✓✓✓			
300	✓☑☑**	✓✓✓			
350	☑☑☑				
400	☑☑☑				
450	☑☑☑				
500	☑☑☑				
550	☑☑☑				
600	☑☑☑				
650	☑☑				
700					

* ✓ represents transmission covered by primary sensor
** ☑ represents transmission distance covered using an additional sensor
✓✓✓ indicates test was conducted 3 times
PSD - personal safety device

The WAS offers a personal safety device (PSD) that produces audible and vibrating (haptic) alarms in addition to the primary visual and audio alarm produced from the main unit. The 3.9” x 2.2” x 1” device is approximately the size of a small cell phone with a short, flexible antenna on one end. The PSD could be strapped on a belt, around an arm, or placed in a vest pocket.

Similar to the Intellicone®, 100% transmission was recorded up to 300 feet for the PSD (see Table 5.4). At 250 feet, 67% (2 out of 3) transmission was recorded but 100% transmission was recorded at 300 feet after which there was no transmission (the visual alarm was activated every time the audio alarm was triggered). Three PSD’s were tested simultaneously to increase the quality of the assessment. All three PSD’s vibrated within 50 feet with the exception of one vibrator that failed to trigger one out of three times at the 50 feet station. All of the PSD’s lost transmissions when the WAS was triggered at 100 feet or farther.

5.5.8 Light Level of Visual Alarm

Pictures of the visual alarm produced by the Intellicone® and WAS were taken at night to visually compare the visual alarm of the alert technologies to reference lights. The nighttime testing was considered important given that the visual alert component of each technology has little or no impact on daytime construction operation. In addition, the nighttime visual assessment was conducted to ensure the lights emitted met Oregon requirements. Oregon Law states that “All warning lights shall be visible from a distance of not less than 500 feet under normal atmospheric conditions at night. [1983 c.338 §458 (25); 1985 c.16 §240 (25); 1985 c.69 §1 (25); 1985 c.71 §4 (25); 1985 c.393 §13 (25); 1985 c.420 §6 (25); 1989 c.402 §10; 1991 c.769 §3; 1993 c.741 §104; 1999 c.497 §1; 2003 c.245 §3]” (OregonLaws 2015). As part of the nighttime assessment, a work light and spotlight were used as reference lights. According to manufacturer’s specifications, the luminance measurements of the work light and spotlight were above 1,700 lumens and 2,800 lumens, respectively.

Prior to taking pictures, the Intellicone® and WAS were placed on a 3-foot tall traffic cone while the reference lights were placed approximately three feet above the ground on the hood of two vehicles. Pictures of the work light (L1), spot light (L2), Intellicone®, and WAS were taken using a DSLR camera, Cannon D5200 with the following settings:

- Aperture – 14 and 10
- Shutter speed – 5 and 10
- ISO – 100 and 200

These settings were used as a control variable to ensure that auto-focusing and auto-adjustments were neglected thereby improving the possibility and validity of a like-for-like comparison (relative comparison) using the photographs. The pictures were taken at 50, 100, 200, and 500 feet away from the subjects. Three pictures were taken for each technology at every given location. This was done to reduce possible errors during image capture thereby ensuring a better visual comparison. To have a sense of the impact of the reference lights on the visual alarm of the intrusion work zone alert technology, the work light (L1) and spot light (L2) were place 10 feet away from each alert technology. Figure 5.31 and Figure 5.32 show the impact of the reference lights on the Intellicone® and WAS, respectively. The pictures were taken at 50 feet away from the technologies using 14, 5, and 100 as the settings for the aperture, shutter speed, and ISO, respectively. Both figures show that the visual alarms of both technologies may not be visually outstanding compared to the work lights. Pictures taken 500 feet away from the alert systems indicate that the visual alert produced by the systems could be detected, meeting Oregon visibility law (see Figure 5.33). The researchers assume that the use of red strobe lights as emergency warning lights in work zones is acceptable in Oregon since Oregon Law does not prohibit the use of red strobe lights on safety equipment (OregonLaws 2015b).

Figure 5.31: Reference Lights at 50 feet away from Intellicone®

Figure 5.32: Reference Lights at 50 feet away from WAS

Figure 5.33: Intellicone® 500 feet away from Camera

To augment the finding, the research team attempted to measure the lumination produced by the alert technologies using an LS - 100 Luminance Meter (see Figure 5.34). Luminance is the preferred measurement unit for light emitting devices (Datta et al. 2010). Ten recordings were taken at a distance of 10 feet away for each technology with the light switched on and off.

Figure 5.34: Light Intensity Measured by Luminance Meter

As seen in Table 5.5, the values recorded for Intellicone® and WAS did not show any clear pattern. One possible reason for this occurrence is the strobe-like nature of the Intellicone® alarm which produces different light intensities. A similar explanation applies to the light (flashing) intensity produced by WAS. According to Moore (2009) and supported by Michael Royer (a lighting expert in Portland, Oregon), it is impractical to measure light intensity using a luminance meter. The most important recordable value is the maximum light intensity (luminance) produced by the work zone intrusion technologies. This assertion is largely based on the limited time differential between the lower and higher light intensity. For instance, when Intellicone® is triggered, a worker’s attention would not be exposed to the lower light intensity for an extended period of time; rather, the worker will likely be affected by the fast oscillating bright lights.

Table 5.5: Recorded Luminance Level of Technologies

	Light Source (Lux)			
	Work Light (L1)	Spot Light (L2)	Intellicone ®	WAS
Light intensity (10 feet from light source)	2177	2971	1453	1870
	2280	3208	2288	1913
	3012	2436	2969	2836
	4617	2467	2521	1577
	1094	2701	2587	2751
	2914	2730	1311	2371
	2421	2207	1016	2516
	2783	2624	2524	1749
	2098	2871	3321	2199
	2089	2844	3403	2390
Median	2350.5	2715.5	2522.5	2285
Minimum	1094	2207	1016	1577
Maximum	**4617**	**3208**	**3403**	**2836**

5.6 SUMMARY OF PILOT TESTING

This section summarizes the noteworthy findings from the seven preliminary testing activities that were carried out on the Intellicone®, SonoBlaster®, and WAS intrusion alert technologies.

1. The possibility of a false positive occurring when using the work zone intrusion alert technologies is very limited if the alert technologies are carefully handled and properly installed. Although the three technologies predominantly recorded zero false negatives, six false negative alarms were observed when using the SonoBlaster®. The false negatives only occurred following cartridge replacement.

2. The research team observed that the Intellicone® produced the most consistent and the longest alarm duration (26 seconds) over multiple attempts. The WAS also produced a consistent duration of sound but lasted for only six seconds. The alarm produced by the SonoBlaster® shows the largest variation (median = 14 seconds; standard deviation = 10.89) and ranged from seven to 41 seconds. Furthermore, the pilot testing revealed that the SonoBlaster® produced the loudest sound across all distances measured. It was also noted that the orientation of all three technologies has an impact on the level of sound produced, which should be considered when deployed in the field.

3. The impact of the sound produced by each technology on a person driving by the work zone with car windows fully closed is limited.

4. The research team attempted to mimic a construction operation by including an excavator and a loader in the pilot testing. Test results indicated that the technologies should be placed as close as possible to the cluster of workers to ensure that workers within close proximity to loud equipment can hear the alarm.

5. Results from the spectral analysis highlighted that the sound produced by all three technologies differed considerably from the mimicked ambient noise. The WAS had the most distinctive sound in terms of clustered sound intensity produced.

6. The transmission distance test showed that the Intellicone® lost 100% transmission after 250 feet while the WAS lost complete transmission after 300 feet. Transmission distance was increased to 650 when a second sensor was added to the transmission network of the Intellicone®. The audible and vibrating personal safety device of the WAS lost 100% transmission after 50 feet.

7. The test of light intensity level did not provide a conclusive, quantifiable conclusion. Based on a qualitative assessment, the visual alarm seems to be relatively distinctive in the dark, but not so much when compared with a spot light and a work light.

The findings from the pilot study provide important information on where each technology excels and some product limitations which would inform future implementations on live projects. In addition, the results assist in developing recommended minimum specifications for future products.

6.0 SELECTION OF TECHNOLOGIES FOR LIVE TESTING

The goal of Task 4 was to gain insights from highway construction professionals on the selected technologies. As part of Task 4, protocols for three focus group sessions (one each with general contractors, traffic control sub-contractors, and ODOT) were developed with the objective of collecting information regarding each work zone intrusion alert technology. This information will guide the selection process tasked with identifying which technologies will be implemented on active work zones. The initial plan of the researchers was to reach out to and have a meeting with each identified category of participants. After several unsuccessful attempts to schedule in-person meetings with the various groups, the research team, with ODOT permission, elected to modify the aggregation process. A two-step approach was undertaken to gather information on each intrusion alert technology. The adopted process is detailed below.

6.1 DEMONSTRATION EVENT

The results from the survey conducted under Task 2 clearly show that work zone intrusion alert technologies are not broadly used. The lack of individuals with firsthand knowledge and experience on using intrusion alert technologies makes it almost impossible to request objective technology-use feedback from professionals in the construction industry. As a result, the research team decided to host a demonstration event to help bridge this gap by enhancing participant’s appreciation of each work zone intrusion technology. For the event, the team invited construction companies and ODOT traffic control/safety staff to take part in the live demonstration. In total, 10 participants (not including the equipment drivers and the ODOT research personnel) took part in the demonstration. Five employees from general contractors and five ODOT staff were involved in the demonstration.

The extent of prior knowledge of the participants regarding intrusion alert devices and work zone design is unknown. The documentation and analysis of this demonstration assumes that the participants had no other background or training regarding the intrusion alert devices. This section of the report documents the initial opinions of the 10 participants in response to the demonstration event.

The event started at approximately 2:00pm on January 21, 2016 at the Corvallis Airport and lasted for approximately 2 hours. Figure 6.1 shows the wheel loader, dump truck, and safety cones that were used to mimic the setup of a real-life work zone.

Figure 6.1: Setup for Demonstration

Following the work zone setup, the research team provided each participant with a document that contained brief background information on each intrusion alert technology, results from the pilot testing, and space to provide written feedback. The objective of the demonstration was communicated to the observers. Each technology was presented to the participants, starting from installation, followed by deployment and retrieval. Multiple demonstrations and tests were carried out on each intrusion alert technology. The participants were asked to take any position within the simulated work zone, away from the passing lane. The entire process was recorded and pictures were taken for future reference and analysis. Upon completion of the demonstration for each technology, the participants were asked to rate the technologies according to the following scale depending on the question answered:

1 = very difficult, very ineffective, or very unlikely

2 = moderately difficult, moderately ineffective, or moderately unlikely

3 = neutral

4 = moderately easy, moderately effective, or moderately likely

5 = very easy, very effective, or very likely

The following sections highlight a detailed summary of the research process and findings for each intrusion alert technology based on the demonstration event.

6.1.1 SonoBlaster®

The participants observed how to install and activate a SonoBlaster®. Observing the installation and activation process was needed for participants to provide objective feedback on "ease of use". After presenting the installation process, the SonoBlaster® was triggered manually by tilting the safety cone (see Figure 6.2). The alarm triggered successfully and lasted for approximately 13 seconds. The researchers also showed the participants how the CO2 cartridge is changed and armed for subsequent use. The second demonstration was designed to mimic the collision between a vehicle and a SonoBlaster®-mounted cone and how the impact may possibly alert construction workers. A sedan, moving at approximately 20 mph struck and successfully triggered the SonoBlaster® intrusion alarm (see Figure 6.3 showing the cone and SonoBlaster® underneath the vehicle and workers trying to free it).

Figure 6.2: SonoBlaster® Activated Manually

Figure 6.3: Retrival of SonoBlaster® after Impact

Each participant assessed the SonoBlaster® based on the rating scale listed above. Figure 6.4 shows the response distribution of the participants, indicating that 60% of the participants believe that the triggering mechanism of the SonoBlaster® is at least moderately effective. Also, 50% of the participants are of the opinion that the SonoBlaster® is moderately easy to use while 50% believe the alarm produced by the SonoBlaster® in moderately ineffective.

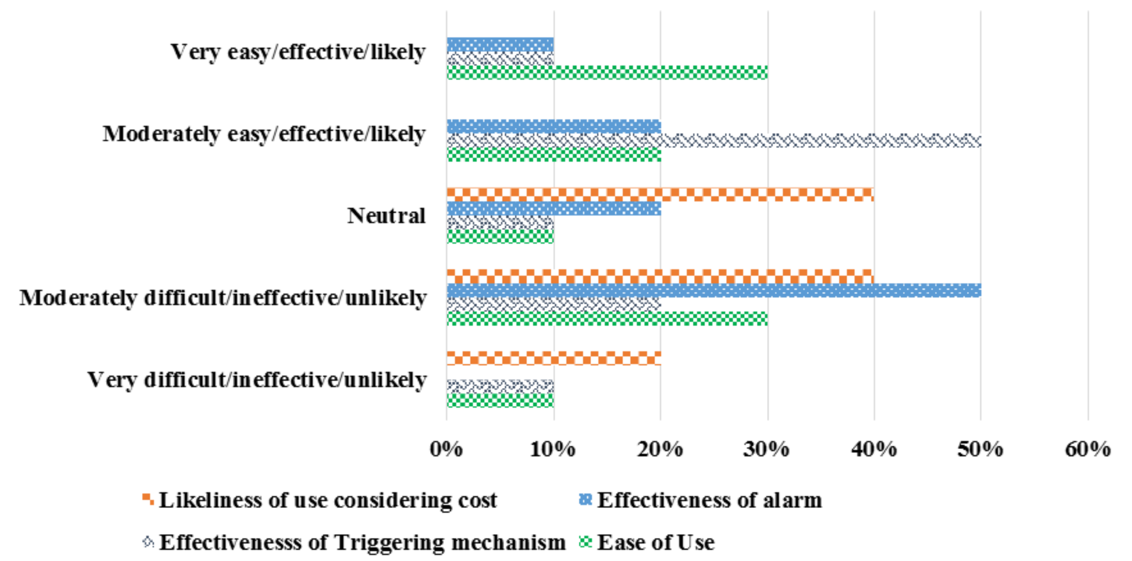

Figure 6.4: Distribution of Participants' Rating for SonoBlaster® (n = 10)

Some issues related to the SonoBlaster® that were highlighted by the participants are listed below:

- [The alarm was] "loud but faded quickly"
- "Not loud enough"
- "Traffic going by "may suck" device over – activating alarm – false intrusion alert!"
- "Would need to be heard 500 feet away to give enough time to get out of the way"
- "Reload (cartridge) is a concern, worker in traffic to retrieve and replace. Cone has to be modified, two roles?"
- "One time use might limit use - workers unwilling to recharge"
- "Alarm was audible – first reaction was to look to see what happened"
- [Alarm] "Sounds like metal on metal – could be mistaken for equipment"

6.1.2 Intellicone®

The participants were also given an opportunity to evaluate the effectiveness of the Intellicone®. After showing the participants how to set up the Intellicone®, the Intellicone® was triggered manually by tilting a cone that had a strobe affixed on it (see Figure 6.5). Following the manual activation, the same sedan used to activate the SonoBlaster® was used to run over the cone (with the activated strobe). The Portable Site Alarm (PSA) unit was positioned within the work zone, about 50 feet from the construction equipment. Surprisingly, the Intellicone® did not activate after the vehicle impacted the strobe, thereby creating a false negative error. The strobes were switched and the activity was repeated. This time, the alarm triggered once the strobe hit the ground (see Figure 6.6).

Figure 6.5: Intellicone® Activated Manually

Figure 6.6: Intellicone® Activated on Impact

Figure 6.7 summarizes the responses on the assessment of the Intellicone® that were received from the participants. “Ease of use” was identified as the most compelling factor for using the Intellicone®. Out of 10 participants, only one observer rated any of the five criteria a maximum score of 5. Seventy-three percent of the participants highlighted that due to the cost of the equipment, it is not likely that they will implement it on future projects.

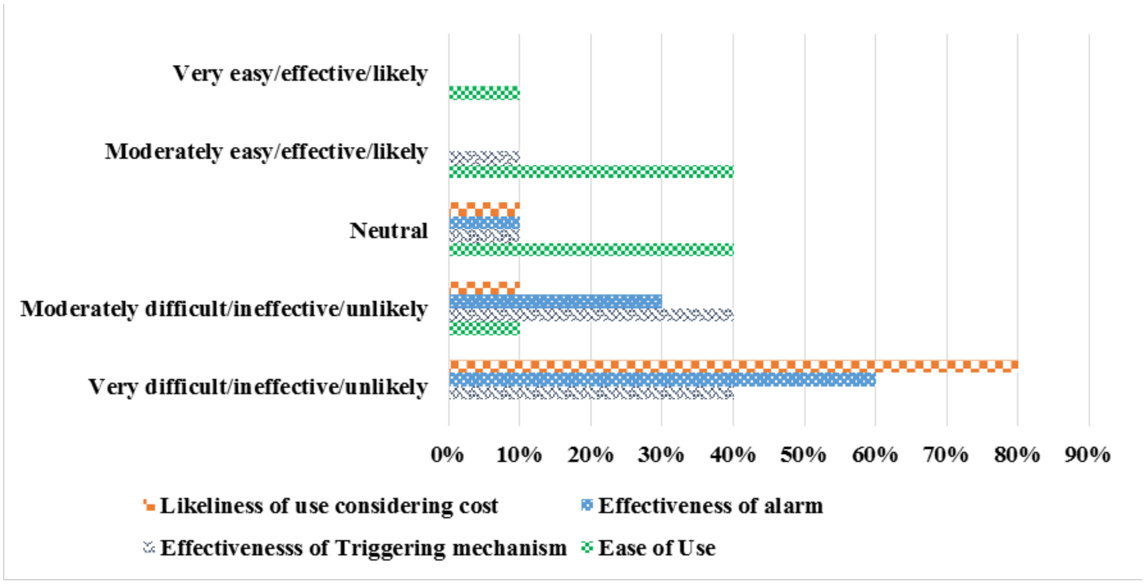

Figure 6.7: Distribution of Respondents Rating for Intellicone® (n = 10)

As previously mentioned, the Intellicone® recorded a false negative alarm during the demonstration. It is speculated that this may contribute to some of the negative responses observed in Figure 6.7. It is important to note that prior to the demonstration, the Intellicone® recorded zero operation-related false positive and false negative alarms (100% trigger activation) during pilot testing.

Below are some comments extracted from the technology assessment forms submitted by the participants:

- "Too quiet. Too much like a back-up alarm, but would easily be drowned out by equipment noise, traffic noises"
- "Not loud enough to compete with operational background noise, i.e., heavy equipment, traffic, back-up alarms, etc."
- "Standing between equipment with no line of sight. Had to ask if it (Intellicone®) went off!"
- [Audio alarm] "Needs to be high-low-high-low or some alternation"
- "Strobe unit can fly, potentially hitting worker"
- "Light not effective during the day"

Regardless of the relatively adverse comments, the participants noted that with some changes (sound level, quality/frequency of sound, and light intensity) to the current configuration, the Intellicone® held significant promise. Of particular note was the ability to separate the location of the alarm from the location of the trigger. For mobile operations, for example, the alarm can move with the workers while the trigger mechanism remains in a location that is vulnerable to intrusions.

6.1.3 Worker Alert System (WAS)

Similar to the previous two work zone intrusion technologies, the WAS technology was deployed and activated multiple times. The participants observed how to activate the WAS and how it could be installed along a work zone. The WAS was triggered manually by stepping on the pneumatic tube. For the first round of testing, the WAS was placed 50 feet away from the equipment, and then triggered by a moving vehicle. Next, the WAS alarm unit was attached to a wheel loader (using the base magnet). Furthermore, varying approach speeds of the sedan were tested to mimic the impact of different levels of speed on the WAS pneumatic unit. Changing the vehicle speed created the opportunity to evaluate how the relationship between triggered alarm and vehicle speed impacts a worker. Figures 6.8 and 6.9 show the different locations where the WAS alarm unit was placed.

Figure 6.8: WAS Located 50ft from Equipment while Activated by Intruding Vehicle

Figure 6.9: WAS Located on Wheel Loader

After observing the demonstration, the participants evaluated the WAS technology based on all five options in the rating scale. The assessment results are summarized in Figure 6.10.

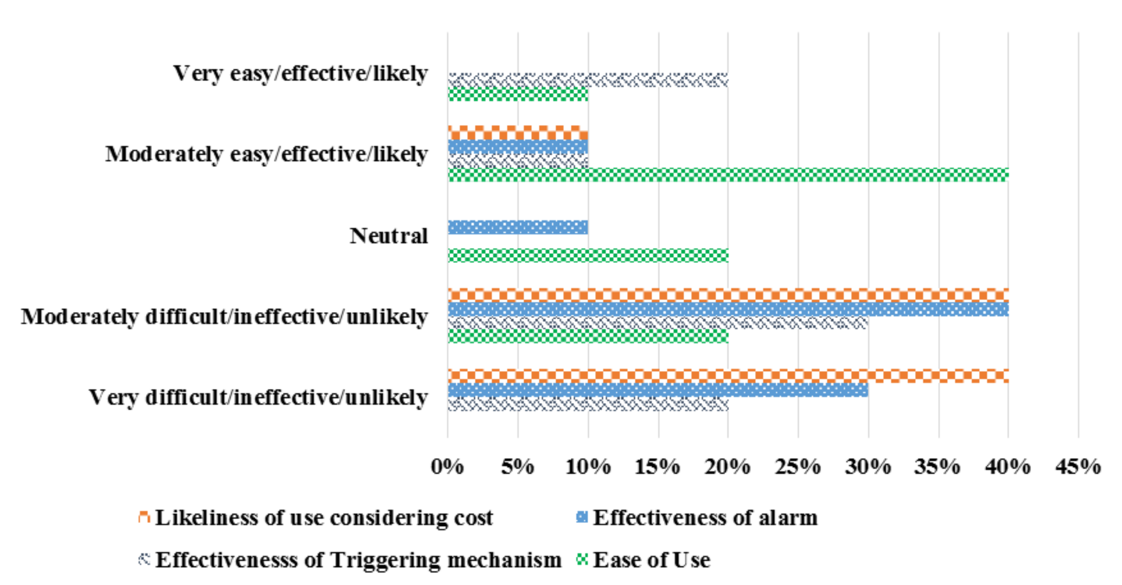

Figure 6.10: Distribution of Respondent Ratings for WAS (n = 10)

The aggregated result from the assessment shows that "ease of use" and "effectiveness of triggering mechanism" are the noted as strengths of the WAS technology. In contrast, the cost and effectiveness of the technology's alarm were highlighted as significant drawbacks to use of the technology.

Compared to the other two technologies, one unique feature of the WAS is the presence of both an audio and vibratory (haptic) alarm produced by the personal safety device (PSD) that workers can carry around. The vibration can be felt by having the device around one's arm or in a pocket. Although the PSD could be an important component for creating extra reaction time for workers, it is important to note that there might be some resistance from contractors to use of this accessory. According to one participant, "Our workers are not allowed to wear headphones in ears, only hearing protection". A common consensus was that the approximately 50 feet coverage distance of the PSD is inadequate. Also noted was the inconsistent alarm (vibration and audio) produced by the PSD when triggered. One of the participants commented as follows:

"[PSD] only triggered [vibrated] 20% of the time – 1 out of 5 times at 30 – 35 feet"; "personal unit only worked [vibrated] three times".

Regarding possible scenarios where the WAS could be applicable, the participants recommended that the WAS technology be used on small scale operations such as city streets or on a project with slow traffic, but not on a freeway project. This application recommendation was based on the delay (lag time) observed between the time the pneumatic tube is pressured and the time when the alarm triggered. When a vehicle traveling at about 50 mph pressurizes the tube, the vehicle covers over 100 feet before the alarm is activated (alarm lag time is between 47 milliseconds and 1 second). Regarding the quality of the audio alarm, one participant recommended that the “frequency is okay, but needs to vary”. When standing very close to a large piece of equipment, it is perceived that the alarm produced by the WAS is drowned out by ambient noise. One participant commented as follows:

”I was standing between loader and truck and not watching and did not know it (WAS) was activated!”

6.1.4 Summary of Technology Demonstration Event Results

Analysis results from the data captured during the demonstration event are displayed in Table 6.1.

Table 6.1: Summary Table of Participant Feedback (n = 10)

	Criteria	SonoBlaster®		Intellicone®		WAS	
		Mean Rating	Std. Dev.	Mean Rating	Std. Dev.	Mean Rating	Std. Dev.
1	Ease of use	3.30	1.49	3.50	0.85	3.44	1.01
2	Effectiveness of triggering mechanism	3.30	1.25	1.90	0.99	2.75	1.67
3	Effectiveness of alarm	2.90	1.10	1.50	0.71	1.89	0.78
4	Likeliness of use considering cost	2.20	0.79	1.30	0.67	1.88	0.99

Table 6.1 shows that the three technologies were rated relatively high in the ease-of-use category with the Intellicone® having the highest average rating and lowest standard deviation. Conversely, the Intellicone® received the lowest rating when considering the effectiveness of the triggering mechanism with the SonoBlaster® recording the highest rating.

6.2 FOCUS GROUPS

6.2.1 Methods

Considering the difficulty encountered in setting up multiple in-person focus groups, the research team elected to perform online focus groups, targeting general contractors, traffic control subcontractors, and Department of Transportation (DOT) staff. The documents developed for the focus groups include: (1) a PowerPoint presentation of the three technologies including results from the pilot testing; and (2) a questionnaire (online and fillable .pdf) for feedback on each technology. The participants had the option of either filling out the form online or using the fillable .pdf form. The participants were asked to first go through the presentation slides before filling out the focus group form in order to become familiar with each technology.

Three short video clips (from the demonstration exercise) showing how each technology is used were included as part of the PowerPoint presentation to provide the participants with information that would improve feedback quality. In the focus group form, the participants were asked demographic questions followed by soliciting recommendations of likely locations where each technology could be placed in a work zone. Participants were asked to provide their opinions on the use of each technology based on two types of work zones: (1) mobile operations and (2) stationary operations. Similar to the demonstration event, the participants were also asked to rate the effectiveness of the alarm, ease of use, effectiveness of triggering mechanism, the cost of technology, and usefulness of each technology.

Emails containing the documents and link to the online form were sent to 74 potential participants in the three identified groups (DOT = 32, general contractors = 22, and traffic control subcontractor = 20). A total of 23 responses were received, 12 from general contractors, seven from DOTs, and four from traffic control subcontractors. Following close inspection of the responses, it was discovered that four participants completed less than 20% of the focus group form. Therefore, the four significantly incomplete responses (three traffic control subcontractors and one general contractor) were excluded from the analysis, resulting in 11 general contractor employees, seven DOT staff, and one traffic control subcontractor (n=19). It should be noted that no participant from the demonstration event participated in the survey. As a result, the responses from the demonstration event are in addition to those collected from the focus groups.

6.2.2 Results

One important contributor to the quality of feedback in a focus group is the subject-matter experience of the participants. Ninety-one percent of the participants have at least 5 years of experience in heavy civil construction while 27.3% have more than 20 years of work experience.

Prior to rating each technology using the five criteria described in Section 6.2.1, participants were asked to rate each evaluation criterion using a rating of 1 to 5 according to the level of importance (1 = least importance and 5 = most important). This rating from the participants helps determine a priority between categories, per the group that completed the surveys. Figure 6.11 shows that the participants consider ease of use to be the least important criterion while effectiveness of alarm as the most important.

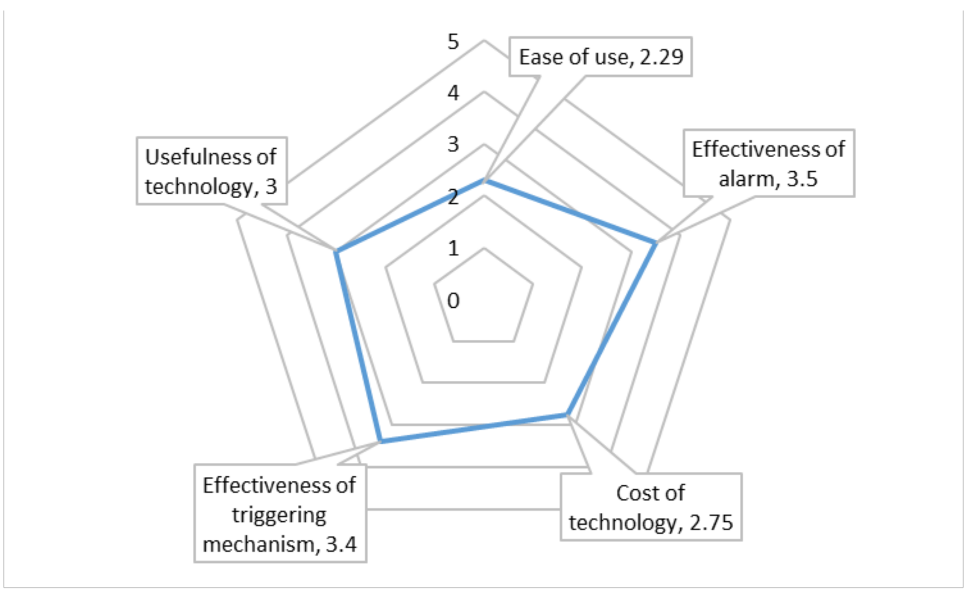

Figure 6.11: Mean Ratings of Evaluation Criterion (n = 16)

Although a total of 19 participants provided responses that were recorded as “complete”, only 16 participants rated the three intrusion alert technologies. These responses are summarized below for each technology.

6.2.2.1 SonoBlaster®

Analysis of the input received from participants provides some insight on the participants’ perceptions as related to the five evaluation criteria. As highlighted in Table 6.2, the triggering mechanism of the SonoBlaster® was adjudged to be somewhat effective with a mean rating of 3.56 (between neutral and moderately effective). In terms of usefulness of the SonoBlaster®, a significant difference was observed in how general contractors and DOTs perceive this criterion for the SonoBlaster®.

Table 6.2: Recorded Mean Response and Standard Deviation for SonoBlaster®

	Evaluation Criteria	**Cumulative Mean Rating (n = 19)**	**Std. Dev.**	**GC Mean Rating (n = 11)**	**DOT Mean Rating (n = 7)**	**SC Mean Rating (n = 1)**
1	Ease of use	3.11	1.15	3.30	3.00	2.00
2	Effectiveness of triggering mechanism	3.56	0.96	3.50	3.67	3.00
3	Effectiveness of alarm	3.33	1.20	3.30	3.17	3.00
4	Likeliness of use considering cost	3.17	1.26	3.40	3.00	2.00
5	Usefulness of technology	3.50	1.30	3.90	3.17	2.00

Work zone related construction operations are either stationary or mobile, or a combination of both. The type of work zone plays an important role in the actual implementation of the work zone intrusion technologies. Sections 6.2.2.1.1 through 6.2.2.1.3 denote some suggestions for implementing the SonoBlaster® followed by general comments on the technology. These comments were extracted from the focus group responses. Each comment is uniquely identified from each focus group.

6.2.2.1.1 Stationary Work Zone

- “If you are going to have a system in place it really needs to cover the entire work zone. If the goal is to make the worker feel safe and truly have time to get out of the way, then you need to cover the entire area, vehicles aren't limited as to where they can enter. You would want to gap out a small section for contractor access to cut down on the false alarms, as these will just make the work crew not even worry about it after a few of these.” (DOT 2)

- “Typically I have seen the traffic breach closures at the taper. The notification system would be most effective in the taper in my opinion.” (GC 3)

- “I would use the SonoBlaster® in the Transition Zone and in the Buffer Space. Secondarily, I would place the SonoBlaster® alongside of the Work Space.”(DOT 5)

- “SonoBlaster should be positioned in the transition area/buffer space of the work zone in order to give the workers enough time to react to a work zone intrusion. Depending on the buffer necessary for the work zone (based on TCD spacing table), I believe you'd need a minimum of 8 SonoBlasters for a 25 MPH work zone, with the # of SonoBlasters® increasing with the speed of traffic.”(GC 6)

- “Need to be placed close enough to the workers in order for them to hear. Most workers may be in a trench or operating equipment and will not be able to hear audio alarms with any of these systems.” (GC 7)

6.2.2.1.2 Mobile Work Zone

- “I would not recommend this for a mobile operation. A mobile operation is typically continuously moving and standard channelizing devices are substituted for a more dominant vehicle mounted device.”(DOT 1)

- “Mobile operations move continuously or intermittently and would create too much Worker exposure to traffic to be continually resetting these devices for a mobile operations.” (DOT 4)

- “This is not as practical for a mobile striping/paving operation. You would need a plethora of SonoBlasters® and it would place a large burden on the Traffic Control Supervisor trying to keep up with the work zone. This may work better than the WAS in multiple work zones -- someone would have to be responsible for moving the SonoBlasters® with the work zone” (GC 6).

- “At a consistent distance behind the crew as they move down the road (regardless of where the non-smart cone taper is set).” (GC 7)

- “Almost impossible to set up and keep it in the transition zone of a mobile operation” (GC 8)

6.2.2.1.3 Additional Comments

- “There are too many false alarms with this system from workers or contractors hitting the system. Also the wind and semi-trucks have blown the cones over and once this happens a few times the workers just stop using it or listening to it as they don't have the time to deal with it. It becomes more of a pain having to go and walk next to the cone/drum line and reset the alarm, which in some cases could actually increase your exposure.” (DOT 2)

- “Seems like a decent idea and would provide an added level of protection to crews in active work zones. No matter which system is chosen you would most likely be replacing the units often, low cost will be a big consideration in deciding which systems to implement.”(GC 3)

- “The relative low cost of the unit and the CO2 cartridges is very attractive. The overall ease of use of this unit is another huge advantage in the real world of construction. Educating the workers to be aware of this new sound is critical to the effectiveness of the SonoBlaster®. One advantage that I see for this unit compared to other units, is that the workers will know from the location and direction of the sound where the intrusion has occurred.”(DOT 5)

- “Most of our work zones are in high speed and high volume multi lane roadways. This creates a unique problem both with the amount of equipment needed for a job, (creating an issue of amount of equipment needed to carry the set up as well as the number of personnel needed for set up and take down), and, work zones are always temporary never usually longer than a few hours and between the hours of 7pm - 5:30am Because of the way these are mounted etc. they would create space issues along with cost issues. The other problem we usually need to use barrels and tall boy delineators for space and so they don't get blown over. This can create an issue with the amount of these devices we would need.” (GC 5)

- “Placement of the SonoBlasters® is essentially no different than placing candlesticks or traffic cones. Also, my understanding from the video is that the SonoBlaster® axis must be disturbed by 70-90 degrees. This would be a little bit of concern, since you are depending on the cone to bend and not necessarily for physical force or contact. I didn't understand how the C02 is actually released from the 70-90 degree disturbance. How often do the SonoBlasters® misfire? Overall, I think that these devices are worthy of consideration -- although it seems like movement from employees or from construction equipment coming into contact with the SonoBlasters® would happen fairly often.”(GC 6)

- “I think the sound of the SonoBlaster® itself would be enough to scare someone into slamming on the brakes. Cost effective and easy to replace. I like that is mechanical and there is no computer system to it.” (GC 6)

- “Again, on high speed roadways decibel levels are around 90+. I'm not sure that an air horn will provided any mechanism of safety in the big picture here, especially when cars are traveling 50-70 MPH and you need to be within 50 feet of a cone to hear the horn. Say if you did hear the horn at 70 MPH, it's too late. In my opinion this might be useful where the speed limit is 25 mph or less and in work zones where people walking, or outside of their truck/equipment will be able to hear it and safely move out of harm's way." (GC 7)

6.2.2.2 Intellicone®

The results related to the Intellicone® are shown in Table 6.3. According to the focus group participants, the relatively high cost of the Intellicone® could play a significant role in deciding if the technology should be used on a construction project. DOT employees' hinted that it is unlikely that an Intellicone® will be used on a project given its current cost (mean rating = 2.0). Effectiveness of triggering mechanism was highlighted as a major benefit when considering the use of an Intellicone® on a project.

Table 6.3: Recorded Mean Response and Standard Deviation for Intellicone®

	Evaluation Criteria	Cumulative Mean Rating (n = 19)	Std. Dev.	GC Mean Rating (n = 6)	DOT Mean Rating (n = 6)	SC Mean Rating (n = 1)
1	Ease of use	3.56	1.26	3.60	3.83	2.00
2	Effectiveness of triggering mechanism	3.67	1.25	3.70	3.83	3.00
3	Effectiveness of alarm	3.56	1.17	3.70	3.33	4.00
4	Likeliness of use considering cost	2.33	1.11	2.7	2.00	1.00
5	Usefulness of technology	3.61	1.38	3.80	3.67	3.00

Provided below are examples of comments received from the participants regarding the Intellicone®.

6.2.2.2.1 Stationary Work Zone

- "I would use the Intellicone® motion detectors in the Transition Zone and in the Buffer Space. The difficult challenge to this unit is where to place the command center unit. That unit must be strategically placed in order to correctly inform the workers of where the intrusion threat is coming from. This challenge makes for confusion with the Intellicone® system. I think that workers will always first look towards the sound, which may NOT be in the correct location, thus losing response time." (DOT 5)

- "Somewhere away from construction equipment and trucks and in a spot where it won't pick up oncoming traffic in its sensor. Again, closer to the crew from the taper and out of the way of cones that may get hit and trigger alarms." (GC 5)

- "This would be a great device for a stationary work zone, cones to be placed in transition area and the buffer space. However, work zones that are 45 MPH or up you would need at least 2 command centers to include for the buffer zone and for the work space." (GC 6)

- “Transition and longitudinal buffers well as workspace min half way up the workspace for the sensors. The alarm itself would be in front of our buffer vehicle near the work zone”(GC 7)

6.2.2.2.2 Mobile Work Zone

- “I would use a TMA for the mobile work zone to protect the Transition area, then I would use the Intellicone® motion detectors alongside of the Work Space. The Command Center could be set up in a mobile situation - on a pick-up truck ahead of the TMA or perhaps on the front end of the TMA.” (DOT 5)

- “Notification technology at the taper, alarm technology adjacent to the workers.” (GC 4)

- “All cone devices are difficult to place in mobile work zones. It requires a TCS whom is able to keep pace with all different work zones and keep them all protected. This seems like an expensive and difficult option for mobile work zones, specifically paving where you would have potentially 3-4 different simultaneous work zones (grinder, dump person, paver, breakdown roller, finish roller, etc.)”(GC 6)

6.2.2.2.3 Additional Comments

- “I like this device. It would be easy to set up the traffic control plan and have a traffic control technician follow through by placing the devices. Likewise, before removing the traffic control simply send a technician through to remove the device before removing the devices. I like the visual an audio alarm mechanism that is able to be located near the workers. The only downside is the price.”(DOT 1)

- “Too spendy.” (GC 2)

- “Rather expensive given the possibility of cones being hit in the taper and buffer space tangent; I imagine the equipment would be potentially destroyed on impact, especially at higher freeway speeds.”(DOT 3)

- “This appears to be a viable option. You're putting a lot of faith in a wireless system to work, and also faith in workers/supervisor to make sure the units are properly charged and working correctly before use. The drop off in the dB's would make me curious to see how audible it is next to a paver, dumping trucks, rolling, next to a grinder, etc. The visual alarm is a useful addition for night work -- I'd be curious to see how visible it is with all the amber construction strobe lights concurrently turned on as well.” (GC 6)

- “Audio visual alarm is useful, especially at night. Although, cones are knocked over frequently, I’m wondering if over time workers would become complacent to every time a cone would be knocked down. You’d want to put these cones on the interior of the zone so that every time a cone was knocked over it wouldn’t alarm workers. dB drop off significantly after 50’, makes me wonder if someone next to the paver, dumping trucks, or on a roller would be able to hear the alarm. Easy attachment to cones, but needs batteries/charging making it more impractical for construction crews.” (GC 6)

- “Most of our work zones are in high speed and high volume multi lane roadways. This creates a unique problem both with the amount of equipment needed for a job, (creating an issue of amount of equipment needed to carry the set up as well as the number of personnel needed for set up and take down), and, work zones are always temporary never usually longer than a few hours and between the hours of 7pm - 5:30am The other problem we usually need to use barrels and tall boy delineators for space and so they don't get blown over. This can create an issue with the amount of these devices we would need. This device would probably be the most useful for our needs because of ease of set up etc.” (GC 7)

6.2.2.3 Worker Alert System

Table 6.4 provides a summary of the analysis of the participant input related to the WAS. Usefulness of technology and ease of use were identified by the general contractors as significant motivations towards the possible adoption of the WAS (mean ratings of 3.80 and 3.70 respectively).

Table 6.4: Recorded Mean Response and Standard Deviation for WAS

	Evaluation Criteria	Cumulative Mean Rating (n = 19)	Std. Dev.	GC Mean Rating (n = 11)	DOT Mean Rating (n = 7)	SC Mean Rating (n = 1)
1	Ease of use	3.71	1.18	3.70	3.83	n/a
2	Effectiveness of triggering mechanism	3.59	1.09	3.60	3.50	n/a
3	Effectiveness of alarm	3.53	1.09	3.60	3.50	n/a
4	Likeliness of use considering cost	3.56	1.17	3.67	3.33	n/a
5	Usefulness of technology	3.65	1.08	3.80	3.50	n/a

Provided below are examples of comments received from the participants regarding the WAS.

6.2.2.3.1 Stationary Work Zone

- “I would set up the hose at the line of Advance Warning - Transition Area going perpendicular to traffic. I would then use additional hoses along the buffer space and work space running parallel with the traffic. The challenge is where to set up the yellow master unit."(DOT 5)

- "Along taper and along closure if feasible. Strategic points would be along the way an adequate distance to allow warning system to work."(GC 4)

- "Beginning of the buffer space across the road for the tune as well as longitudinal along the work zone area. the alarm device would go on the buffer vehicle just prior to the work zone" (GC 5)

- "Would likely need 2-3 pneumatic tubes placed in Transition Area and Buffer Space. Should be placed along the inside of the cones." (GC 6)

6.2.2.3.2 Mobile Work Zone

- "Difficult to keep in transition zone in a mobile zone."(GC 2)

- "I would not use this system in a mobile operation because of the constant need to move the pneumatic hose."(DOT 5)

- "Seems impractical to constantly be moving and placing the pneumatic tube. Also, I wonder about the durability of the tube being run over by equipment and traveling public." (GC 6)

- "You would put the hose area longitudinal by the work zone and the alarm on the buffer vehicle" (GC 7)

6.2.2.3.3 Additional Comments

- "This product seems most effective given the area that could be covered, not allowing for any gaps between cones. It also seems the easiest to set up and less likely to incur damage to the device." (DOT 1)

- "This system is a bit better in regards to the fact that it has parts that will attach to worker vehicles. The issue is still where do you place this and how far do you run the hose? This is something that if it was at a traffic regulator station it could be used to alert the workers that a vehicle ran the stop sign, the regulator (flagger) could step on the hose and it would alert the workers. The bigger issue with this one is how to keep the hose down and make sure that it doesn't blow into the active lane. And if you marked the edge of the work zone, how do you stop contractors from driving over it? Once again it's all about the false calls as soon as you have 2 false calls people will stop listening to it, as if it's a true call you don't have time to wonder if this one is real."(DOT 2)

- "I like this one best on paper just because it isn't mounted to a cone." (GC 3)

- “I like the idea of a personal alarm but did not see any information on cost of extra vibrators. The hoses seem to be limited as to how far the sensor can extend down the roadway. Long hoses would be needed to parallel the taper or tangent area. The vibratory, auditory and visual aspects of the alarm are plusses. I also like the magnetic mounting capability.”(DOT 4)

- “This system does not work in a mobile work zone setting. I think that the "sound" of the unit is not loud enough for an average work zone. Construction trucks could inadvertently run over this hose at night, whereas with a cone system, trucks could drive between the cones as needed. The need for construction vehicles to travel into and out of a work zone is a reality in construction - this system does not easily allow for this need, especially at night under low light conditions.”(DOT 5)

- “Vibration is a useful tool, but from only 50' away does not seem useful on most construction projects. Alarm does not seem as obnoxious or loud as the other alarms -- possibly not as effective. I do not feel like there was enough information given to accurately dissect this method.” (GC 6)

- “Most comprehensive alarm. 1,000’ range is a nice feature. Needs batteries – another thing to remember to take care of for employees/managers. Pneumatic tube seems to be reliable technology. Only vibrates from 50’ away – does not seem to be practical to mount to a piece of equipment. Alarm does not seem to be as loud or intimidating as the other two alarms.” (GC 6)

- “Most of our work zones are in high speed and high volume multi lane roadways. This creates a unique problem both with the amount of equipment needed for a job, (creating an issue of amount of equipment needed to carry the set up as well as the number of personnel needed for set up and take down), and, work zones are always temporary never usually longer than a few hours and between the hours of 7pm - 5:30am The problem we may see with these devices is the amount of synchronization the devices need as well as ensuring devices turned on and batteries required etc. The ease of the hose is great but the alignment with the equipment is less than desirable.” (GC 7)

- “I think this one had the better concept where workers had the vibration alert on their person. However, the activation system was not very impressive. Seems as if the traffic and wind could cause the rope to blow around. I wonder if someone could devise a trigger that used lasers or LIDAR that was set-up from a distance such as possibly from the arrow board or TMA truck. Another issue with this is material delivery trucks that need to enter the work zone in certain areas and these areas may vary throughout the course of the shift depending on what kind of work is going on.”(GC 8)

6.3 CONCLUSIONS OF TECHNOLOGY SELECTION

Feedback from the focus groups (Task 4) provided invaluable inputs to the research study. The results indicated that although all three work zone intrusion alert technologies have the potential to increase a construction worker's reaction time in a work zone, the technologies also have some limitations. The following comment from one of the participants describes some limitations:

- "My main concern with all these devices is, how effective are they after more than one use? We need something easy to maintain, replacing batteries is not ideal because it adds item to be checked off and requires, albeit small, another degree of maintenance. I don't see any of these devices being exceptionally useful in a mobile work zone. Even a dedicated and competent TCS would have difficulty keeping the alert systems in the proper locations as 3-4 different work zones progress on a paving project."

The findings from the focus groups can be concisely summarized by a participant's comment as follows:

- "These systems seem to be a valuable tool that would be effective in preventing some traffic caused injuries. As do all traffic control devices these will have a shelf life and likely need to be replaced often, I think developing a technology that is cognizant of cost will be a large factor for making this technology something that contractors will choose to implement on their job sites."

Based on the results of Task 4, Task 5 involves deploying all three work zone intrusion alert technologies on live projects to evaluate the impact that the technologies could have on construction workers.

7.0 IMPLEMENTATION AND TESTING OF SELECTED TECHNOLOGIES

7.1 INTRODUCTION

Task 5 of the work plan focused on assessing the effectiveness of the intrusion alert technologies on live projects. Following feedback received from the focus groups conducted in Task 4, all three technologies were approved for field testing. Candidate case study projects for the research were identified and determined by the researchers and the TAC members in consultation with general contractors of candidate projects. For each case study, the three intrusion alert technologies would be implemented to determine their effectiveness. Using multiple data collection streams (explained in Section 7.3), the researchers' aggregated useful data for determining the effectiveness of intrusion alert technologies. The research plan for the live testing was designed to accommodate possible variations/iterations due to specific constraints of each project. Close coordination among the researchers, ODOT staff, and construction contractors was maintained to ensure proper implementation of the research plan and data collection.

7.2 PROJECT IDENTIFICATION

Considering that the primary objective of the study is to determine the impact of intrusion alert technologies on workers in roadway construction work zones, it is paramount that case study projects must be representative and prototypical projects. A list of potential projects for the case study projects was generated by the researchers in consultation with the ODOT TAC. Table 7.1 highlights the list of candidate projects.

Table 7.1: Candidate Projects for Live Testing

No.	Project Name
1	I-84: Cascade Locks - Hood River
2	I-84: Sandy River - Multnomah Falls
3	I-84: Mosier - The Dalles
4	US 30: Swedetown Road - Wonderly Road
5	US-30: NW McNamee Rd. - NW Bridge Ave.
6	I-5: Southbound ramp improvements at Exit 252
7	U.S. 101 Oregon Coast Highway: Yachats -Florence
8	OR 140: Klamath Falls – Lakeview Highway

The researchers contacted the ODOT project managers of each identified project to determine the feasibility of performing live testing on their projects. In particular, the researchers inquired about project scope, plans, and schedule. Due to various constraints including the timing of the project, scope of work, and accessibility to the researchers, the following three projects were selected from the list as the case study projects:

1. US-30 Swedetown Road to Wonderly Road (Columbia County)
2. I-84 Cascade Locks to Hood River
3. I-84 Mosier to The Dalles

7.3 PROPOSED DATA COLLECTION MATRIX

Table 7.2 summarizes the planned measurements and observations during the live testing on the case study projects and how they are relevant to the data to be collected.

Table 7.2: Data Collection Matrix

Data to be Collected	Measurements and Observations Recorded				
	A	**B**	**C**	**D**	**E**
	Demonstration of technologies	**Clicker response**	**Video observation**	**Interview ODOT personnel**	**Interview contractor personnel**
How to use alert technology	X			X	X
Audibility and visibility		X	X		
Loudness of sound relative to distance				X	X
Distinctiveness of sound relative to distance and ambient noise				X	X
False alarm	X		X		
Reaction time relative to distance		X	X		

Demonstration

Prior to testing each alert technology, a demonstration session was arranged so test participants would know what the alert sounds like, looks like, and when applicable, feels like. The session also provided workers and ODOT personnel with firsthand information on how each technology is installed, activated, triggered, and dismantled.

Clicker Response

One of the objectives of the live testing was to estimate worker reaction time for each technology. Reaction time, within the context of the present study, is the amount of time between alarm triggering and worker realization of the alarm. The present study employs clickers as a means to collect real-time data. In certain cases, the researchers were asked to use a clicker while observing assigned workers. Clickers were also given to available researchers for additional data collection. Refer to Section 7.4.2.1 for more information on clickers.

Video Observation

The researchers observed and recorded the construction operation using camcorders. The purpose of videotaping the workers was to record the reaction of different workers to each intrusion alert technology. By recording the operation, primary data on a worker's reaction time would be documented. As well, the researchers were required to call out (i.e., talk to the camcorders while videotaping) any environmental conditions, roadway conditions, traffic control device setup, and construction procedure that might influence the quality of data being collected.

Interview ODOT Personnel

The selected work zone intrusion alert technologies were tested and evaluated at specific times during the live testing. ODOT personnel working on the selected projects (e.g., inspectors) were asked to provide feedback at the demonstration session prior to the live testing as well as after triggering each technology during the testing. Feedback from ODOT personnel was considered to provide significant insights and recommendations as to how ODOT can utilize the technologies in their future projects.

Interview Contractor Personnel

Similar to the interviews performed with ODOT personnel, contractor personnel were asked to provide feedback on each alert technology pre- and post-live testing. Information regarding ease of use, sound level, and sound distinction were collected from contractor personnel as the end-users of the technologies.

7.4 DATA COLLECTION

7.4.1 Research Plan

The research team developed two adaptable plans for the case study projects. Tables 7.3 and 7.4 describe planned timelines and activities for each case study project for mobile and stationary operations.

7.4.1.1 Mobile Work Zone for Paving

The following activities were repeated for each technology. Testing of two different technologies was planned for each night.

Table 7.3: Planned Activities for Mobile Operation

Timeline	Planned Field Activity	Research Activity
At the start	• Host a prep meeting with workers to teach how to use each technology • Show a suggested deployment and have workers decide where they want to use it	• Video recording • Survey
For the first 2 hours	• Observe the workers' use of technology and their movements • Measure the sound levels workers are exposed to	• Video recording • Sound level measuring
After 3 hours	• Determine and mark interval (distance from alarm) • Trigger alarm intentionally and observe how workers react • Measure the sound levels of alarm	• Video recording • Sound level measuring • Aggregate clicker data
After 3.5 hours	• Perform a quick interview of each worker to get their feedback	• Audio recording • Survey

7.4.1.2 Stationary Work Zone for Bridge Repaving

The following activities were repeated for each technology. Testing of two technologies was planned for each night.

Table 7.4: Planned Activities for Stationary Operation

Timeline	Planned Field Activity	Research Activity
At the start	• Host a prep meeting with workers to teach how to use each technology • Show a suggested deployment and have workers decide where they want to use it	• Video recording • Survey
For the first 2 hours	• Observe the workers' use of each technology and their movement • Measure the sound levels workers are exposed to	• Video recording • Sound level measuring
After 3 hours	• Determine and mark interval (distance from operation) • Trigger alarm intentionally and observe how workers react • Measure the sound levels of alarm • Move alert technologies based on predetermined intervals	• Video recording • Sound level measuring • Aggregate clicker data
After 3.5 hours	• Perform a quick interview of each worker to get their feedback	• Audio recording • Survey

7.4.2 Equipment and Tools

A number of pieces of equipment, resources, and tools were used to achieve the objective of the live testing. Surveys and interviews were used to gather subjective data while video and clickers were used as a means to produce objective data.

7.4.2.1 Clickers

The live testing involved determining whether construction workers were able to recognize the sound and visual alarms when triggered. In addition, determining the amount of time taken between alarm trigger and worker reaction (i.e., reaction time) provides valuable information for developing specification and guidelines for use and future research. To achieve this goal, a mechanism for collecting real-time data would be required, and the research team decided to use clickers. Clickers are predominantly used in educational environments to increase student engagement through real-time involvement in class discussions. Students are required to provide feedback or response by clicking a device. The device is approximately the size of a thin cell phone, and contains a numerical keypad for entering responses. Information from the clickers is collected and aggregated real-time using a receiver (a transmitter connected via USB to a desktop or laptop computer). Each clicker has a unique identification number and can be tagged to an individual. Reaction time can be estimated by recording the time when a question was asked (activated) and the time when the student clicked the clicker (response received). For the current research, reaction time was estimated using time elapsed between opening a session (synchronized with the time alarm is triggered) and the time when the worker clicked the clicker.

To ascertain the effectiveness of clickers for live testing, the researchers conducted an activation test in a controlled environment. In total, 10 clickers were tested using varied configurations to ensure device effectiveness across different work conditions applicable to the live testing. Specifically, activation tests were conducted along horizontal, vertical, and diagonal grid lines (see Figure 7.1). To account for possible interference of construction equipment, the researchers created a test scenario with obstacles between the receiver and the clicker. In addition, the possible impact of an elevation difference between the clicker and the receiver was considered during the assessment. Test results showed that the clickers effectively (100%) transmitted a signal to the receiver between 0 - 250 feet horizontally, and (320 feet) diagonally with and without obstruction. Activation tests with obstructions were conducted in a parking lot where stationary vehicles acted as obstructions between the clicker and the receiver. Importantly, it was observed that if the receiver was positioned approximately 3 feet below the clicker, signal transmission was approximately 20% at 250ft. Therefore, it was concluded that the receiver should be carried by a researcher at waist level to minimize any potential transmission issue due to an elevation difference.

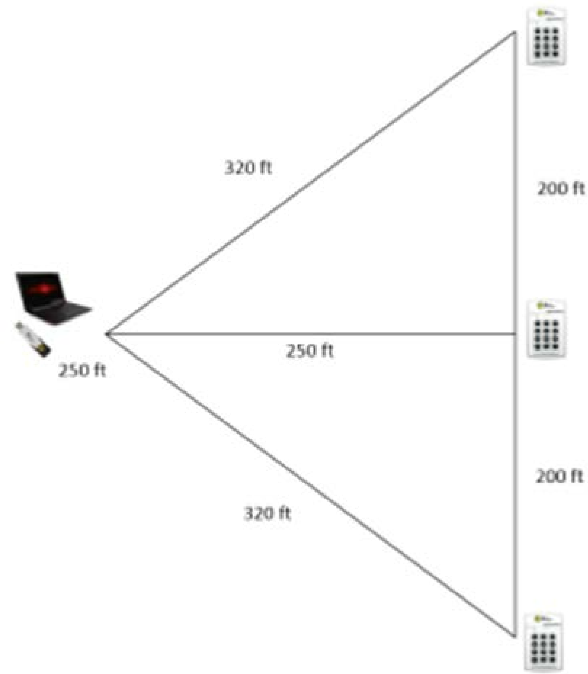

Figure 7.1: Clicker Test Set-Up

7.4.2.2 Sound Level Meter

The Extech HD 600 sound level meter used in the pilot test was used again in the live testing to record the sound level of construction equipment in live operations (see Appendix D). The sound level around the construction equipment was recorded to provide more realistic construction site ambient and equipment sound that could be compared with the intrusion alert sound levels documented in Task 3.

7.4.2.3 Camera and Video Recorder

Camcorders and a digital camera were used to capture the construction workers' reactions to the activated work zone alert technologies, the ongoing construction operation, and other interesting observations. Data from recorded videos provide additional insight on the impact of the intrusion alert technologies on the worker. Each graduate student researcher had a camcorder focused on a particular operation or worker depending on the primary objective of the case study.

7.4.2.4 MP4 Recorder

Similar to the sound level meter, a MP4 recorder was used to record the sound level emitted by the construction equipment. The overlap sound level of construction equipment and intrusion alert technology was also recorded to enable the researchers to conduct a spectral analysis.

7.4.3 Other Equipment and Tools

In addition to the aforementioned primary tools required to achieve the research objectives, other resources played important roles to ensure efficient and effective data collection. A laptop computer was used as a receiver that collected and recorded signals from the clickers. A measuring tape was used to measure distances needed for conducting the research plan and performing the data analysis. Reflective spray paint was used to mark the location on the edge of the paver and along the shoulder to ensure that predetermined testing locations can be identified easily. Finally, questionnaires were used as a means of collecting quantifiable data from participants during the interviews.

7.5 CASE STUDY PROJECT #1: US-30 SWEDETOWN ROAD TO WONDERLY ROAD

7.5.1 Project Description

The first case study project was conducted in Columbia County on the US-30 Swedetown to Wonderly Road project. The project encompassed east and west bound single lanes and spanned 10 miles starting at mile point 60.91 and terminating at mile point 50.34. Figure 7.2 shows the location of the project.

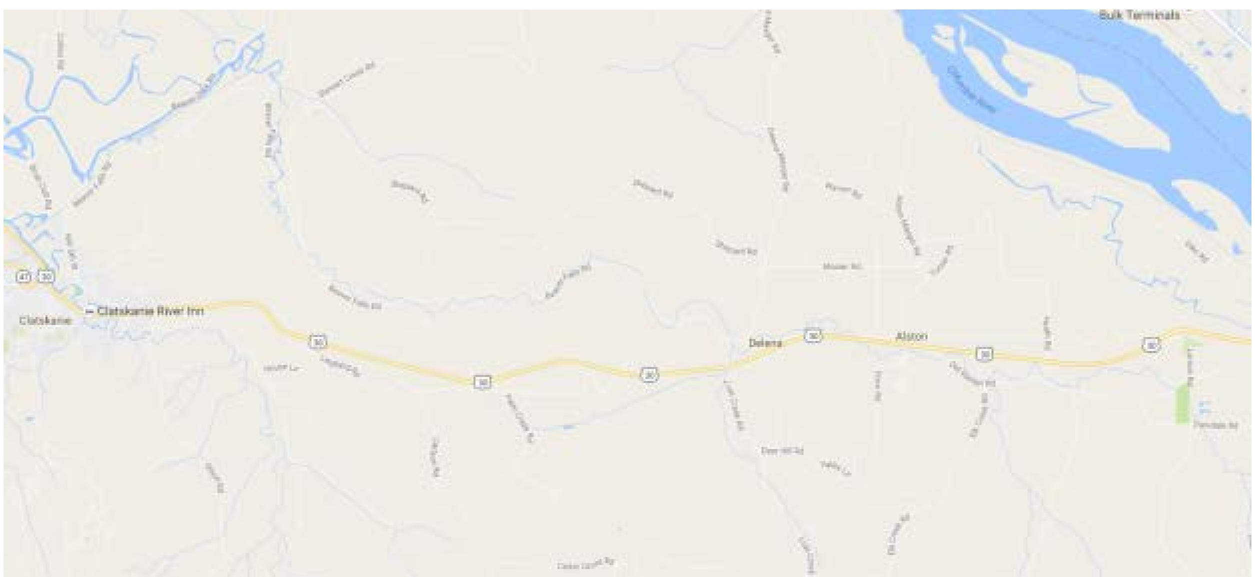

Figure 7.2: Location of US-30 Swedetown to Wonderly Road Project (Image from Google Maps 2016)

The construction activities on the project included re-paving, replacement of barriers and medians, and bridge joint repair. Given the complex nature of the project, a pilot car method of One-Lane, Two-Way traffic control setup was implemented on this project. The work zone was typically setup at 6:00pm and removed at 6:00am, Sunday through Thursday. The data collection focused on the repaving operation in the eastbound shoulder on July 13, 2016.

7.5.2 Research Plan

The research team, alongside the TAC members, held meetings with the contractors to determine the project schedule, staffing, etc. Following these preliminary discussions, a research plan was developed by the research team prior to arriving at the testing location. Since the target operation was a mobile operation, the activities depicted in Table7.4 were proposed for data collection for Case Study Project #1.

Day 1:

Prior to deploying the intrusion alert technologies for live testing on the first day, a coordination meeting was held with ODOT staff and contractor workers at 5:30pm. Following discussions with ODOT and contractor personnel, the research study design was altered to accommodate project constraints while ensuring that adequate analyzable data would be collected. Table 7.5 depicts the updated (final) live testing plan for Day 1 of Case Study Project #1. The strike-through portions indicate actions that were changed (dropped) from the planned activities.

Table 7.5: Updated Research Plan for Case Study Project #1

Planned Field Activity	Research Activity
• Host a prep meeting with workers to teach how to use each technology • Show a suggested deployment and have workers decide where they want to use it	• Video recording • Survey
• ~~Observe the workers' use of tech and their movements~~ • Measure the sound levels workers are exposed to	• Video recording • Sound level measuring
• Determine and mark distance between operation and alarm • 35ft, 50ft, 100ft, 300ft • Trigger alarm intentionally and observe how workers react • Measure the sound levels of alarm	• Video recording • Sound level measuring • Aggregate clicker data
• Perform a quick interview with each worker to get their feedback	• Audio recording • Survey

The ODOT staff observed how each technology is activated, deployed, triggered, and deactivated (Figure 7.3). Following the demonstration, a survey questionnaire was distributed to the ODOT personnel to collect feedback. After collecting the survey forms, the researchers repeated the demonstration to construction crews involved in the paving, grinding, and rolling operation procedure. It should be noted that the workers were not asked to use the alert technology. The clickers were also distributed to each worker who was willing to be part of the study. The identification numbers of each clicker were recorded along with the job function of the worker handling the clicker to ensure accurate interpretation of data. An instruction was given as to how to respond using the clicker if the alarm was heard, seen, or felt. Due to time limitations, feedback from the participants could not be collected using a survey questionnaire. In total, 12 clickers were distributed to construction workers and ODOT inspection personnel (11 contractor workers, one ODOT personnel). In addition, four out of the six researchers involved in the data collection process received clickers.

Figure 7.3: Demonstration Prior to Live Testing, Case Study Project #1, Day 1

Due to safety concerns around limited shoulder space on the east bound lane and the need to conceal the alert technologies from easy detection by workers, the researchers set up the alarms approximately 1 mile from the paving start point for the night (see Figure 7.4).

Figure 7.4: Site for Live Testing, Case Study Project #1, Day 1 (Image from Google Maps 2016)

Reference points were marked along the road in 50 foot intervals to ensure consistency. Reference points at 35 feet and 300 feet were added to the research plan to capture roller operation data. The researchers made an effort to conceal the intrusion alert technologies from the direct view of the passing operation to ensure the element of surprise played a role in their reaction (see Figure 7.5). As shown in Figure 7.5, the alarms were set up approximately 25 feet from the repaving operation.

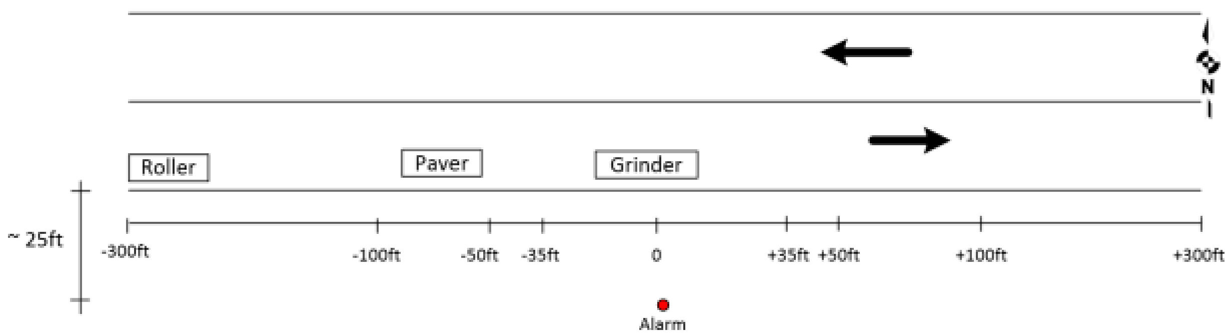

Figure 7.5: Day 1 Data Collection Setup for Case Study Project #1

Typically, the contractor closed the lane with channelizers and drums at approximately 7:00pm, the grinding operation starts at about 8:00pm, and the paving operation commenced at approximately 9:00pm. In most cases, the paving operation followed behind the grinding, sweeping, and tacking operations. On this day, the paver started paving at about 10:00pm.

All planned data collection activities were successfully executed by the research team. Between 8:00pm and 10:00pm, the research team recorded sound levels of major operation equipment (grinder, paver, and roller) to create a baseline for ambient and equipment noise level without the alarm. This project made use of two pavers. While maintaining the same position all through data collection (approximately 1 mile from the starting point), the research team activated the SonoBlaster® and Intellicone® as the paving operation train passed by. The research focused on the sweeping, water tank, and grinding crew for the first round of triggering due to the (long) distance between the grinding and paving operations. First, the SonoBlaster® was activated as the grinder crossed the -100ft station (left of the base location in Figure 7.5), and followed by another activation when the grinder passed the -50 feet location. The SonoBlaster® was also triggered when the sweeper passed by the test location. When the grinder crossed the +50 feet (right of the base location in Figure 7.5) and +100 feet locations, the Intellicone® was triggered accordingly. Following the triggering of each technology, participants were asked for their opinion regarding the loudness and distinctiveness of the alarm triggered.

Research data on the paving and compacting operation was collected between 12:00am and 1:40am on July 14. Each technology was triggered in a similar sequence as was done for the grinding and sweeping operation. In addition to the mentioned sequence, the Intellicone® and WAS were activated 300 feet behind the paver (upstream) to include the rollers. Responses from all participants were recorded using camcorders and clickers. Unlike the other operations described above, the compacting operation (roller) proved difficult to observe due to the equipment speed and the lack of consistency in their movement pattern. Following the conclusion of data collection, the researchers asked each participant for feedback on loudness and distinctiveness of each alarm. Figure 7.6 depicts the leg-traffic of workers around the entire repaving operation. The size and color of each circle in the figure graphically represents the number of workers typically on foot around each piece of equipment (i.e., a larger circle represents more people). The most human movement occurs between the pavers and the rollers.

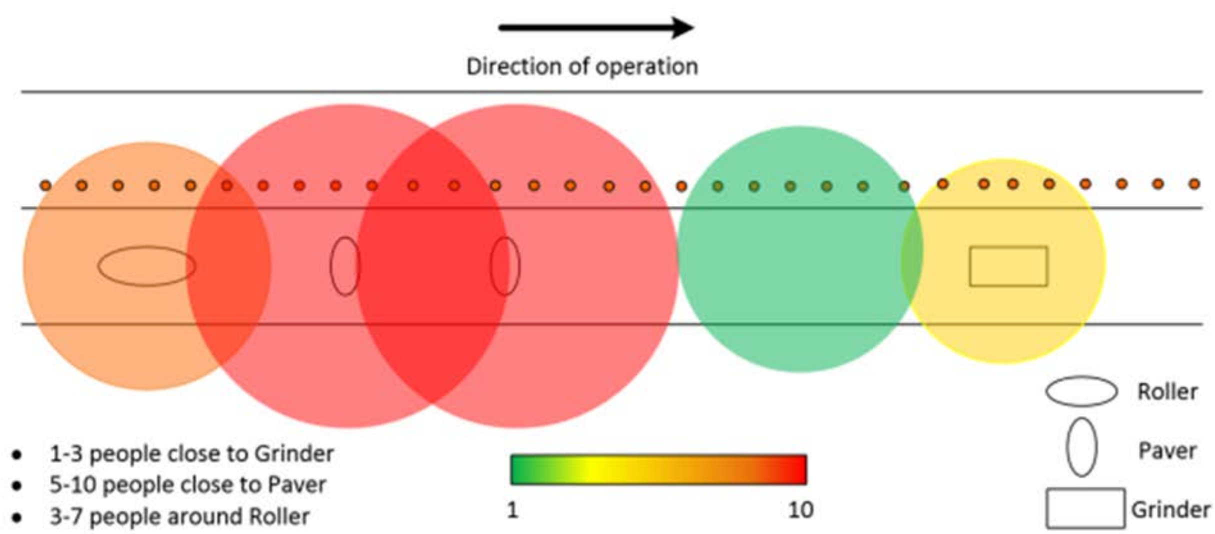

Figure 7.6: Visualization of Work Zone Leg-Traffic for Day 1 of Case Study Project #1

Day 2:

The research design for the second day was similar to that implemented on Day 1. Since the same crew members were used by ODOT and the contractor, the research team did not hold another demonstration prior to live testing. Based on results from the first night, the research focus was limited to the paving and roller operation due to the higher amount of leg traffic around these two operations (see Figure 7.7). In total, 9 clickers (8 for contractor and 1 for ODOT) were distributed to the construction workers and ODOT inspector. Five researchers coordinated the data collection effort. The project began in the eastbound lane. The safest location found by the researchers and ODOT personnel was within close proximity to the endpoint for the day's operation. As a result, the researchers began data collection at 3:00am on July 15. As shown in Figure 7.7, the distance between the alarm and the paver was kept at 50 foot increments, i.e., 150 feet, 100 feet, and 50 feet. There was no need to include 35 feet and 300 feet on the second day. The WAS technology was triggered three times at stipulated intervals ahead of the paving and compacting operation. The testing of the WAS technology was followed by the Intellicone® using a similar setup, but behind the paving operation (i.e., +50 feet, +100 feet, and + 150 feet). Next, the WAS technology was activated three more times following the same sequence but this time, the relative distance was based on the first roller in the compacting operation. Audio recording was conducted for the Intellicone® and WAS at specified distances. Data collection ended at 6:05am.

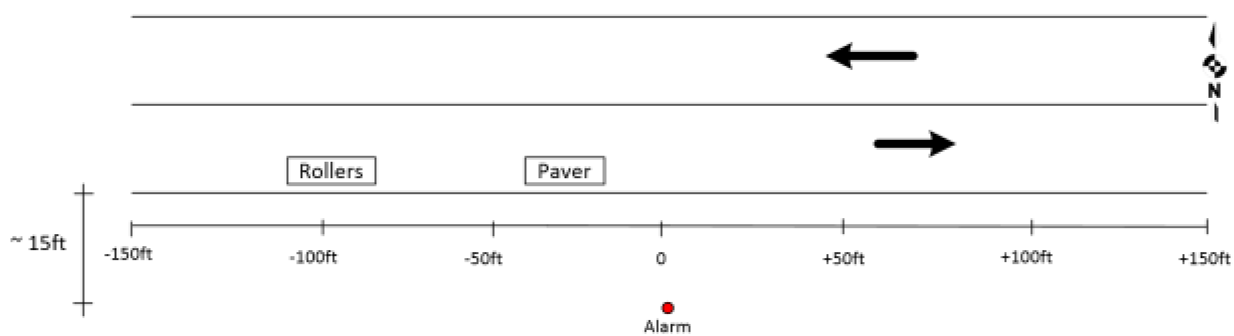

Figure 7.7: Day 2 Data Collection Setup for Case Study Project #1

7.6 CASE STUDY PROJECT #2: I-84 CASCADE LOCKS TO HOOD RIVER

7.6.1 Project Description

The Interstate 84 Cascade Locks to Hood River project was selected by the research team and members of the TAC as Case Study Project #2. The repaving project was located in Hood River County with project limits of MP 46 and MP 64. The project scope involved repaving of shoulder, slow lane, and fast lane on the eastbound and westbound lanes. Thus, the research study focused on the roadway paving operation. Figure 7.8 shows the project location. The project location was relatively cold and windy at night during the live testing.

Figure 7.8: Location of I-84 Cascade Locks - Hood River Project (Image from Google Maps 2016)

On July 24, the paving operation was heading east towards Hood River. The contractor’s work plan for July 24 was to pave approximately 2.5 miles of the eastbound (EB) slow lane starting at mile point 44.5. Similar to Case Study Project #1, the task for the day was scheduled to begin at approximately 7:00pm as traffic control personnel started setting up channelizers. For this project, only one lane would be closed at any given time.

7.6.2 Research Plan

Following analysis of data collected from Case Study Project #1, the research team made a few adjustments to improve the quality of collected data. Specifically, the research team opted to focus solely on activities around the paver. This was largely due to inconsistent observed result from the compacting (roller) operation due to several reasons discussed above. In order to maintain consistency across case study projects, the research team ensured that the 50 feet (increments) between the alert technology and paving operation were maintained regardless of updates made to the research plan. Table 7.6 shows the adapted research plan for Case Study Project #2. The strike-through portions indicate actions that were changed (dropped) from the planned activities.

Table 7.6: Updated Research Plan, Day 1 of Case Study Project #2

Planned Field Activity	Research Activity
• Host a prep meeting with workers to teach how to use each technology • Show a suggested deployment and have workers decide where they want to use it	• Video recording • Survey
• ~~Observe the workers' use of tech and their movements~~ • ~~Measure the sound levels workers are exposed to~~	• Video recording • Sound level measuring
• Determine and mark distance between operation and alarm • -100ft, -50ft, +50ft, +100ft • Trigger alarm intentionally and observe how workers react • Measure the sound levels of alarm	• Video recording • Sound level measuring • Aggregate clicker data
• Perform a quick interview with each worker to get their feedback	• Audio recording • Survey

Day 1:

Similar to Case Study Project #1, the research team held a demonstration session with one ODOT personnel and 10 workers from the contractor to ensure the participants were provided with relevant background information on each technology to be tested on the I-84 project (see Figure 7.9). A questionnaire was completed by each participant at the end of the demonstration, providing feedback on the evaluation criteria for each technology.

Figure 7.9: Demonstration Prior to Live Testing, Day 1 of Case Study Project #2

After the demonstration session, ODOT personnel, alongside the research team proceeded to secure an ideal location for setting up the alert technologies for data collection. The research team set up equipment and tools behind the guardrail close to mile point 46, right before the NW Forest Lane crossover (see Figure 7.10).

Figure 7.10: Site for Data Collection, Case Study Project #2, Day 1 (Image from Google Maps 2016)

Following the research plan, the research team marked the predetermined distance for each technology. Approximately 200ft was provided between the SonoBlaster®'s +100ft station and the Intellicone®'s -100ft station to account for time required to transfer the required research tools and equipment from one base location to the other (See Figure 7.11). As the paver got close to the test location, audio recording for each technology was conducted to provide data for determining sound distinctiveness.

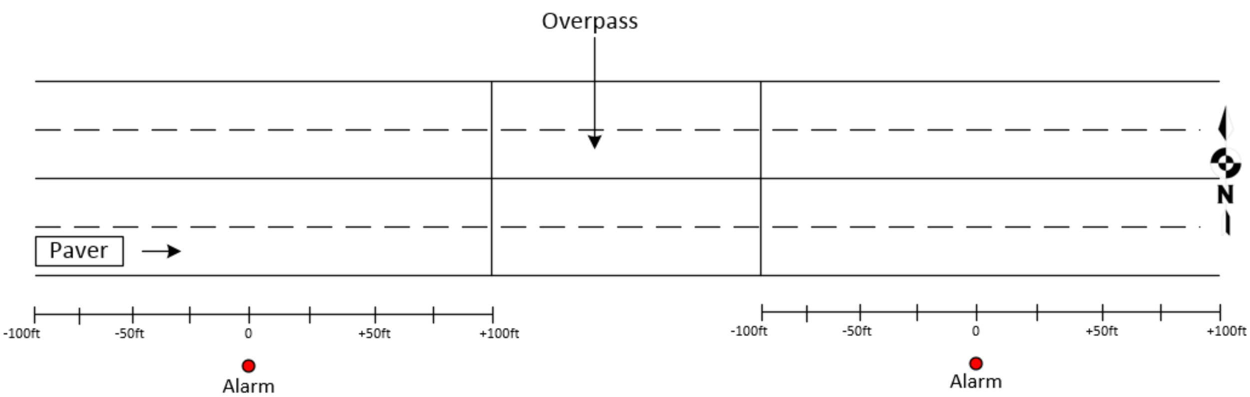

Figure 7.11: Data Collection Setup, Day 1 of Case Study Project #2

Paving started at approximately 10:00pm, with the paver arriving at the -100ft station before the NW Forest Lane overpass at 11:07pm. Each technology was triggered four times at different distances relative to the paver: first, at –100ft, followed by – 0ft, +50ft, and +100ft stations. A video camera captured the entire process while the clickers provided quantifiable data regarding worker response. Due to the continuous movement of the operation and workers being busy, questions on loudness and distinctiveness were only asked once – after the Intellicone® was triggered. Figure 7.12 shows the magnitude of foot traffic around the repaving operation. The size and color of each circle graphically represents the number of workers in the area.

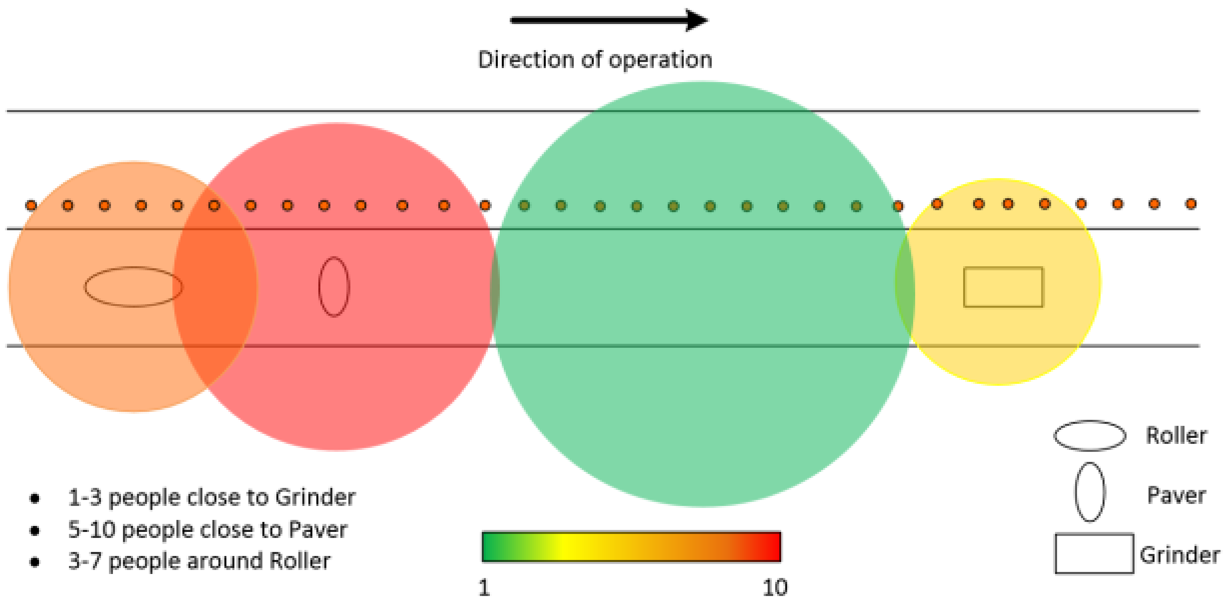

Figure 7.12: Visualization of Work Zone Leg-Traffic, Day 1 of Case Study Project #2

Day 2:

The plan executed for data collection on Day 2 differed from the plan implemented on Day 1 because space beyond the shoulder was limited on the EB lane between the MP 47 on-ramp and the target end mile point for the night. To maximize the available space, the research team adapted the research plan, setting up the base station at one point while performing the assessment of each technology on both sides of the base station. Figure 7.13 shows the adjusted data collection setup. The distance between the alarm and the paver was kept at 50 foot increments, i.e., 50 feet, 100 feet, and 150 feet. The same paving crew from Day 1 took part in Day 2 data collection thereby eliminating the need for an additional pre-live testing demonstration. Eight contractor workers and one ODOT inspector were given clickers after agreeing to be part of the study for the night. Five researchers took part in data collection. The paving operation started at approximately 10:00pm and the data collection ended at 10:30pm.

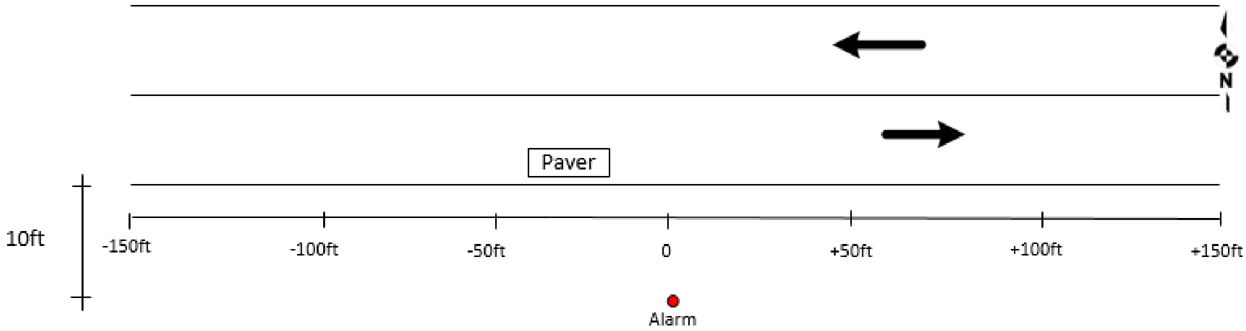

Figure 7.13: Data Collection Setup, Case Study Project #2, Day 2

Data on the effectiveness of the WAS was collected first by triggering the alarm three times – at -150 feet, -100 feet, and -50 feet. Participant feedback on loudness and distinctiveness was collected at the end of the triggering session. The Intellicone® was triggered three times – first, when the paving operation crossed the +50 feet station, followed by the +100 feet station (see Figure 7.14), and finally, when the paver crossed +150 feet.

Figure 7.14: Intellicone® triggered 100 feet away from Paver

While collecting data, it was observed that at different times, traffic moving through the activity zone hit traffic cones, thereby causing the cones to fall over (see Figure 7.15). It is speculated that this event could lead to multiple false positive alarms for the SonoBlaster® and the

Intellicone® considering their design is dependent on the reliability and orientation of work zone cones.

Figure 7.15: Cone in Work Zone Knocked Over

7.7 CASE STUDY PROJECT #3: I-84 MOSIER TO THE DALLES

7.7.1 Project Description

The third case study project for live testing was the 14 mile-long Mosier to The Dalles Interstate 84 paving project. This I-84 project covered eastbound and westbound lanes, extending from mile point 70.4 to mile point 84.3. Figure 7.16 shows the location of the project.

Figure 7.16: Location of I-84 Mosier to The Dalles Project (Image from Google Maps 2016)

For operational reasons, the contractor elected to pave two 200-foot impact panels before and after three bridges on the eastbound lane for the night's operation. Accordingly, the third case study project was conducted within three hours on October 1, 2016. All three intrusion alert technologies were tested by the researchers during one night. The area was so cold and windy at night that the triggering mechanism of the SonoBlaster® showed signs of being susceptible to cold weather and rain.

7.7.2 Research Plan

Due to uncertainties surrounding the weather and project schedule, overlap with a different ODOT research study, and limited research personnel, a revised 1-day data collection research plan was developed based on the contractor's operation for the day. Table 7.7 shows the research plan updated for Case Study Project #3 (strikethrough shown for omitted activities). The strike-through portions indicate actions that were changed (dropped) from the planned activities.

Table 7.7: Updated Research Plan, Day 1 of Case Study Project #3

Planned Field Activity	Research Activity
• ~~a prep meeting with workers to Host teach how to use each technology~~ • Explain research objective to workers • ~~Show a suggested deployment and have workers decide where they want to use it~~	• Video recording • ~~Survey~~
• ~~Observe the workers' use of each technology and their movements~~ • ~~Measure the sound levels workers are exposed to~~	• ~~Video recording~~ • ~~Sound level measuring~~
• Determine and mark distance between operation and alarm • -100ft, -75ft, -50ft, -25ft, +25ft, +50ft, +75ft, +100ft • Trigger alarm intentionally and observe how workers react • Measure the sound levels of alarm	• Video recording • Sound level measuring • Aggregate clicker data
• Perform a quick interview with each worker to get their feedback	• Audio recording • Survey

The selected operation for data collection involved slow lane paving 200ft before and 200ft after the bridge identified in Figure 7.17. Consistent with Case Study Project #2, the researchers chose to focus solely on the paving activity. A total of 10 contractor workers and two ODOT staff were involved in the activity. It is important to note that the crew involved in Case Study Project #3 were almost identical as those on Case Study Project #2 (the same contractor worked on both projects), so the research team decided not to host a demonstration session prior to live testing. Of the 10 active workers, four decided to take part in the research alongside one ODOT inspector. The participants were subsequently briefed on the research objectives by the researchers. Due to the study's complex setup, a group of six researchers took part in data collection to help improve the quality of data collected.

Figure 7.17: Site for Data Collection, Case Study Project #3 (Image from Google Maps 2016)

Following previously mentioned project-specific limitations coupled with findings from Case Study Projects #1 and #2, and the researchers elected to make the following changes to the testing setup:

- Each technology was triggered four times (100 feet, 75 feet, 50 feet, and 25 feet away from the paving operation)
- Two base station locations were used
- Each technology was tested once with the exception of the Intellicone® which was tested twice
- One researcher for every worker (one researcher was assigned to only one worker to improve quality of observation)
- Workers were asked to raise their hand if the alarm was heard

The testing setup created for Case Study Project #3 is shown in Figure 7.18.

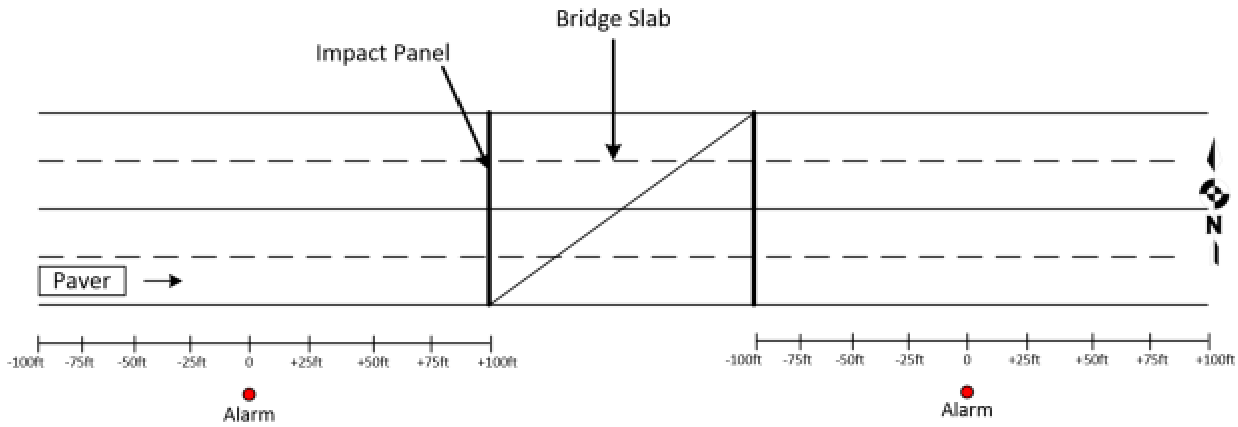

Figure 7.18: Data Collection Setup, Case Study Project #3

Similar to the two previous case study projects, the workers were initially asked to click the clicker to indicate that they heard the alarm. However, following the review of videos from the past case study projects, an additional response mechanism that depicts confirmation of hearing the alarm was deemed necessary (See Figure 7.19). Therefore, the workers were asked to raise their hand if they heard the alarm in addition to using the clicker. Following the triggering of each technology, the researchers asked each worker questions regarding the loudness and distinctiveness of the alarms. Also, the workers were asked for additional comments on where and how the technology could be used the most.

Figure 7.19: Two Workers Indicating Alarm was Heard, Case Study Project #3

7.8 SUMMARY OF TECHNOLOGY IMPLEMENTATION

Case study projects for evaluating the three alert technologies were conducted on three paving projects between July 13 and October 1, 2016. Testing was conducted on paving operations over five nights. The number of research participants on each project ranged from 5 to 12, mainly consisting of the ODOT inspector, dump person, screeder, and paver operator. Table 7.8 summarizes the activities conducted as part of Task 5.

Table 7.8: Summary of Activities Conducted for Live Testing

Testing Information	Case Study Project		
	Case Study Project #1: US-30 Swedetown Rd. to Wonderly Rd. (Contractor A)	**Case Study Project #2: I-84 Cascade Locks to Hood River (Contractor B)**	**Case Study Project #3: I-84 Mosier to The Dalles (Contractor B)**
Type of operation	Nighttime slow lane paving	Nighttime slow lane paving	Nighttime slow lane paving
Testing dates	Two nights on 7/13 and 7/14	Two nights on 7/24 and 7/25	One night on 10/1
Testing participants	Grinder, paver, roller, ODOT inspector, and OSU students	Grinder, paver, roller, ODOT inspector, and OSU students	Grinder, paver, ODOT inspector, and OSU students
# of researchers	6	5	6
Method to collect feedback	Clickers, interviews	Clickers, interviews	Clickers, interviews, hand signals

8.0 RESULTS

Section 8 of this report presents the results of the three case studies conducted as part of the project. The results will be presented in the following order:

1. Pre-live testing survey
2. Live testing on case study projects
3. Post-live testing survey

8.1 PRE-LIVE TESTING SURVEY

Prior to live testing, ODOT staff and contractor personnel were given an opportunity to observe controlled deployment of each intrusion alert technology. The objectives were to ensure actual live testing participants were familiar with the technologies, to receive useful feedback that could inform future deployment, and to streamline the daily testing plan. Over the course of three case study projects, a total of nine on-duty staff provided feedback on the three technologies. Of the nine participants, six were ODOT staff while three were with general contractors. Table 8.1 shows the roles and organizations represented in the pre-assessment.

Table 8.1: Pre-Live Testing Evaluation Participants

Role	Organization
Inspector (3)	ODOT
Safety Manager	ODOT
Project Coordinator (2)	ODOT
Paver operator	Contractor
Paving Foreman	Contractor
Project Manager	Contractor

To maintain consistency across the study, the researchers collected feedback using a survey questionnaire similar to that used for Task 4. First, the participants were asked to rate each evaluation criterion using a rating scale of 1 to 5 according to the level of importance (1 = least important and 5 = most important). In contrast to findings displayed in Figure 6.11 (Task 4), Figure 8.1 shows that the cost of the technology was identified by the participants as the least important criterion when selecting a technology to be deployed on live projects. The most important criterion for the participants was consistent with findings from Task 4 (effectiveness of the alarm).

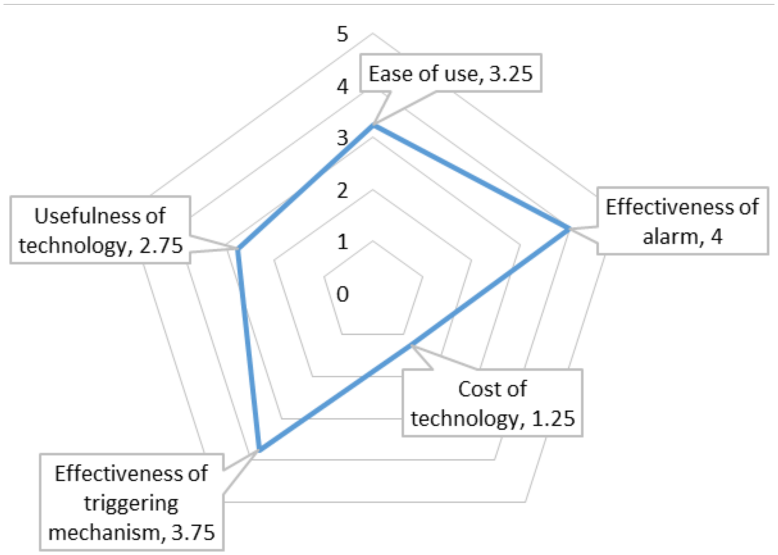

Figure 8.1: Mean Ratings of Evaluation Criteria (n = 9)

8.2 CRITERIA WEIGHTING

Consistent with analysis conducted in Section 6.2, feedback received from participants was divided into two categories: ODOT and Contractors. Results displayed in Table 8.2 indicate that although the mean and standard deviation differed between ODOT personnel and contractors, the ranking trend remained identical with the exception of usefulness of technology and ease of use.

Table 8.2: Mean and Standard deviation of Evaluation Criterion Ratings

	Evaluation Criteria	ODOT (n = 6)		Contractor (n = 3)	
		Mean Rating	Std. Dev.	Mean Rating	Std. Dev.
1	Ease of use	3.00	1.41	3.67	0.47
2	Effectiveness of triggering mechanism	3.60	1.02	4.00	0.82
3	Effectiveness of alarm	3.80	0.75	4.33	0.94
4	Likeliness of use considering cost	1.40	0.80	1.00	0
5	Usefulness of technology	3.20	1.47	2.00	0

In addition to weighting the criteria (see Table 8.2), all nine participants were provided complete information for each intrusion alert technology. The research team demonstrated how each technology is deployed, armed, triggered, and retrieved. Upon completion of the demonstration for each technology, the participants were asked to rate the technologies according to the following scales as applicable:

1 = very difficult, very ineffective, or very unlikely

2 = moderately difficult, moderately ineffective, or moderately unlikely

3 = neutral

4 = moderately easy, moderately effective, or moderately likely

5 = very easy, very effective, or very likely

Using the ratings presented above, Sections 8.1.1 to 8.1.3 discusses the respondents' perceptions concerning each intrusion alert technology.

8.2.1 SonoBlaster®

Participants' perceptions of the SonoBlaster® effectiveness were evaluated. As highlighted in Table 8.3, the alarm effectiveness was considered very effective with a mean rating of 4.22. With the exception of the effectiveness of the triggering mechanism, ODOT and contractor personnel rated each criteria in similar categories. Regardless of the difference in category placement between ODOT and contractor personnel, effectiveness of triggering mechanism received the lowest rating (neutral and moderately ineffective, respectively). It is important to note that the SonoBlaster® had a false negative on the first try for an unknown reason, but worked when activated the second time.

Table 8.3: Recorded Mean Response and Standard Deviation for SonoBlaster®

	Evaluation Criteria	Cumulative Mean Rating (n = 9)	Std. Dev.	GC Mean Rating (n = 3)	DOT Mean Rating (n = 6)
1	Ease of use	3.11	0.99	2.67	3.33
2	Effectiveness of triggering mechanism	2.78	1.03	2.33	3.00
3	Effectiveness of alarm	4.22	0.79	4.00	4.33
4	Likeliness of use considering cost	3.00	0.82	3.00	3.00
5	Usefulness of technology	3.33	1.05	3.00	3.50

General comments and concerns regarding deployment of the SonoBlaster® were solicited. Suggestions received are highlighted below:

- "It is hard to determine the usefulness without knowing how motorists will react to the noise. Can it be heard over equipment and traffic?" (DOT 1)
- "Didn't work on the first try - we need an alarm that works every time" (GC 1)
- "I am concerned the sound will distract driver even more and will be looking for where sound is coming from and possibly hit someone (I think it will cause more harm than good)" (DOT 2)

- “Cost adds up with needing them on several cones, pick and takedown everyday makes it hard”(DOT 3)

8.2.2 Intellicone®

The analysis of participant feedback related to the Intellicone® is summarized in Table 8.4. Consistent with results from Task 4, the cost of the Intellicone® was highlighted as the main factor that could impact the adoption of the Intellicone®. Both groups suggest that the use of the Intellicone® on projects is unlikely given its current cost (mean ratings = 2.0 and 2.17 for the ODOT and contractor personnel, respectively). Likewise, “ease of use” was considered a major benefit when contemplating the use of the Intellicone® on a project.

Table 8.4: Recorded Mean Response and Standard Deviation for Intellicone®

	Evaluation Criteria	Cumulative Mean Rating (n = 9)	Std. Dev.	GC Mean Rating (n = 3)	DOT Mean Rating (n = 6)
1	Ease of use	3.78	1.55	3.67	3.83
2	Effectiveness of triggering mechanism	3.67	0.94	3.67	3.67
3	Effectiveness of alarm	3.67	0.67	3.33	3.83
4	Likeliness of use considering cost	2.11	0.87	2.0	2.17
5	Usefulness of technology	3.33	0.82	3.33	3.33

Participants provided the following comments regarding the use of the Intellicone® on live projects:

- “More useful to paving and moving operation. What ABC is working on tonight” (DOT 4)
- “Much better than the SonoBlaster®. It has a visual and audible alert, relatively straightforward and should grab the attention of workers well. Once again, it is hard to tell the effectiveness without live traffic” (DOT1)
- “Very spendy. Not loud enough for construction environment. Needs more range i.e., 1500 each. Remote unit also needs to flash”(GC 1)
- “If a car enters work zone and doesn't hit the cone with the device, it's useless” (DOT 3)

8.2.3 Worker Alert System (WAS)

The results relating to the WAS technology are captured in Table 8.5. The effectiveness of the WAS was judged to be its strongest attribute with a cumulative rating of 4.00. When analyzed separately by each organization, responses from general contractors indicate that the ease of use and triggering mechanism are the driving attributes for possible adoption of the WAS (mean rating = 3.67 for both criteria). ODOT personnel consider the cost of the WAS as a possible hindrance to adoption (mean rating = 2.50).

Table 8.5: Recorded Mean Response and Standard Deviation for WAS

	Evaluation Criteria	Cumulative Mean Rating (n = 9)	Std. Dev.	GC Mean Rating (n = 3)	DOT Mean Rating (n = 6)
1	Ease of use	3.30	1.33	3.67	3.17
2	Effectiveness of triggering mechanism	3.56	0.68	3.67	3.50
3	Effectiveness of alarm	4.00	0.67	3.33	4.33
4	Likeliness of use considering cost	2.67	1.05	3.00	2.50
5	Usefulness of technology	3.33	0.82	3.33	3.33

Provided below are comments received from the participants regarding the WAS:

- “For individual workers bringing up the rear of work zone. Roller operators, sticky tab installers, sign guys.”(DOT 4)
- “Seems effective. Relatively easy to use, little set up. The most important of all technologies is its effectiveness in traffic. At least from the safety side of the house”(DOT 1)
- “Poor coverage range (remote units and pneumatic tube - unit distance)” (GC 1)
- “I think this is the best of the 3. it will work great on a closure that is stationary” (DOT 3)

8.2.4 Summary

An overview of the feedback received indicates that each intrusion alert technology has individual strengths and limitations based on the five assessment criteria provided. Although cost was identified as a barrier to the adoption of the Intellicone®, Figure 8.2 indicates that among the three technologies, the Intellicone® was considered the easiest to use and also the preferred triggering mechanism, closely followed by the WAS. Intellicone®’s mean rating for each criterion aligned the most with the respondents’ perception of the most important criteria. The SonoBlaster® was preferred in terms of effectiveness of alarm and cost.

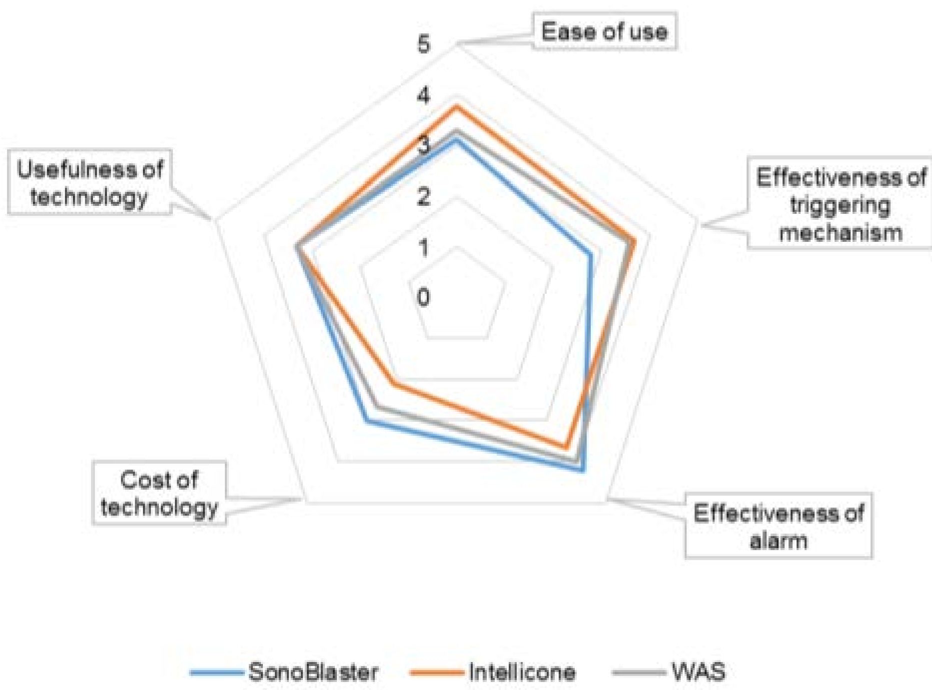

Figure 8.2: Mean Ratings of Evaluation Criteria for SonoBlaster®, Intellicone®, and WAS

8.3 LIVE TESTING ON CASE STUDY PROJECTS

As mentioned previously, data was collected on the three case study projects described in Task 5. Analyses of the data collected from the projects will be presented as follows:

- Equipment noise level evaluation
- Participants' response rate on each project
- Response rate by work role
- Reaction time for each work role
- Impact of location on response rate

8.3.1 Equipment Noise Level Evaluation

In line with the research plan, the researchers observed the construction process, collecting the baseline data on equipment noise level. Following discussions with general contractor and ODOT safety personnel, the study was limited mainly to rolling and paving operations (reasons given in Task 5). Figure 8.3 depicts the ambient sound (regular passing traffic) in a work zone measured approximately 5 feet from the work zone cones (inside work zone). Figure 8.4 shows the measured noise level five feet away from a paver. The sound level trend depicted represents

2.5 minutes of the paving operation. The decline in sound level was due to a combination of the mobile paving operation and the stationary sound recording device. After 151 seconds, the paver was approximately 15 feet away.

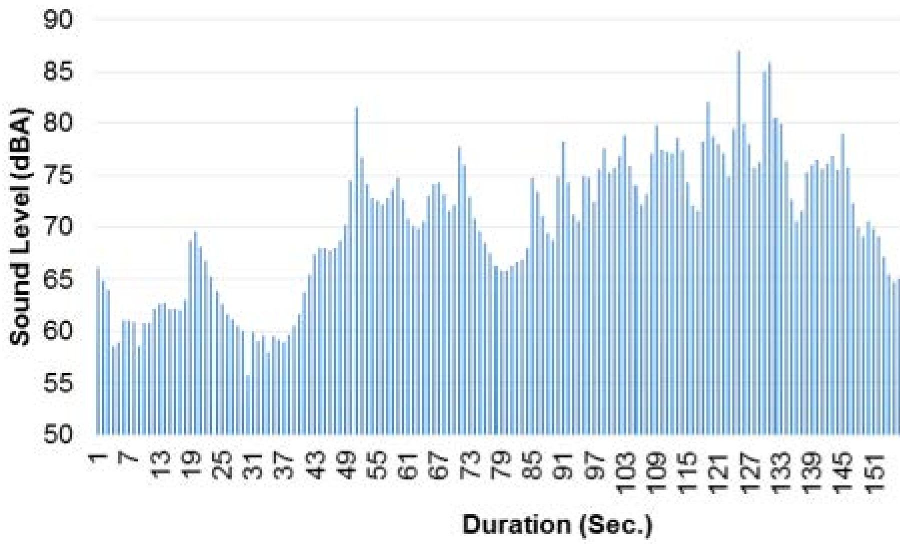

Figure 8.3: Ambient Sound in Work Zone (without Equipment)

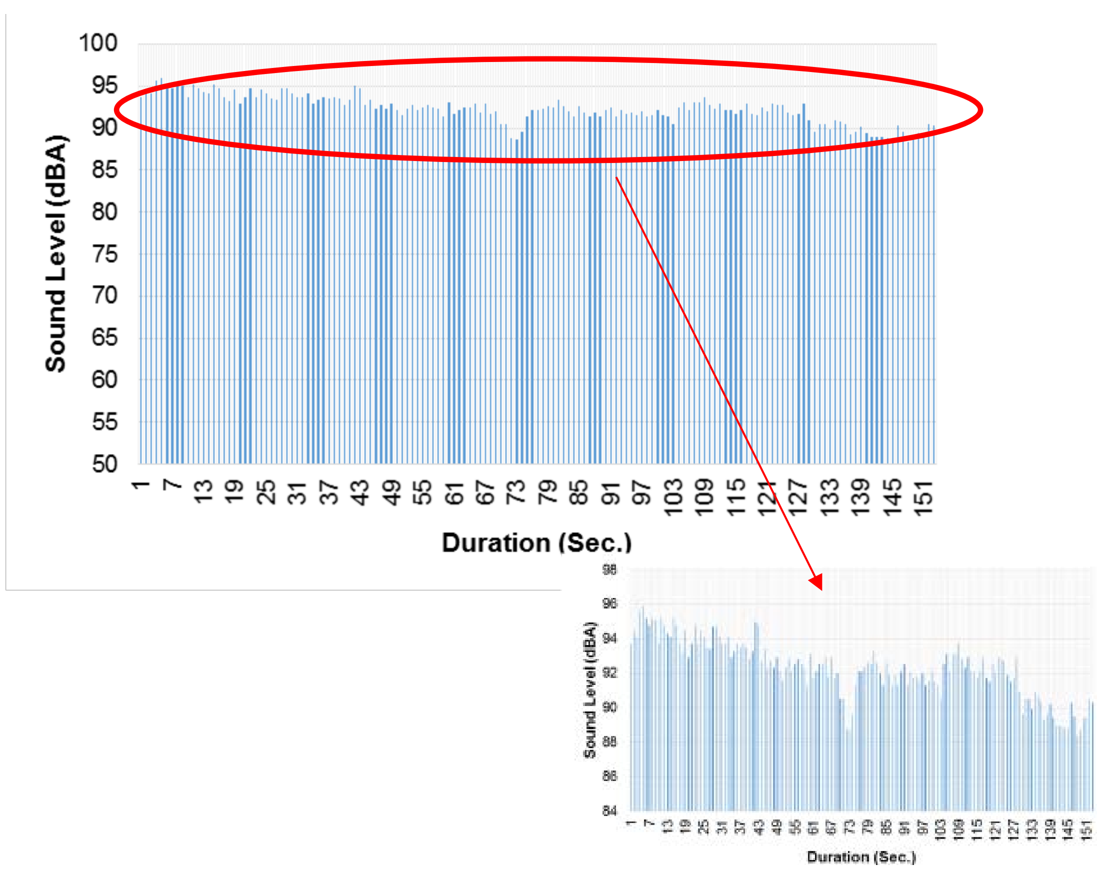

Figure 8.4: Sound Level 5 feet away from a Paver in Work Zone

The sound level within close proximity of the rollers was also measured to provide the baseline data for noise exposure around workers. The observed rolling operation involved three rollers moving at different speeds and patterns. The sound level was recorded using the first roller as a reference. Due to the rolling pattern and the static nature of the data collection process, the sound levels oscillated between 70 and 110 decibels (see Figure 8.5). When the roller was within close proximity, the sound level increased significantly. At every given time during data collection, the primary observed roller was within ±100 feet of the sound meter. As a result of the movement pattern observed, an overlap between two rollers occurred approximately 15 feet away from the sound recorder (note the peak at 106 seconds).

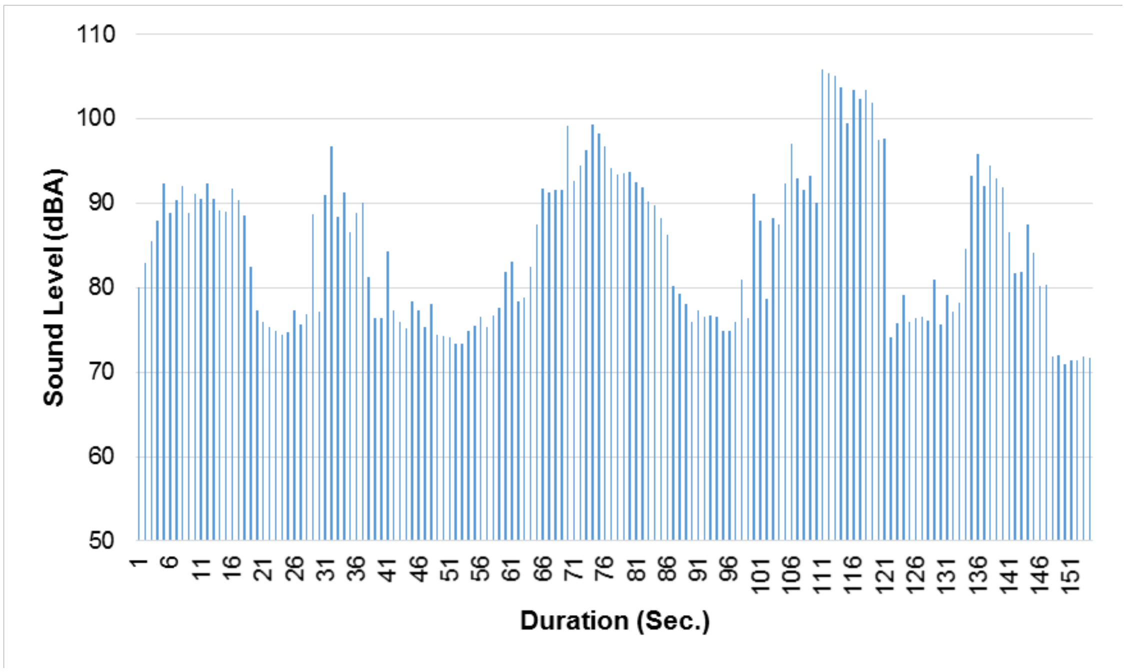

Figure 8.5: Sound Level 5 feet away from Operational Roller

8.3.2 Participant Response Rate

For each case study project, the research team collected data related to the construction crew members that were targeted by each technology. Clickers and video cameras were used as the primary means of collecting data on the participants' response rate. To determine how many participants heard each technology, workers were asked to click the clicker when they hear the alarm sound, feel the vibration of the handheld device, or see the visuals of an alarm. The research team included video coverage of the participants to provide complementary data which reduces the limitations of using clickers for data collection. Specifically, the research team assumed that while working, it may be difficult for a worker to stop and click the clicker. Using the video evidence, the workers' reactions to the intrusion alert were monitored. Data analysis focused primarily on the five workers with relatively high leg-traffic in the work zone and in close proximity to the paver (see Figure 8.6):

- ODOT inspector
- Paver Operator (drives paver)
- Dump Person (dump operator)
- Screed Operator (controls screed levers)
- Screed Worker (works beside the screed operator)

Data received from observing the five workers in each case study project is reported in Section 8.2.2. For the three case study projects, each technology was triggered multiple times at predetermined distances from the paving operation. To maintain consistency and ability to overlap data as a way to improve data quality, the analysis focuses on worker response rates recorded when the technology was triggered 100 feet and 50 feet away from the paving operation.

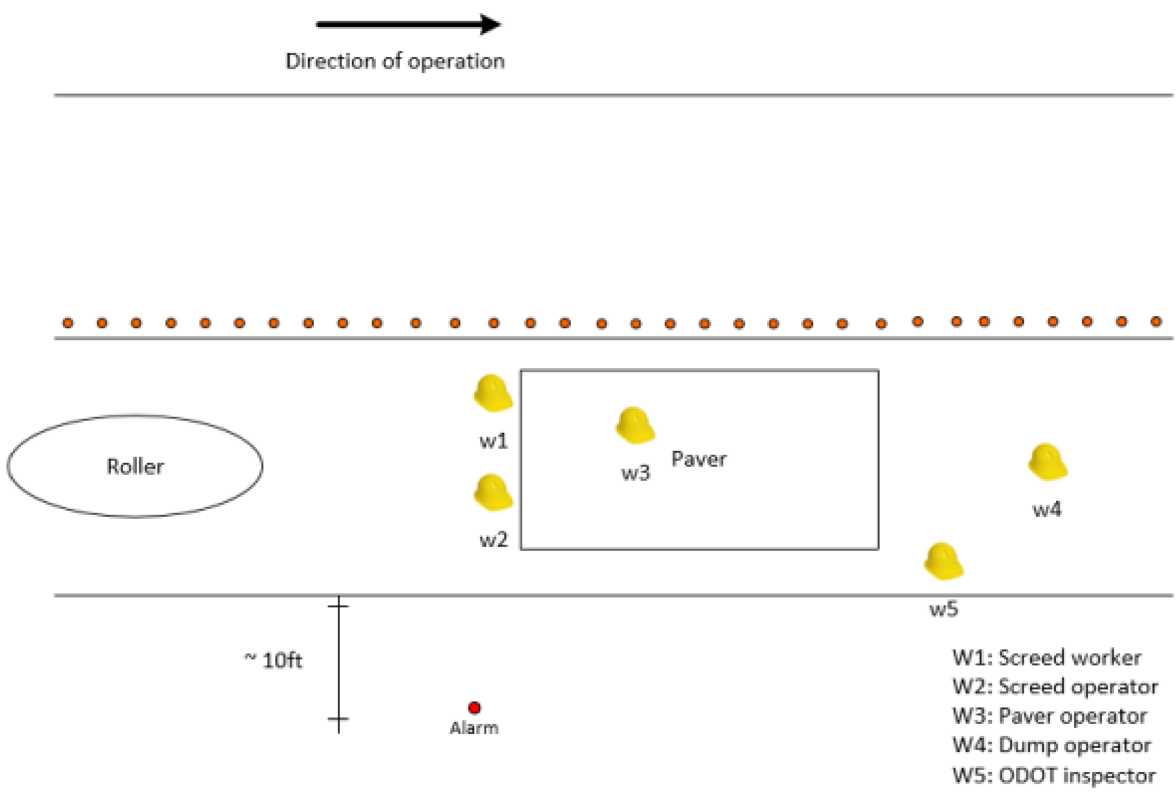

Figure 8.6: Target Worker Locations

Case Study Project #1: US-30 Swedetown Road to Wonderly Road

Over a period of two days, the three intrusion alert technologies were deployed on this project. Results from case study project #1 data analysis indicate that the response rate differs according to the technology and distance from the alarm to the paver. As depicted in Table 8.6, all five participants heard the SonoBlaster® and Intellicone® when triggered 50 and 100 feet away from the paving operation. Against expectations, a direct relationship was observed between distance from the paving operation and participants' response rate when the WAS was triggered. Forty percent of participants (2) responded when the WAS was triggered 50 feet away from the paving operation while four out of five workers heard the alarm when triggered 100 feet away from the paver. Although all participants heard the SonoBlaster® and Intellicone® when triggered 50 and 100 feet away, only the inspector heard the WAS at both 50 and 100 feet.

Table 8.6: Percentage of Workers who Heard, Felt, or Saw the Alarm, Case Study Project #1 (n = 5)

Technology	% of Workers based on Distance from Paving Operation (ft.)	
	50	100
SonoBlaster®	100%	100%
Intellicone®	100%	100%
WAS	40%	80%

Case Study Project #2: I-84 Cascade Locks to Hood River

Similar to case study project #1, data was collected on the Cascade Locks to Hood River project over the period of two nights. Although the Intellicone® led to 20 percent more responses than the WAS, both technologies showed a 20 percent reduction in response rate as the distance between the paving operation and the alert technology increased (see Table 8.7). The response rate for the SonoBlaster® remained constant (at 60%) across both distances. It is important to note that the screed worker was absent during the paving operation, and therefore the analysis conducted was based on four workers, not five. When triggered, the alarm produced by the WAS was not picked up by the paver operator irrespective of distance from the alarm. Although the dump operator heard the alarm produced by the WAS when triggered 50 feet and 100 feet away from the paving operation, the dump operator only heard the Intellicone® when triggered 50 feet from the paving operation.

Table 8.7: Percentage of Workers who Heard, Felt, or Saw the Alarm, Case Study Project #2 (n = 4)

Technology	% of Workers based on Distance from Paving Operation (ft.)	
	50	100
SonoBlaster®	60%	60%
Intellicone®	80%	60%
WAS	60%	40%

Case Study Project #3: I-84 Mosier to The Dalles

Due to project constraints, all three technologies were evaluated in one night on case study project #3. As listed in Table 8.8, the SonoBlaster® resulted in a 100% response rate at 50 feet and 80% at 100 feet, the highest response rate among the three technologies. Following the SonoBlaster®, the WAS led to a response rate of 80 and 40 percent for 50 and 100 feet, respectively. The inspector did not hear the alarm produced by the WAS when the paver was 50 feet and 100 feet away from the alert technology. Conversely, the inspector and screed worker heard the Intellicone® irrespective of the technology's distance from the paving operation. Nevertheless, the Intellicone® seemed ineffective (with the exception of the inspector and screed worker) when placed beyond 50 feet from the paving operation. Similar to the phenomenon observed in case study project #1, the response rate recorded for the Intellicone® showed a direct relationship between distance away from the paving operation and response rate. A 40% response rate was noted when the Intellicone® was triggered 50 feet away from the paving operation and 60% when 100 feet away. The difference was a result of the dump person's response. Prior to the 100 feet mark, the dump person was preoccupied about 60 feet ahead of the paving crew (creating extra separation) and did not hear the alarm when triggered at 50 feet. The recorded response was a result of visual warning, not audio.

Table 8.8: Percentage of Workers who Heard, Felt, or Saw the Alarm, Case Study Project #3 (n = 5)

Technology	**% of Workers based on Distance from Paving Operation (ft.)**	
	50	**100**
SonoBlaster®	100%	80%
Intellicone®	40%	60%
WAS	80%	0%

Cumulative (All Three Case Study Projects Combined)

Table 8.9 combines the results from the three case study projects. The SonoBlaster® recorded the highest response rate when triggered 50 feet and 100 feet away from the paving operation (92% and 85%, respectively). The response rates for the Intellicone® were 80% and 78% for 50 feet and 100 feet, correspondingly. Response rates of 65% and 57% were noted for the WAS. The response rate for the SonoBlaster® is likely a result of its loudness. Figure 8.7 shows the response rates for each of the three case study projects (CP) as well as the cumulative response rate.

Table 8.9: Percent of Workers who heard or saw the Alarm, All Case Study Projects (n = 14)

Technology	**% of Workers based on Distance from Paving Operation (ft.)**	
	50	**100**
SonoBlaster®	92%	85%
Intellicone®	80%	78%
WAS	65%	57%

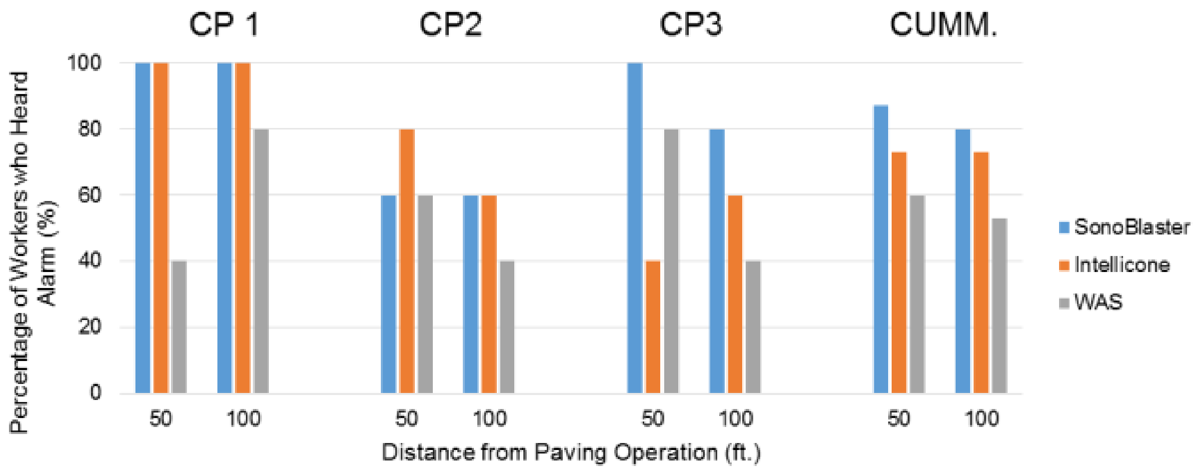

Figure 8.7: Response Rates for Case Study Projects 1, 2, 3, and Cumulative

8.3.3 Response Rate by Work Role

In addition to determining the response rate for each intrusion alert technology, it is paramount to evaluate how workers performing similar tasks responded to each technology across the three case study projects. Section 8.2.3 presents results from analyzing the response rate data, defined by work role.

SonoBlaster®

Table 8.10 depicts the response rate at 50 feet and 100 feet for each worker category. The results from pooling the worker-based data from the three case study projects indicate that only the screed operator had a 100% response rate when the SonoBlaster® was triggered 100 feet away from the paving operation. Both the screed worker and paver operator recorded the lowest response rate when the SonoBlaster® was triggered 50 feet away from the paving operation. The response rates of the dump person and inspector followed a similar trend recording 100% at 50 feet and 67% at 100 feet on average.

Table 8.10: Worker Response Rate for SonoBlaster®, All Case Study Projects (n = 14)

Worker / Location	**Response Rate based on Distance of Paving Operation from SonoBlaster® (ft.)**	
	50	**100**
Dump operator / on ground	100%	67%
Inspector / on ground	100%	67%
Screed Operator / on tailgate	100%	100%
Screed Worker / on tailgate	67%	67%
Paver Operator / on vehicle	67%	67%

Intellicone®

Consistent with the findings when analyzing the worker-based average response rate for the SonoBlaster®, the screed operator averaged 100% response rate when the Intellicone® was triggered 50 feet and 100 feet away from the paving operation (see Tables 8.11). The inspector also averaged 100% response rate for both distances. When triggered 50 feet away, the average response rate of the dump person across the three case study projects was 33%. The average response rate uncharacteristically doubled when the Intellicone® was triggered 100 feet away from the paving operation. The paver operator's average response rate for the Intellicone® was consistent with the recorded response rate for the SonoBlaster®. In comparison to the SonoBlaster®, the average response rate for the screed worker when the Intellicone ®was triggered 50 feet from the paving operation increased from 67% to 100%.

Table 8.11: Worker Response Rate for Intellicone®, All Case Study Projects (n = 14)

Worker / Location	Response Rate based on Distance of Paving Operation from Intellicone® (ft.)	
	50	100
Dump operator / on ground	33%	67%
Inspector / on ground	100%	100%
Screed Operator / on tailgate	100%	100%
Screed Worker / on tailgate	100%	67%
Paver Operator / on vehicle	67%	67%

Worker Alert System (WAS)

The results from consolidating the data from all three case study projects showed that only one work role averaged 100% response rate across the three projects. Although the inspector averaged 100% when the WAS was triggered 50 feet away from the paving operation, no worker had 100% response rate when the WAS was activated 100 feet away from the target operation (see Table 8.12). On average, the dump person response rate was 67% across the three case study projects. Unlike the average response rate recorded for the SonoBlaster® and Intellicone®, the screed operator response rate dropped from 100% (at 50 feet and 100 feet) to 33% (at 50 feet and 100 feet). Surprisingly, the paver operator consistently failed to hear the WAS alarm when triggered 100 feet away from the paving operation. Figure 8.8 shows the response rate for each worker. It is important to note that the distances were estimates using the paver machine screed as reference. In certain cases, workers were not exactly 50 feet and 100 feet from the triggered technology.

Table 8.12: Worker Response Rate for WAS, All Case Study Projects (n = 14)

Worker / Location	Response Rate based on Distance of Paving Operation from WAS (ft.)	
	50	**100**
Dump operator / on ground	67%	67%
Inspector / on ground	100%	33%
Screed Operator / on tailgate	33%	33%
Screed Worker / on tailgate	33%	67%
Paver Operator / on vehicle	67%	0%

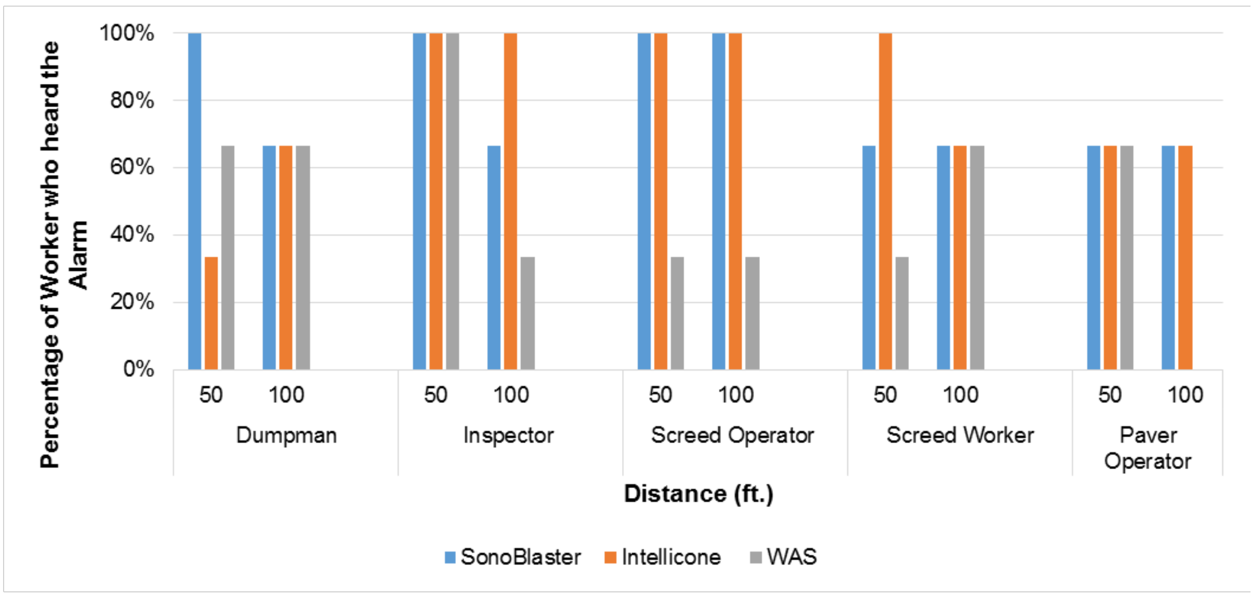

Figure 8.8: Summary Response Rate for each Worker, All Case Study Projects

8.3.4 Reaction Time for each Work Role

Generally speaking, reaction time can be defined as the time it takes for one to react to stimuli (Oxford Dictionary, n.d.). In terms of the current study, reaction time is the time it takes a construction worker to react to an alarm produced by an intrusion alert technology. Estimating reaction time provides a measurement for determining the effectiveness of a system (albeit with limited precision).

Data from case study project #3 was selected to serve as the basis for estimating reaction time because the quality of data collected from the Mosier to The Dalles project (case study project #3) is superior to the other two case study projects. The data from the other two case study projects was not sufficient to provide much confidence in the analysis results.

In order to estimate a reaction time for each intrusion alert technology, the researchers developed a process that includes creating multiple data points. Considering the limitations of relying solely on the primary response source (clickers) for data collection, the researchers opted to include four other pieces of evidence to reduce bias and a skewed assessment. In total, the following five data points were analyzed for each target worker and each technology:

Target worker clicker: First, the data collected via clickers was synchronized with the triggering process. As clickers keep a record of reaction time by default, the research team ensured that data collection sessions overlapped with alarm triggering.

Researcher clicker: Researchers were assigned a clicker and asked to click the clicker whenever they heard (saw) the alarm produced by the alert technologies. Each researcher was assigned to observe one target worker. The researchers were also asked to maintain close proximity (about 5 feet) with the target worker where possible.

Worker within close proximity: Certain target workers worked in close proximity of other workers. In certain cases, the target worker would hear the alarm but choose not to react for various reasons. Inputting the response data of the worker within 5 feet of the target worker provides secondary data that improves the quality of the analysis.

Target worker's reaction on video: The research team recorded the reaction of each worker when the alarm was triggered. For case study project #3, workers were asked to acknowledge hearing or seeing the alarm by raising their hand. Reaction time was calculated by comparing the video time stamp and observed alarm trigger time (in video). In situations where the alarm trigger time was difficult to access through video, the manual recorded start time and clicker time stamp were referenced.

Researcher reaction on video: In certain cases, the researcher might be preoccupied with observing the target worker or obstructed by the ongoing operation. Researchers were asked to indicate (verbally) in the video if they heard the alarm. The approximate time was reversed-engineered using the same process implemented in calculating the target worker's reaction on the video.

Finally, due to the high likelihood of varying numbers and presence of outliers, the research team included a median line to normalize the data. Considering it is almost impossible to determine the exact reaction time using one data point, an approximate reaction time was determined using the median rating of aggregated data points.

Section 8.3.4.1 and 8.3.4.2 provides graphs for each intrusion alert technology for the dump person and inspector. Figures showing the results for other workers can be found in Appendix F.

8.3.4.1 Dump Person (Dump Operator)

Although the researchers were asked to stay within close proximity of the target workers, it was difficult to maintain close proximity with the dump person as a result of his closeness to live traffic in the fast lane and frequent movements to other locations in the area. The varying distance between the dump person and the paving operation and lack of direct line of sight could impact the number of data points recorded and the dump person's ability to hear and see the alarm.

SonoBlaster®

The location of the dump person likely plays a part in the counter-intuitive median line depicted in Figure 8.9. When the SonoBlaster® was triggered based on the relative distance between the paver and the alert technology, the dump person was a considerable distance away from the operation. When the paving operation was 75 feet and 100 feet away from the SonoBlaster®, median reaction times of 2.75 and 3 seconds were estimated, respectively.

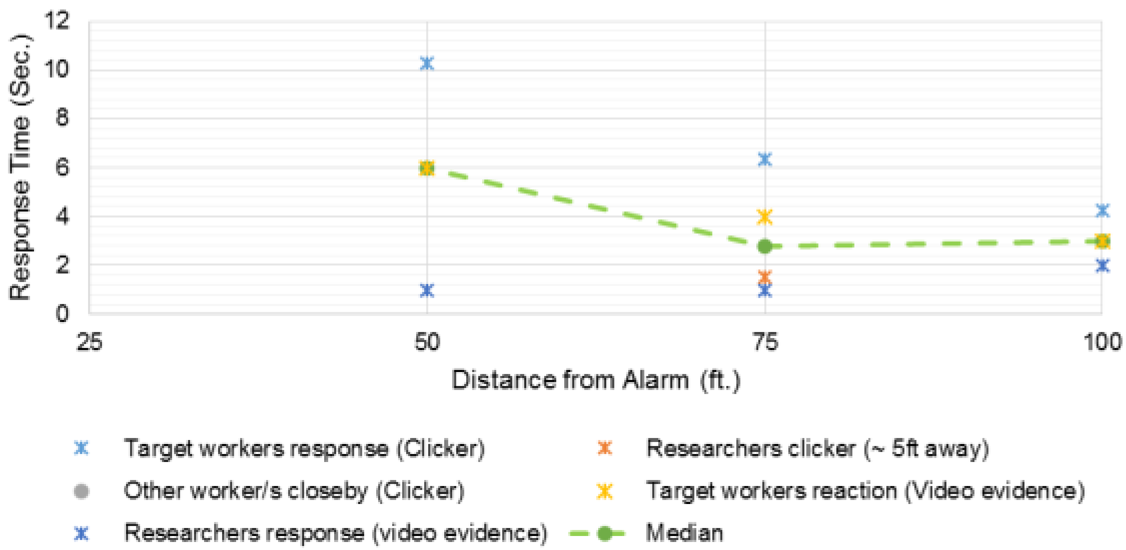

Figure 8.9: Dump person Reaction Time, Case Study Project #3 (SonoBlaster®)

Intellicone®

The Intellicone® was triggered after the paving operation passed by the alert technology. The sound produced by the Intellicone® was drowned out by the rollers which impacted the dump person's ability to hear the alarm. Also, the dump person's line of sight (to the alarm station) was blocked by the paver, rollers, and/or dump trucks when the Intellicone® was triggered. As previously explained in Section 8.2.4, the dump person saw the visual alarm when a truck moved out of his line of sight and then clicked the clicker. Video evidence was used to correct the dump person's reaction time. Since there is no data for 50 feet and 75 feet, a linear line was used to connect the median response of 25 feet to that of 100 feet. It took the dump person less than 2 seconds to react when the Intellicone® was triggered 25 feet away from the paving operation (see Figure 8.10).

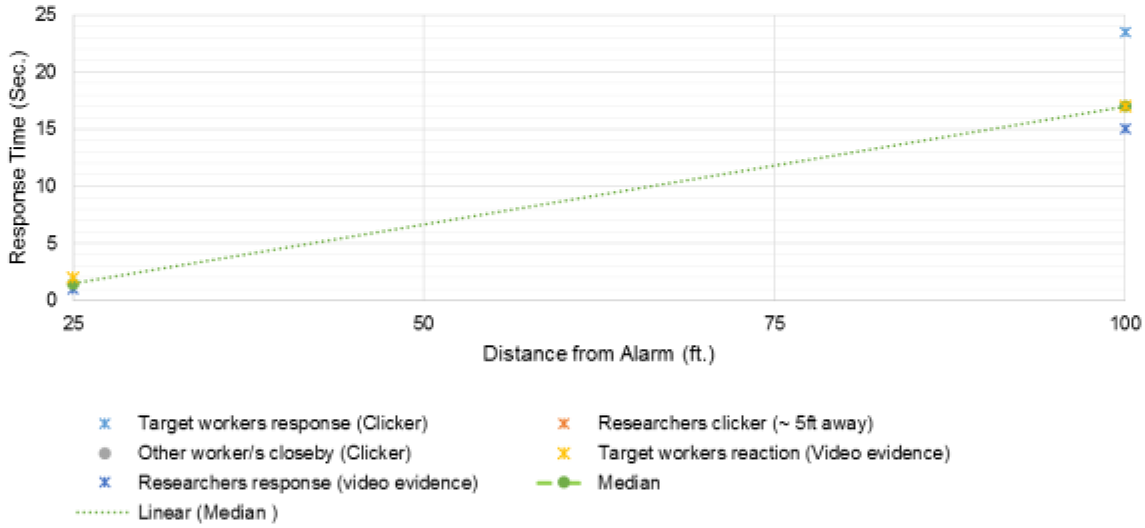

Figure 8.10: Dump person, Case Study Project #3 (Intellicone®)

Worker Alert System (WAS)

As depicted in Figure 8.11, the dump persons' reaction time for the WAS gradually increased as the distance between the WAS and the paving operation increased.

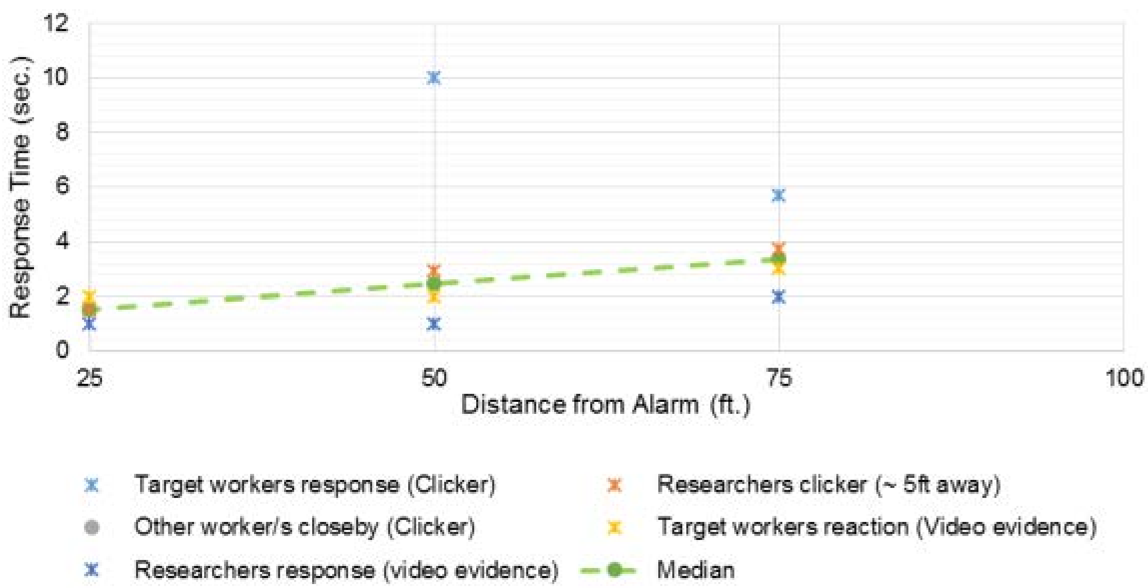

Figure 8.11: Dump person Reaction Time, Case Study Project #3 (WAS)

8.3.4.2 Inspector

SonoBlaster®

When the SonoBlaster® was triggered 50 feet away from the paving operation, the inspector clicked the clicker after 2.55 seconds (see Figure 8.12). Video evidence and the researcher's response show that the inspector heard the alarm once it was triggered (less than 1 second). A similar trend was observed when the alarm was triggered 75 feet away from the paving operation. Evidence from three data points show that the reaction time increased considerably when triggered 100 feet away from the paving operation. The inspector was moving (walking in the work zone) when the alarm was triggered.

Figure 8.12: Inspector's Reaction Time, Case Study Project #3 (SonoBlaster®)

Intellicone®

The inspector responded using the clicker and simultaneously raising his hand within 2 seconds when the Intellicone® was triggered 25 feet away from the paving operation (see Figure 8.13). When triggered at 50 feet, the sound produced by the Intellicone® was muffled by the roller, thereby increasing the reaction time of the inspector. Although the clicker recorded a reaction time of 12 seconds, video evidence showed that the inspector reacted 6 seconds after the alarm was triggered. The reaction times recorded at 75 feet and 100 feet from the paving operation were not true representations of response versus distance since the inspector was standing very close to the Intellicone® alarm and not next to the paver.

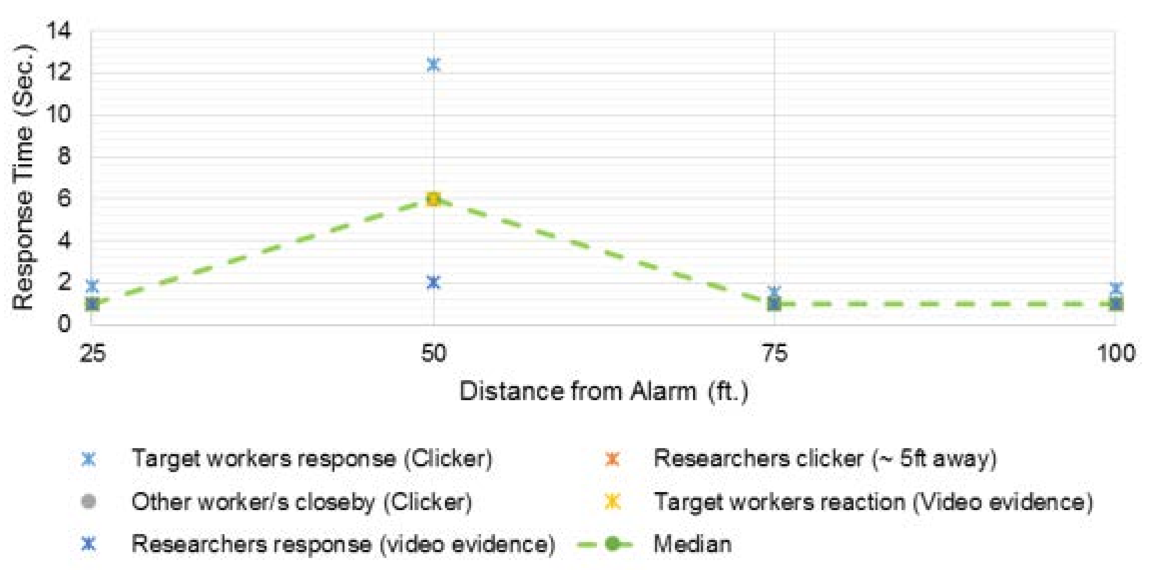

Figure 8.13: Inspector's Reaction Time, Case Study Project #3 (Intellicone®)

Worker Alert System (WAS)

Figure 8.14 shows that the inspector heard the WAS alarm only once. Based on clicker information, it took the inspector 6 seconds to react to the warning produced by the WAS. Video evidence showed that the inspector actually heard the alarm within a second of it being triggered.

Figure 8.14: Inspector's Reaction Time, Case Study Project #3 (WAS)

8.3.5 Impact of Location on Response Rate (In Front of vs. Behind Paver)

Several factors impact the ability of an intrusion alert technology to effectively transmit its alarm to the target audience. Given the workers' exposure to different ambient and construction equipment noise levels, it is important to determine the optimal location for an intrusion alert technology in a work zone when used for a mobile operation. One way to determine the ideal location for an intrusion alert technology is to verify how the alarm location relative to the mobile equipment impacts response rate.

Intellicone®

The Intellicone® was selected as the most liked technology to assess the impact of the paver's location based on the response rate because it was triggered more often than the other two technologies in the research study. Figure 8.15 shows the response rate relative to the distance of the Intellicone® from the paver. When triggered 50 feet before (downstream of) the paver, 80% of the 14 participants heard the alarm compared to 40% when the Intellicone® was triggered behind (upstream of) the paver. One reason for the reduced response rate is the close proximity of the rolling operation to the paving operation. In addition, the difference in response rate could be attributed to the location of the visual and audio alert produced by the Intellicone® since most workers face the direction of the paving operation. As seen in Figure 8.15 the rollers produce a considerable level of sound which easily drowns out the sound of the Intellicone® alarm. Surprisingly, when the Intellicone® was triggered 100 feet behind the paver (upstream), the response rate increased by 50% over the response rate when it was triggered before the paver (downstream). Although this data suggest that placing the Intellicone® before (downstream of) the paving crew is more beneficial, it is important to verify this finding through multiple case study analyses.

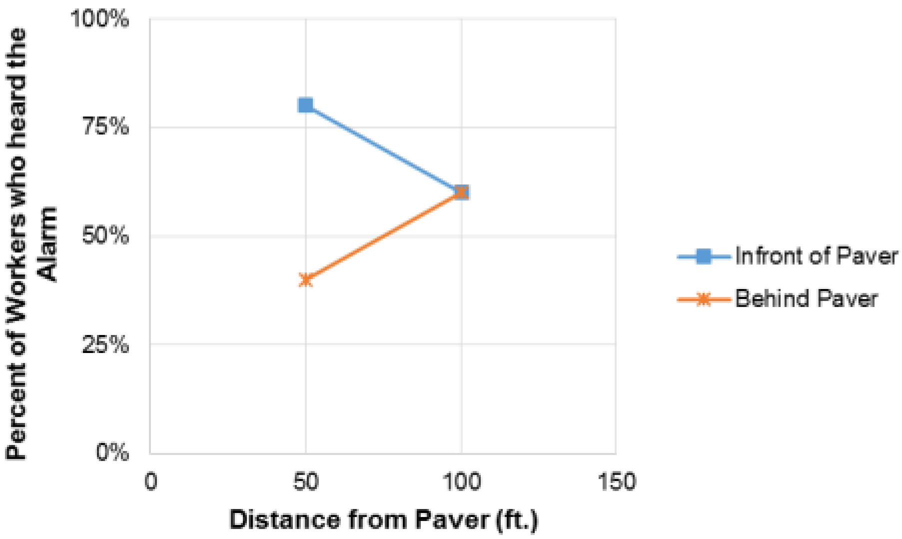

Figure 8.15: Response Rates when Intellicone® is triggered in Front (Downstream) of and Behind (Upstream of) the Paver (n = 14)

8.4 POST-LIVE TESTING SURVEY

Following completion of live testing on the case study projects, participants were asked to provide feedback on each intrusion alert technology. Section 8.4 presents the feedback received from the five (four members of paving crew and one inspector) participants on a project level and from a technology perspective. The exit-survey focused on the following two questions:

- Was the alarm produced by the technology loud?
- Was the alarm produced by the technology distinct?

Using the four response options provided below, the questions above were answered after each technology was activated.

0 = Did not hear/see anything

1 = Not distinct/loud

2 = Somewhat distinct/loud

3 = Distinct/loud

8.4.1 Project Level

For each case study project, three graphs representing the participants' responses for the intrusion alert technologies are presented. A summary of the participants' comments regarding each technology is also documented for each project.

8.4.1.1 Case Study Project #1

Results from feedback provided by the four members of the paving crew and the project inspector indicate that two workers consider the alarm produced by the SonoBlaster® to be somewhat distinct and loud, while two and three participants do not consider the alarm distinct and loud, respectively (see Figure 8.16). Figures 8.17 and 8.18 summarize the participants' perception on loudness and distinctiveness for the Intellicone® and WAS, respectively.

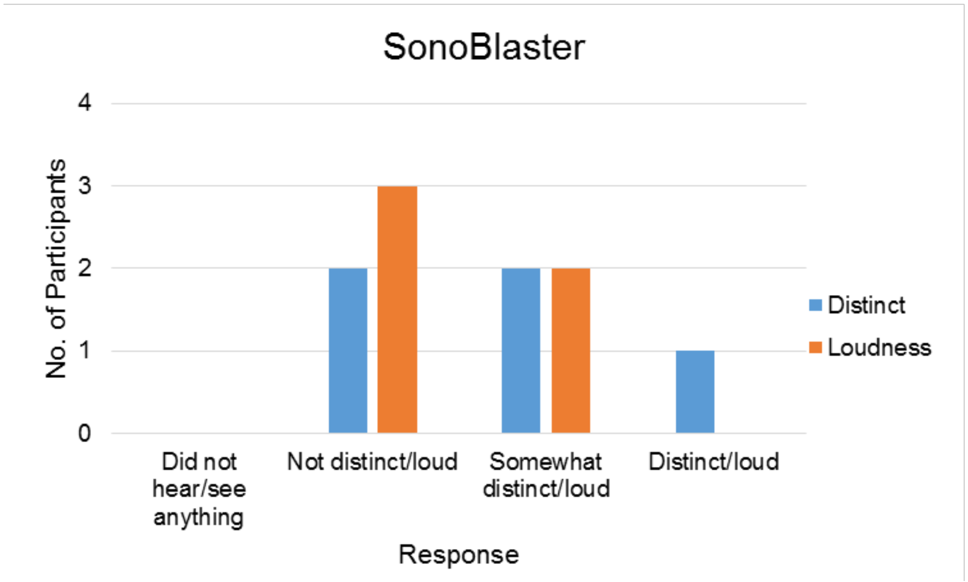

Figure 8.16: Combined Paving Crew and Inspector Perception of SonoBlaster® Distinctiveness and Loudness (Case Study Project #1)

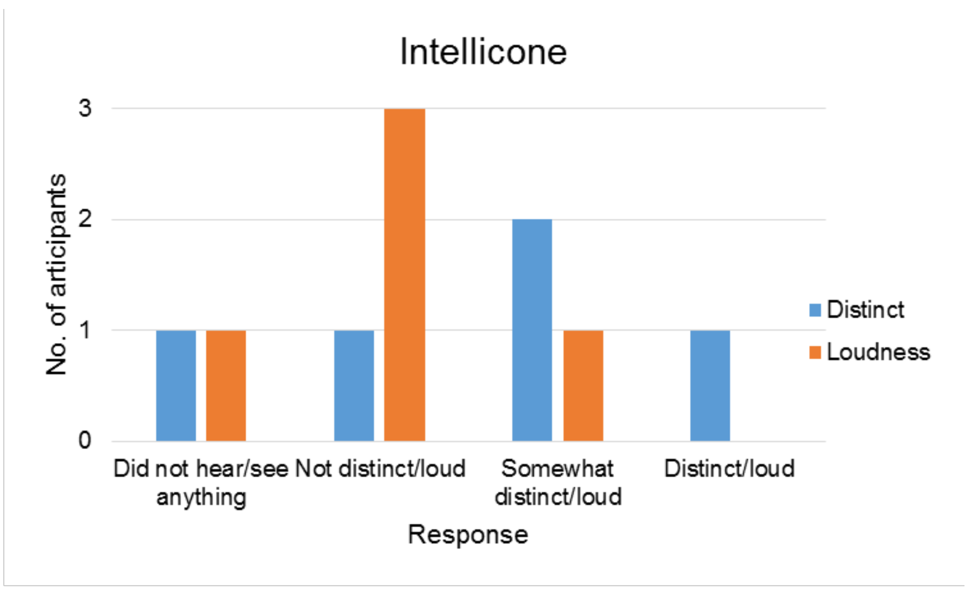

Figure 8.17: Combined Paving Crew and Inspector Perception of Intellicone® Distinctiveness and Loudness (Case Study Project #1)

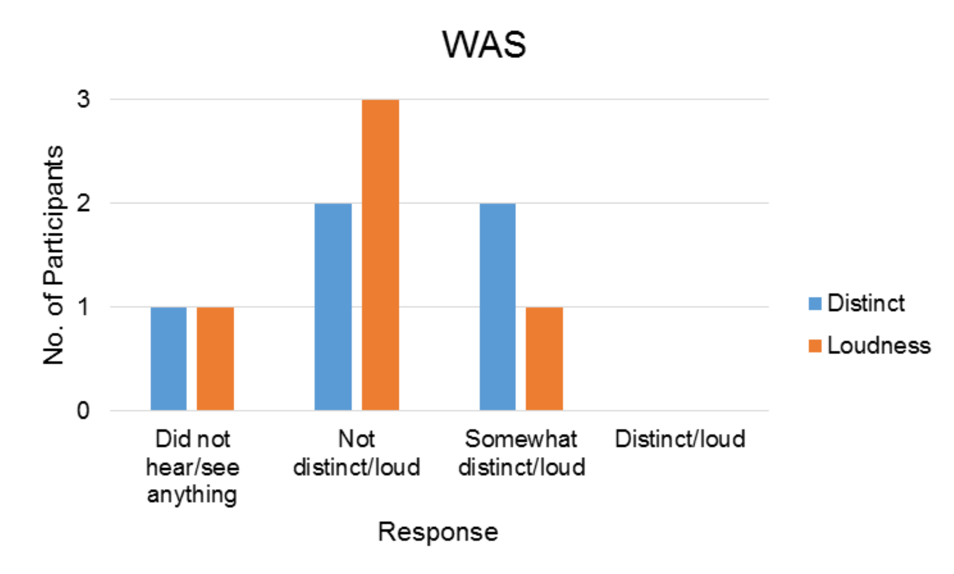

Figure 8.18: Paving Crew and Inspector Perception of WAS Distinctiveness and Loudness (Case Study Project #1)

The following comments regarding each alert technology were provided by the inspector, paving crew members, and roller operator:

Inspector:

- "The sound of the Intellicone® was somewhat distinct but wasn't always loud enough, especially when I am further away. The oscillating visual helps."
- "SonoBlaster® was loud and stood out within close proximity."
- The inspector heard the WAS alarm but not at 150ft (he was always relatively closer to the alarm compared to the paving operation).

Paving Crew:

- "Heard the Intellicone® but thought it was the roller. Clicked anyway."
- "I heard the SonoBlaster® clearly a couple times."
- "I thought I heard something (WAS) at 100 feet before the alarm station. Clicked anyways."
- At 150 feet prior to the alarm station, workers around the paver said they did not hear the WAS alarm.
- At 50 feet before the alarm location, some workers clearly heard the WAS alarm.

Roller operator:

- “The Intellicone® was visually effective but the sound level was only effective when within close range. The red oscillating light stood out.”
- The roller operators did not hear the SonoBlaster®.
- All three roller drivers did not hear or see the visuals produced by the WAS.
- “The Intellicone® caught my attention three times (combination of visual and audio) but was too busy to click the clicker.”
- “I heard/saw the alarm twice especially when right next to the alarm.”
- It was recommended that a notification device (e.g., visual alarm) installed inside the roller would be helpful.

Based on the feedback received from the participants, the paving operation crew preferred the SonoBlaster® due to its loudness. The visual display of the Intellicone® was useful especially when the workers had earplugs on or were at a considerable distance away from the alarm. A notification device that could be installed in the rollers was recommended.

8.4.1.2 Case Study Project #2

Figures 8.19, 8.20, and 8.21 show the workers’ perceptions regarding intrusion alert technology alarm effectiveness. Three out of five participants were of the opinion that the Intellicone® was not loud enough. Two participants indicated that the alarm produced by the Intellicone® was distinct (see Figure 8.20).

Figure 8.19: Paving Crew and Inspector Perception of SonoBlaster® Distinctiveness and Loudness (Case Study Project #2)

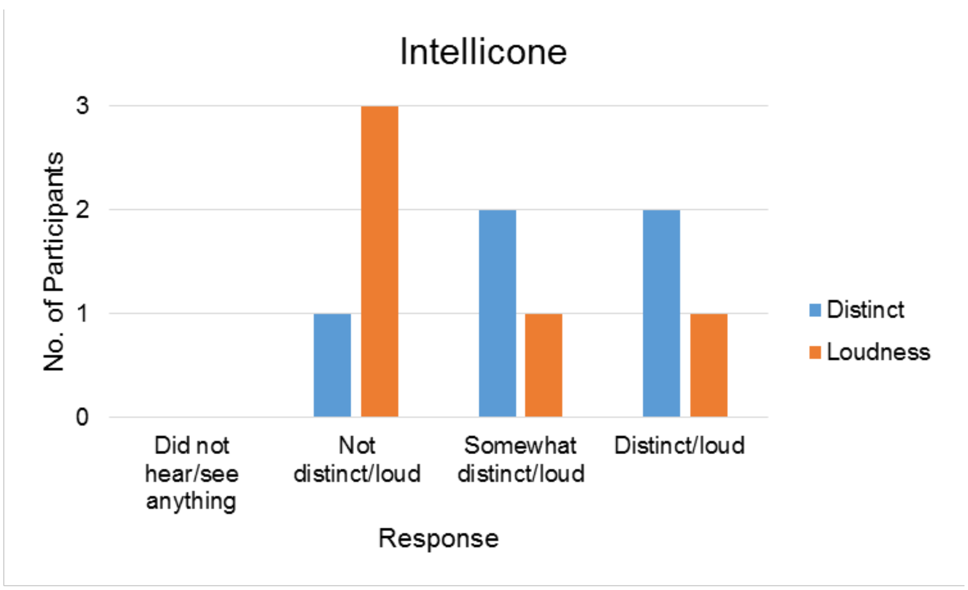

Figure 8.20: Paving Crew and Inspector Perception of Intellicone® Distinctiveness and Loudness (Case Study Project #2)

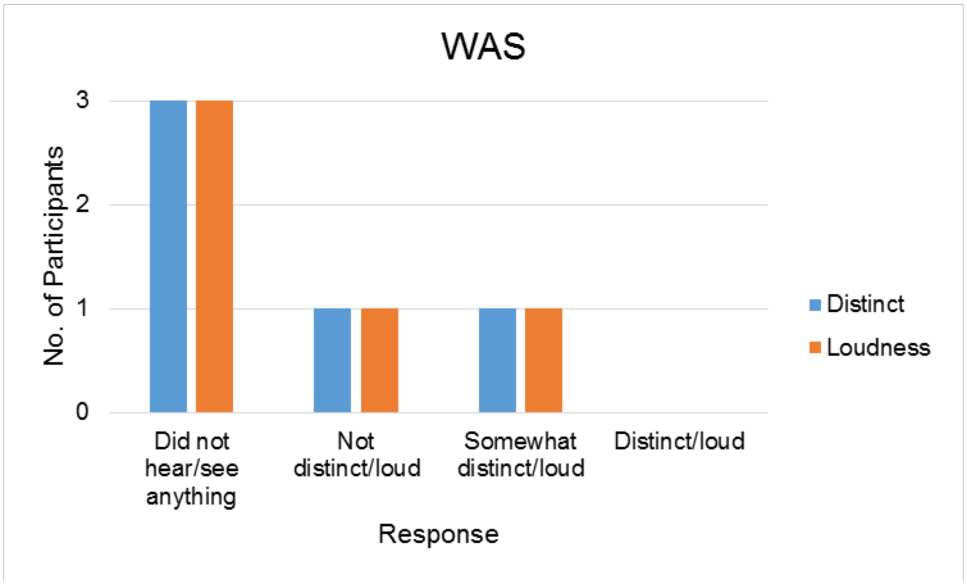

Figure 8.21: Paving Crew and Inspector Perception of WAS Distinctiveness and Loudness (Case Study Project #2)

The following comments regarding each alert technology were provided by the inspector, paving crew members, and roller operator:

Inspector:

- “The SonoBlaster® was loud at a distance of 50 feet away. When 100 feet away, the sound produced by the SonoBlaster® was audible but difficult to differentiate from equipment and ambient sound.”
- “At 100 feet away, I saw the oscillating light but didn’t hear the sounds clearly. At 50 feet, both the sound and visual alarm were effective.”
- The inspector felt that the WAS was not effective over 100 feet away.

Paving Crew:

- Workers heard the Intellicone® only when within 50 feet. The oscillating visual alarm helped when they could see it in front of them.
- Most workers around the paver heard the WAS alarm twice (100 feet and 50 feet) as the paver approached the alarm.
- One worker indicated that he had hearing difficulty due to constant exposure to the high level of noise from the paver (he always works on the paver).
- “I heard the WAS once but it was not distinct.”

Roller operator:

- The compacting crew (rollers) could not hear the sound produced by the SonoBlaster® (first, second, and third roller operators).
- "I never heard anything!"
- "I did not hear the audio alarm or see the visual alarm produced by WAS."
- "I had my earplugs on so I could barely hear any sound, but I saw the oscillating visual alarm."

Responses received from the participants in case study project #2 indicate that the alarm produced by the WAS was not effective when the distance to the alarm was more than 50 feet. Consistent with case study project #1, oscillating lights produced by the Intellicone® provide an effective warning alarm for the workers.

8.4.1.3 Case Study Project #3

Feedback received from the participants indicates that four out of five workers consider the alarm produced by the SonoBlaster® to be both loud and distinct. All respondents are of the opinion that the SonoBlaster® is at least "somewhat distinct/loud" (see Figure 8.22). Only one respondent considered the alarm produced by the Intellicone® as distinct (see Figure 8.23). Figure 8.24 summarizes the participants' perception on loudness and distinctiveness for the WAS.

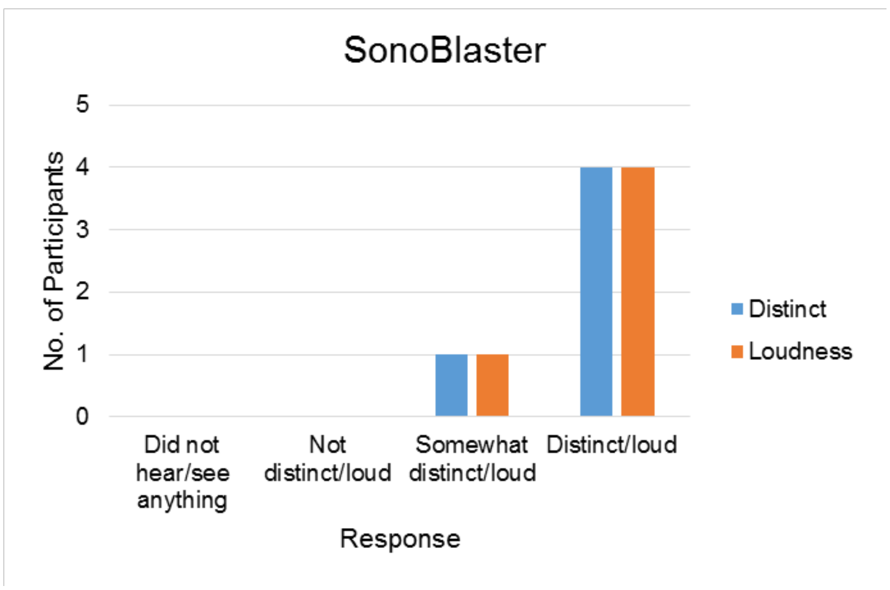

Figure 8.22: Paving Crew and Inspector Perception of SonoBlaster® Distinctiveness and Loudness (Case Study Project #3)

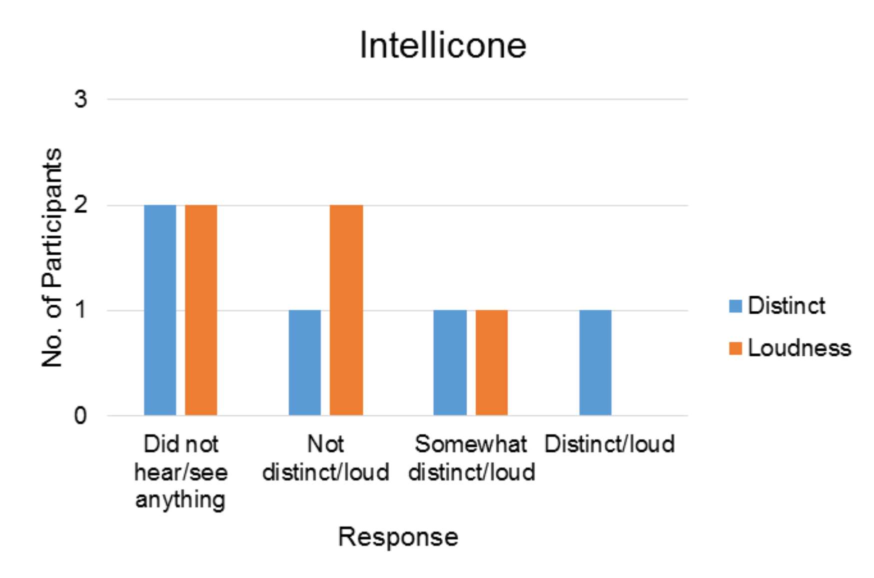

Figure 8.23: Paving Crew and Inspector Perception of Intellicone® Distinctiveness and Loudness (Case Study Project #3)

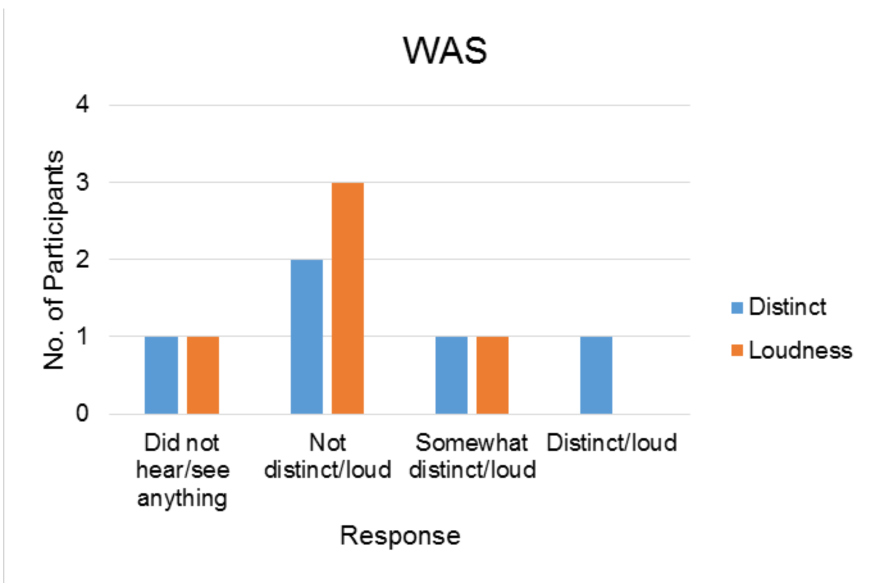

Figure 8.24: Paving Crew and Inspector Perception of WAS Distinctiveness and Loudness (Case Study Project #3

The following comments regarding each alert technology were provided by the inspector, paving crew members, and roller operator:

Inspector:

- "The visual alarm and the sound of the Intellicone® are distinct although the sound could be muffled by the rollers. Sound should be louder."
- "The SonoBlaster® is loud."
- "The WAS was not so loud if you are some paces away. The visual rarely caught my attention."

Paving Crew:

- "The WAS should be made to be louder. He wasn't sure if he heard the WAS or some other sound."
- Found it difficult to hear the Intellicone®. Since the Intellicone® was triggered behind the paving operation, he couldn't observe the visual alarm.
- "The SonoBlaster® seems to be the most effective. Loud and catchy".
- One worker reported having hearing problems which could impact his assessment of the technologies. Overall, he didn't hear the WAS. The Intellicone® wasn't very loud but could be heard (and the visual alarm definitely helps). "The SonoBlaster® was loud!"
- "The WAS was loud within close proximity. It was a little difficult to differentiate the WAS from other sounds."
- "Sound produced by the Intellicone® was easily drowned out by the rollers. The Intellicone® was only effective 50 feet before the paver. The sound will be more effective when placed before or beside the paver".
- "I saw the Intellicone® visual alarm once but did not hear the alarm." (Worker100 feet away).
- In total, one worker only heard two sounds – the SonoBlaster® and WAS – of which he prefers the SonoBlaster®
- "The SonoBlaster® is more distinct. It would be great to have a vibrating device attached to my body since the visual and sound alarms could be blocked by line of sight."
- "The sound level on all the devices should be increased to ensure folks a little farther away can be alerted of an intrusion."

According to participants' comments, the SonoBlaster® was the preferred choice in terms of loudness and distinction. The alarm produced by the Intellicone® was drowned out by the rollers due to the closeness between both operations. The workers' line of sight was also impacted by the rollers, making it more difficult to see the visual alarm produced by the Intellicone® and WAS.

8.4.1.4 All Case Study Projects Combined

To gain a comprehensive overview of worker perception as it concerns the loudness and distinction of each intrusion alert technology, responses received from the three case study projects were combined. Figure 8.25 shows the workers' cumulative response for the Intellicone®. Figures for the SonoBlaster® and WAS can be found in Appendix B. On average, the participants were of the opinion that the alarm produced by the Intellicone® was somewhat distinct but not very loud (see Figure 8.25).

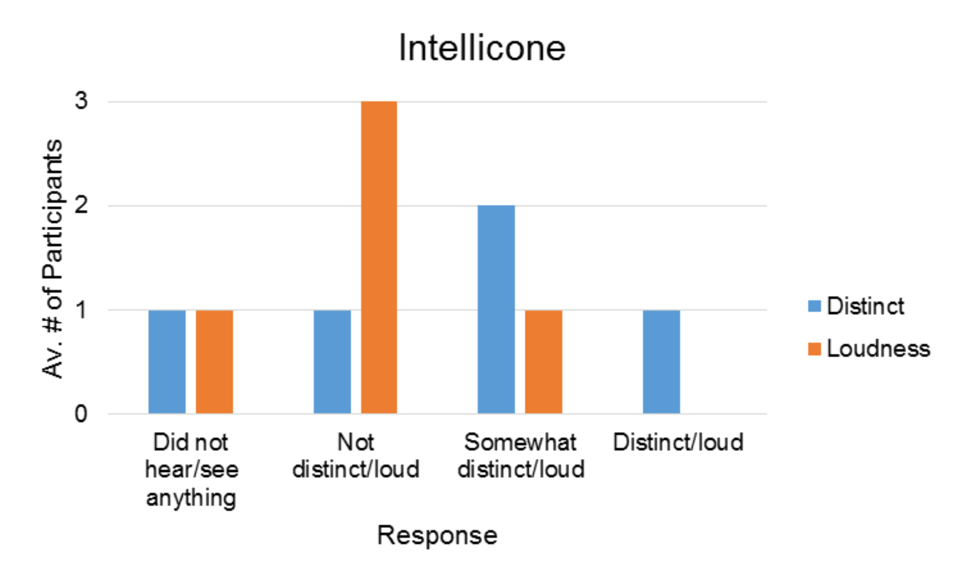

Figure 8.25: Perception of Intellicone® Distinctiveness and Loudness, All Case Study Projects (n=14)

8.5 SUMMARY OF LIVE TESTING

The results from the three case study projects indicate that although the three technologies evaluated had an impact on workers, the level of effectiveness varied. Feedback received from the ODOT and contractor personnel who took part in a pre-live testing evaluation indicate that the effectiveness of the alarm produced by the intrusion alert technology was the most important criteria followed by the effectiveness of the triggering mechanism.

The evaluations conducted on the case study projects revealed that across all three projects, no technology consistently recorded a 100% response rate when triggered 50 feet and 100 feet away from workers. The SonoBlaster® elicited the highest response rate (92% at 50 feet and 85 at 100 feet). In terms of work-role based response rate, the inspector recorded 100% response rate for each case study project when each technology was triggered 50 feet away. No work role recorded 100% response rate for each case study project when the three alert technologies were triggered 100 feet away from the worker’s location.

In terms of reaction time, multiple data points were used to estimate how long it took workers to react to the alert produced by the technologies. Using a median estimate, the researchers discovered that in most cases, the reaction time increases as the distance between the workers and the intrusion alert technologies increases. In addition, positioning the intrusion alarm technology upstream of the operation could have more impact on workers.

Finally results from the post-live testing survey indicate that participants consider the alert produced by the Intellicone® and SonoBlaster® somewhat distinct.

It should be noted that the effectiveness of audio alarms is dependent on the hearing abilities of the workers. Some workers may have hearing loss, while others may be wearing earmuffs or ear plugs for hearing protection. These impacts should be taken into consideration when considering the test results and also when selecting and implementing intrusion alert technologies in practice.

The overall finding from the live testing indicates that although intrusion alert technologies have the potential to improve workers safety, providing recommended minimum specifications could significantly improve the usefulness of the technologies in practice.

9.0 SPECIFICATION FOR FUTURE PRODUCTS

The intrusion alert technologies tested in the present study showed some potential for enhancing work zone safety, yet revealed noticeable limitations. Using qualitative and quantitative data collected as part of the study, this chapter is intended to provide a guideline and recommendations that ODOT can use when specifying the use of intrusion alert technologies on projects and manufacturers can use for the development of their future intrusion alert technologies.

9.1 SOUND LEVEL

Data collected by the researchers indicated that, based on the level of exposure to live traffic, workers who are on foot and located around the paving and rolling operation appear to be the most susceptible to intrusions in the work zone. The study results also found that when the roller approaches the paver, the noise to which the screed operator and any worker within close proximity are exposed is found to increase significantly, as represented in Figure 9.1.

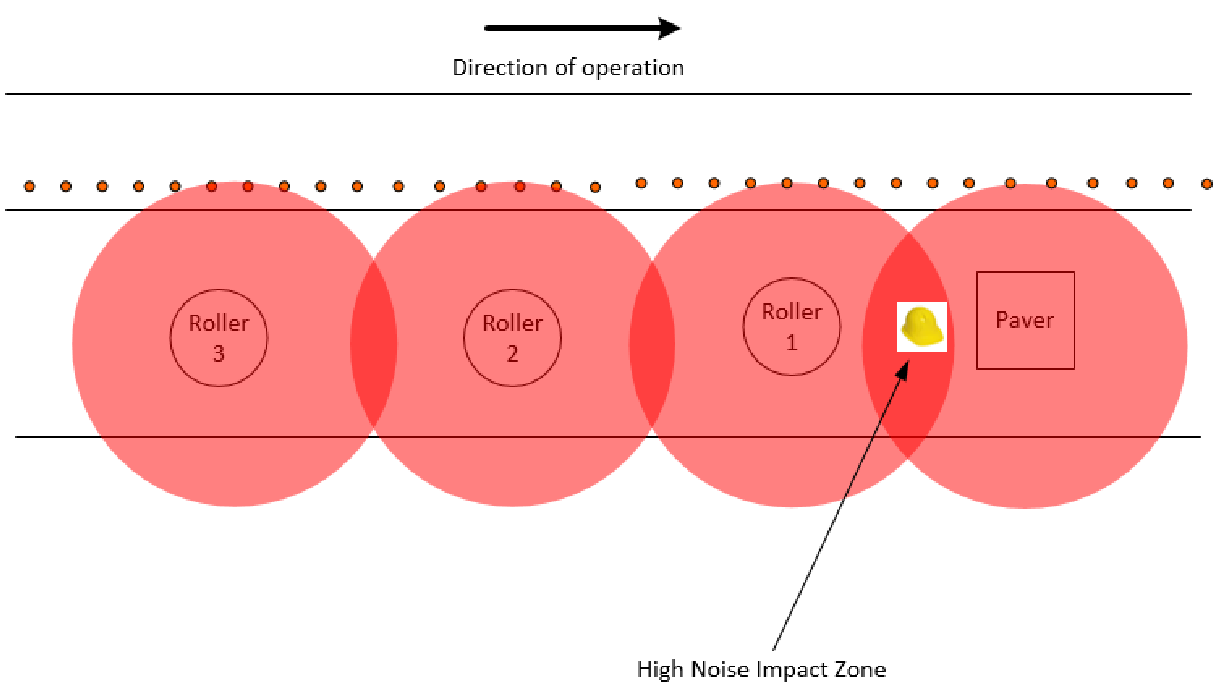

Figure 9.1: Equipment Noise Level Impact on Worker

Based on the quantitative data collected and analyzed, the research team recommends that the sound alarm produced by the work zone intrusion alert technology should be at least 110 dB when the alarm is located 50 feet away from workers, and above 95 dB when the alarm is 100 feet away. Types of sounds, such as a screeching noise or that emitted by an emergency vehicle siren, that differ from the noises heard during the operation (e.g., diesel engine noise from equipment, backup alarm on truck, passing cars) are preferred to improve sound distinction. In addition, short-burst alarms should be avoided if possible. Alarms that provide longer, continuous sound improve the potential/possibility of capturing the workers' attention.

9.2 TRANSMISSION DISTANCE

Expected vehicle travel speed and time required for a worker to dodge the intrusion are key factors when determining the amount of adequate transmission distance. Figure 9.2 shows the transmission distance relative to the speed of a vehicle for different values of "Time to Impact". Time to impact represents the amount of time between the initial triggering of the alarm and the impact of the intruding vehicle on an object. For example, as shown in Figure 9.2, if a vehicle is travelling at 45 mph and the transmission distance is 400 feet, the time to impact (i.e., the allowable reaction time) is 6 seconds. Keeping vehicle speed constant, time to impact increases as the transmission distance increases.

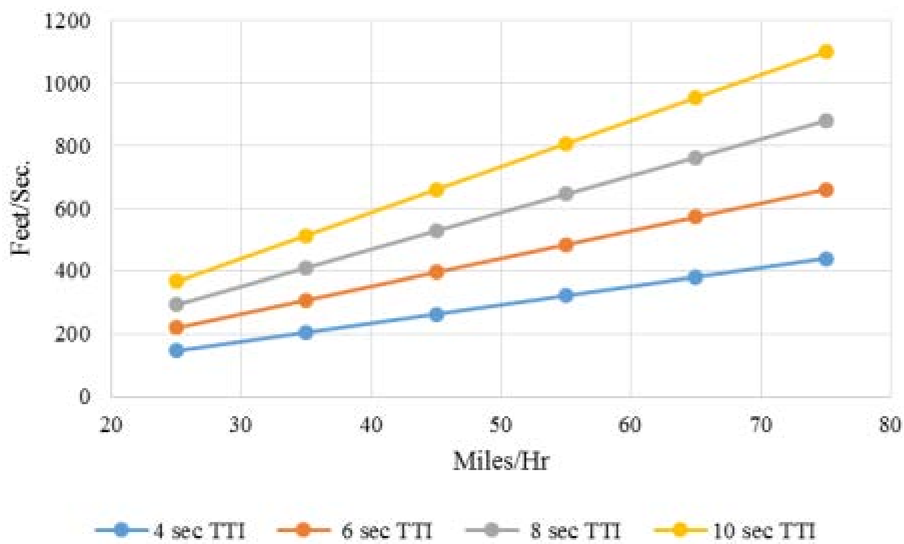

Figure 9.2: Travel Speed and Distance travelled for Different values of "Time to Impact" (TTI = Time to Impact)

The distance a worker can travel on foot to escape an intruding vehicle is also of concern. A vehicle traveling at 65 mph covers 572 feet in 6 seconds. In 6 seconds, it can be calculated that an average individual could cover approximately 72 feet, equivalent of six highway lanes (see Figure 9.3).

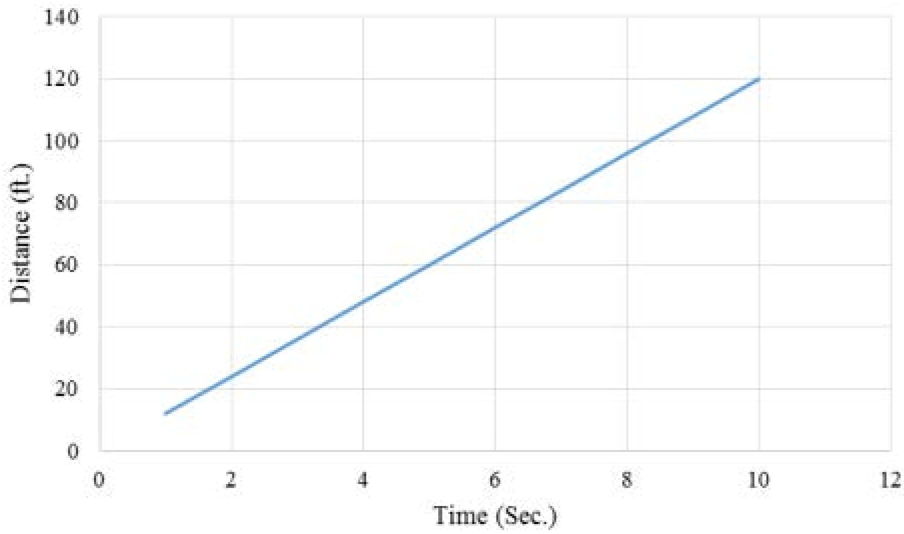

Figure 9.3: Time taken by Worker to Cover Specific Distance

Given the distances between workers within the work zone and the need to provide adequate warning to as many workers as possible, the minimum transmission distance should be 400 feet when the work zone speed is 35 mph (85th percentile). This recommendation is based on the provision of a 6-second reaction time for a worker who is 100 feet behind (or in front of) the paving operation. The transmission distance requirement should increase for work zones with historically higher vehicle travel speed, higher maximum work zone speed limit, and greater expected distances between workers. Nevertheless, it is important to note that regardless of the transmission distance provided by the intrusion alert technologies, if a vehicle breaches the work zone within close proximity to workers, there will be little to no time to react. Placement location of the alert technology relative to the work operation should be considered as well.

In addition, based on findings from the focus groups and live testing, the transmission range for the personal safety device (PSD) should equal the transmission range of the sound alarm to improve effectiveness.

9.3 HAPTIC ALARMS

The study results indicate a consensus that the inclusion of a haptic feature with the alarm technology is beneficial to warn workers of an impending hazard. Providing haptic feedback to workers offers an additional type of warning thereby overcoming the issues related to a masked alarm sound due to heavy equipment noise or blocked line of sight resulting from vehicle movement. Regardless, the interviews highlighted that the haptic device should be mobile, portable, and distinctive from gadgets they currently use (e.g., cell phones). In addition, the battery reliability was pointed out as a possible drawback from the perspective of general contractors. Having to check for battery status and change batteries adds another burdensome task to workers. Developing a system that does not require frequent battery changes would help improve the acceptance and use of the haptic alarm feature.

The interviews also indicated that workers would prefer to have the haptic alarm around their arm or on their hard hat. Therefore, future development of intrusion alert technologies should consider making the haptic alarm wearable on either the worker's arm or on their hard hat. Future development should also avoid a pocket-based haptic design when possible.

Based on haptic systems used in the communication industry, the researchers suggest a patterned vibratory signal that lasts for approximately 14 seconds and creates a vibration frequency of 150 Hz and 9.18m/s2 acceleration (FCC 2008; Hoggan et al. 2009; and Harkins et al. 2010).

9.4 VISUAL ALARMS

Study results indicate that visual alarms tend to be an extremely important part of work zone intrusion alert technologies. On several occasions during live testing, participants highlighted the effectiveness of the visual alarm. In situations where the roller operators could not hear the sound alarm, some were alerted via visual signals. Therefore, future work zone intrusion alert technologies should be equipped with visual warning alerts in addition to sound. Although no minimum "demand" luminance requirement for traffic control devices exists (Datta et al. 2010), the present study recommends the light produced by the intrusion alert should be visible 500 feet away (Alaska 2017; OregonLaw 2015; Wisconsin, n.d.). A quantitative minimum candle effective luminance measurement requirement is not suggested by the researchers at this time due to the absence of applicable standards and the impracticality of measuring oscillating light sources.

Results from the present study suggest that visual alarms complement the audio warning. In certain cases where the audio alert is drowned out by operation noise or workers are uncertain about the sound (i.e., not sure if the sound heard was a warning), the visual alarm helps to confirm an impending hazard. For instance, the roller operators noticed only the visual alarms due to the equipment noise produced by the rollers. To increase the effectiveness, future technologies should consider providing an alert device inside the cabs of rollers and other equipment. The visual alarm produced by the device can help warn the operators of an impending hazard.

Lastly, the interviews indicate that in certain situations, the light produced by the intrusion alert system could be mistaken for "one of the work zone equipment lights". Therefore, oscillating and strobe-like visuals are strongly suggested for future technologies.

9.5 MOBILITY

Based on the evaluated impact of distances between the alarm unit and target operation on the response rate and reaction time of workers, it is recommended that the alarm unit be kept as close as possible to the crew members who are the most exposed to life traffic. In addition to reducing the distance between the work crew and alarm unit, placing the alarm unit on a mobile piece of equipment close to the target workers for a mobile operation reduces the need for constantly moving the alarm unit.

9.6 EASE OF USE

Study results indicate that ease of use plays an important role in the selection and implementation decision for work zone intrusion alert technologies. Workers prefer an intrusion alert technology that is easy to setup, deploy at the beginning of a shift, and retrieve at the end of a shift with limited exposure to traffic and need for workers. In addition, the intrusion alert technology should offer a steep learning curve. The use of an intrusion alert technology should not be time consuming and should not hinder the existing traffic control setup, nor place those setting up the technology in a hazardous situation.

9.7 TRIGGERING MECHANISM

Given that the primary function of an intrusion alert technology is to provide warning to workers when a breach to the work zone occurs, the triggering mechanism of the intrusion alert technology plays a vital role in determining its effectiveness. The study found that most false positives are due to traffic cones with the sensing units being knocked over by mistake, wind, passing vehicles, etc. (Novosel 2014). Therefore, to reduce the rate of false alarms, intrusion alert technologies should reduce their dependence on the existing infrastructure or traffic control devices as locations for the sensing units. Radar or sensor-based work zone coverage that is independent of the roadway infrastructure or traffic control devices, or other non-impact dependent intrusion alert systems, are preferred choices for alert technologies in terms of the triggering mechanism.

9.8 COST

Several focus group and demonstration participants indicated that the upfront cost of the alert technology could be a significant barrier to technology adoption. Most participants indicated relatively higher interest in using the cheapest technology that was tested ($100) over the most expensive technology ($2,600) solely based on cost deference. It is not clear whether the participants compared the technologies based on just the cost of a single unit or took into consideration the number of units required to provide equal coverage in a work zone. Future intrusion alert technology manufacturers should provide information on comprehensive return on investment (ROI) and benefit-cost analysis (BCA) to help educate target users of the long term financial viability of such technologies. The analysis should include information about how many of each type of technology are expected to be used in a work zone; i.e., the low cost of a single unit of a technology may not provide as high an ROI when the required number of units for the technologies (and therefore area of coverage) is included.

10.0 CONCLUSIONS AND FUTURE RESEARCH

The overarching objective of the present study was to assess the feasibility of using intrusion alert technologies to improve the safety of roadway work zones. To achieve this objective, the research team focused on developing guidance on visual, audio, and haptic specifications that ODOT can use to compare across currently available intrusion alert products and future products. Multiple research activities were conducted over a period of 18 months. This section describes conclusions that can be derived from each research task performed as part of the study and provides recommendations for future research.

10.1 AVAILABILITY AND LEVEL OF AWARENESS OF INTRUSION ALERT TECHNOLOGIES

A detailed catalogue of available technologies was developed in the study and is presented in this report. Initially, four commercially available work zone intrusion alert technologies were selected for the study—SonoBlaster®, Intellicone®, Worker Alert System, and IntelliStrobe®.

An online survey, developed and distributed to highway construction stakeholders, aimed to determine how knowledgeable the stakeholders are regarding work zone intrusion alert systems. In addition, the survey aimed to investigate potential barriers and possible benefits associated with application of work zone alert technologies. The survey results suggest that, notwithstanding the possible benefits from the use of work zone alert systems, the application of such systems on live projects has been limited. It was also found that only a small portion of the participants (11 out of 111 respondents) are actually familiar with work zone intrusion alert systems. This current low level of awareness is expected across the industry as well.

10.2 PILOT TEST OF INTRUSION TECHNOLOGIES ALERT

Three out of the four identified work zone intrusion alert technologies (Intellicone®, SonoBlaster®, and WAS) were selected and pilot tested over a period of 10 weeks. Seven different test scenarios were developed and implemented in a controlled environment:

1. False alarm test, either false negative or false positive

    a. If handled carefully, the intrusion alert technology false alarm rate should be relatively low (non-existent). The three technologies predominantly exhibited zero false negatives, while the SonoBlaster® produced six false negatives (20% of triggerings) following cartridge changes.

2. Relationship between sound level and distance, and the impact of alarm direction

    a. The Intellicone® produces the most consistent and longest sound. The SonoBlaster® consistently recorded the loudest sound across all measured distances. The results from a spectral analysis showed that the orientation of all three technologies had an impact on the level of sound produced.

3. Sound level inside a vehicle

    a. The impact of the sound produced by each technology on a person driving by the work zone with car windows fully closed was limited. It is difficult to hear the alarms inside a vehicle. It can be deduced that the primary focus of the alarms is to alert the crew, not the intruding driver.

4. Impact of other nearby equipment on sound quality

    a. The results from replicating live operation constraints indicated that the alarms should be placed as close as possible to the cluster of workers to ensure that workers within close proximity to loud equipment can hear the alarm. When the measurement was taken in close proximity to an idle dump trunk and excavator, the sound produced by the SonoBlaster® remained similar to the noise level recorded without the equipment. The median SonoBlaster® sound levels recorded 50 feet and 100 feet away from the alarm (the alarm was 50 feet away from the equipment while 100 feet between the sound meter and the equipment) were 90 dB and 84 dB, respectively.

5. Alarm distinctiveness

    a. Results from the spectral analysis highlighted that the sound produced by all three technologies differed considerably from the mimicked ambient noise. The WAS was identified as having the most distinctive sound in terms of clustered sound intensity produced in the spectrogram image.

6. Transmission distance

    a. The transmission distance test showed that the Intellicone® was not audible from a distance of 250 feet or more away from the base unit. Transmission distance was increased to 650 feet when a second sensor was added to the transmission network of the Intellicone®. The WAS was not loud enough to hear after 300 feet away from the transmission unit. The audible and vibrating personal safety device of the WAS was not heard or felt when more than 50 feet away from the transmission unit. Due to its sensor-based expandability and the recommended configuration that requires strobes on work zone cones (acts as transmitters), Intellicone®'s transmission range was considered sufficient. The primary concern with Intellicone®'s transmission is its inability to capture a breach that occurs where there is either no cone or a cone without a sensor. At an approach speed of 55 mph, WAS's maximum transmission range will allow workers (at best) 3.7 seconds to react before impact. Although 3.7 seconds "time to impact" could be considered sufficient in certain situations (when workers are close to safe zone), it is imperative that intrusion alert devices should keep improving transmission coverage beyond what is currently offered.

7. Visual alarm intensity

    a. The test of light intensity level did not provide a conclusive, quantifiable conclusion. Based on a qualitative assessment, the visual alarms appear relatively distinctive in the dark, but not as distinctive when compared with a spot light and a work light on the equipment or in the surrounding work zone.

10.3 FOCUS GROUP DEMONSTRATION AND INPUT

The results from the live demonstration and online focus group indicated that although all three intrusion alert technologies have the potential to increase construction worker's reaction time in a work zone, they also have some limitations. Below is a comment from a participant that summarizes the outcome of the focus group activity:

"These systems seem to be a valuable tool that would be effective in preventing some traffic caused injuries. As do all traffic control devices these will have a shelf life and likely need to be replaced often, I think developing a technology that is cognizant of cost will be a large factor for making this technology something that contractors will choose to implement on their job sites."

In addition, participants indicated that the perceived usefulness of an intrusion alert system is the most important factor that influences the decision to adopt the technology in a work zone.

10.4 LIVE TESTING

Three case study projects in Oregon were selected to evaluate the effectiveness of the three alert technologies. Technology evaluation was focused on paving operations over five nights. The number of research participants on the selected projects varied from 5 to 12, consisting mainly of the ODOT inspector, dump person, screed workers, and paver operator. Prior to the live testing, a pre-testing demonstration and survey were conducted. A review of the feedback received indicates that each intrusion alert has strengths and limitations based on the five assessment criteria provided. Although the cost of the Intellicone® was identified as a barrier to its adoption, the Intellicone® was considered the easiest to use and also the preferred triggering mechanism. The Intellicone® was closely followed by the WAS. The SonoBlaster® was preferred in terms of effectiveness of alarm and cost.

Table 10.1 shows that, among the three technologies tested, the SonoBlaster® had the highest worker response rate when the alarm was triggered 50 and 100 feet from the paving operation. The high response rate was largely a function of loudness, not distinctiveness.

Table 10.1: Cumulative Response Rate (n = 14)

Technology	Response Rate based on Distance from Paving Operation	
	50 ft	100 ft
SonoBlaster®	92%	85%
Intellicone®	80%	78%
WAS	65%	57%

The SonoBlaster® repeatedly produced the loudest alert in comparison to the Intellicone® and WAS. At 50 feet and 100 feet, the SonoBlaster® produced 90 dB and 85.7 dB, respectively.

In addition, the response rate was assessed for each worker. The results from consolidating the data from all three case study projects show that the paver operator was the only worker to have no 100% response rates across all three technologies. Conversely, with the exception of when the WAS was triggered 100 feet away from the paving operation, the screed operator recorded a 100% response rate (see Table 10.2).

Table 10.2: Worker Response Rate

Worker / Location	Response Rate based on Distance from Technology					
	SonoBlaster®		Intellicone®		WAS	
	50ft	100ft	50ft	100ft	50ft	100ft
Dump Operator / on ground	100%	67%	33%	67%	50%	100%
Inspector / on ground	100%	67%	100%	100%	67%	67%
Screed Operator / on tailgate	100%	100%	100%	100%	100%	33%
Screed Worker / on tailgate	67%	67%	100%	67%	33%	33%
Paver Operator / on vehicle	67%	67%	67%	67%	33%	67%

The time it takes between alarm triggering and worker reaction was estimated using five data points. The results from the data analysis indicate that when a technology is placed 50 feet away from the paving crew, the workers tend to react faster. This stresses the need for the intrusion alert technology unit to remain within close proximity to the target work crew, but ideally having the triggering mechanism further away to increase the amount of reaction time available.

Finally, a post-testing survey of the workers was conducted after each technology was triggered. The survey focused on assessing the loudness and distinctiveness of the intrusion alarms. More importantly, qualitative information was gathered through interviewing research participants. The findings indicated that workers consider the SonoBlaster® to be loud and distinct. In addition, the workers indicated that the visual alarm produced by the Intellicone® is very useful, suggesting that both alarms together add value to notifying workers about a threat.

In summary, the main objective of this study was to determine the effectiveness of using an intrusion alert technology as an additional safety measure for construction workers in a work zone. Although the present study identified certain technological and operational limitations for each technology, there remains a possibility that intrusion alert technologies could help prevent worker injuries and fatalities due to vehicle intrusions in the work zone. The researchers are of the opinion that, based on the data analyzed, the intrusion alert technologies tested have the potential to improve worker safety if key identified shortcomings are addressed.

10.5 COST ANALYSIS

Study results indicate that cost of the intrusion alert technology plays a significant role in technology selection and acceptance. General contractors and ODOT personnel involved in the study shared their opinion that the less expensive intrusion alert technology would be preferred in comparison to more expensive technologies. Based solely of upfront capital cost of each individual unit, respondents showed preference for the SonoBlaster® due to its relatively inexpensive price per unit. The cost impact of a technology goes beyond the upfront cost. To determine the cost effectiveness of an intrusion device, it is paramount to assess the associated benefits and costs. Due to the difficulty in assessing the benefits of the three technologies, the present study assumes that all three technologies have similar benefits. That is, all three technologies will equally lead to lower risk for the workers. The cost of employing each technology on a project can be calculated using the cost associated with setting up the technology, deploying, retrieving, and maintaining the technology. This implementation cost includes both labor and equipment cost. A hypothetical cost analysis focused on capital costs of the three technologies is explained below:

A hypothetical 1-mile work zone closure for a 12 foot wide lane is used to demonstrate the potential cost impact of using the intrusion alert technologies. The cost estimates below do not take into consideration costs for labor (installing, moving the technologies as the paving operation progresses, and retrieving the technologies).

Transition Area

Equation 1 can be used to calculate the length of a taper in feet when the posted speed is below 45 mph (Infrastructure Training and Safety Institute 2011)

$$\text{Taper length (L)} = \frac{WS^2}{60} \text{ ………. Eqn. 1}$$

- Where:
    - W is the width of the offset in feet, and S is the posted speed limit
    - The taper length will be approximately 245 feet – 255 feet (ODOT 2016)
    - Number of cones = 8 cones
    - Cones for two transition areas (entry and exit transition area) = 16 cones

Activity Area

- Activity area length = 5,280 feet – 510 feet = 4,770 feet (where 5,280 feet = 1 mile)
- Cone spacing should be approximately 1x the speed limit (ODOT 2016). Therefore, the cone spacing along the activity area should be approximately 35 feet apart for a work zone with a 35 mph speed limit. Consequently, approximately 136 cones will be needed along the activity area.

- In total, approximately 152 cones are needed in the work zone.

10.5.1 SonoBlaster®

Kochevar (2002) recommends 17 cones based on a 300 feet coverage area and 20 feet cone spacing. However, the results from the current study suggest 400 feet coverage area to account for workers such as the dump person and inspector who could be 50 - 100 feet ahead of the paving operation (when the workers around the paving operation are the primary target).

Using the maximum allowable cone spacing for a 35 mph speed limit (35 feet spacing), it is estimated that approximately 14 cones equipped with a SonoBlaster® could cover 400 feet before the active working area. If the cone spacing is reduced to 20 feet to further reduce the possibility of a car intruding the work zone without hitting the cones, 22 cones will be required (20 longitudinal along the lane line, 2 transverse across the lane). The costs for the two cone options are shown in Table 10.3. The cost for one SonoBlaster® is $90.

Table 10.3: Cost for SonoBlaster®

	14 cones	22 cones
Equipment cost	$1,260	$1,980

10.5.2 Intellicone®

Considering the Intellicone®'s dependence on cones/delineators and the need to maintain uniformity, the required number of sensors placed on cones will be similar to that required for the SonoBlaster®. Table 10.4 summarizes the cost of implementing the Intellicone® in the work zone. The calculations assume that sensors cost $100 each, and the PSA costs $2,000 (includes 10 sensors).

Table 10.4: Cost for Intellicone®

	14 cones	22 cones
Equipment cost	$2,400	$3,200

* Displayed values for Intellicone® sensors are not exact cost but approximations based on researchers' estimate

10.5.3 Worker Alert System (WAS)

Unlike the other two intrusion alert technologies, the setup layout of the WAS and its transmission unit has no connection to temporary work zone delineators (cones and barrels). The WAS is primarily sold with a 12 foot long pneumatic hose. An extra $3.75 is charged for every foot beyond 12 feet. The integrity of the pneumatic hose is compromised beyond 50 feet. A total of eight WAS alert systems with 50 foot long pneumatic hoses will be required to cover the entire 400 feet length before the activity zone.

The total cost for eight WAS is $5,940 ($742.50 each). Although the cost of implementing the WAS is higher than the other intrusion alert technologies, it is important to note that the WAS provides better coverage since the pneumatic tube covers the entire intrusion path preceding the work activity zone.

10.6 STUDY LIMITATIONS

As with similar research efforts, it is difficult to conduct case studies on identical projects. Although data from three case studies were combined during analysis, it is important to note that the operational and environmental factors differed from project to project. Nevertheless, the research team focused on the paving operation to limit variance across the three case studies.

Based on the study findings, intrusion alert technologies have three primary methods for signaling an intrusion: audio, visual, and haptic. The current study focused more on the audio alarm, thereby providing quantitative results for audio alerts and qualitative results for haptic and visual alerts.

The current study focused on just three available technologies; including other available technologies may provide different overall results. As highlighted in Section 2, additional intrusion alert technologies have also been released during the course of the current study.

The cost analysis conducted in this current study was not extensive due to research constraints. Future studies should recommend a framework for assessing the return of investment, cost effectiveness and benefit-cost ratio of implementing intrusion alert technologies on repaving projects. Ideally, a life cycle analysis approach (upfront cost, operation cost, and maintenance cost) should be used.

10.7 FUTURE RESEARCH

The results from the present study show that certain intrusion alert technologies could be more impactful in certain work zone construction operations, e.g., mobile operation vs. stationary operation; daytime vs. nighttime work; short vs. long work zone; and varied speed limits. Therefore, it is important to develop intrusion alert technology selection protocols to ensure that the best technology is selected to fit the work zone design and environmental project constraints.

The present study estimated the cost effectiveness based on uniform benefits for each technology. A more precise study that assesses the cost effectiveness of individual technologies using a generic unit cost for estimating the cost associated with implementing the work zone intrusion technology, labor cost associated with installation, retrieval, maintenance cost, etc. should be conducted.

The data collection in the present study focused primarily on data needed to determine the effectiveness of each technology. Although the technology effectiveness in alerting the workers is important, results from both the demonstration sessions and the pre- and post- testing surveys indicate that ease of use is an important metric for technology acceptance. Ideally, a more accurate assessment of ease of use should be measured based on actual use of the technology rather than via perceived use. Users (i.e., construction crew members) should be given an opportunity to use each intrusion alert technology to determine ease of use. Future studies should include users as first-hand testers of each technology, ensuring more accurate depiction of actual usefulness and ease of use of each technology.

Typically, many different types of work operations, such as expansion joint replacement, barrier replacement, and routine maintenance work (lamp maintenance, road sweeping, etc.), are undertaken in construction work zones across Oregon. In addition, operations are conducted during the day and at night. The current research focused mainly on repaving projects at night. Specifically, the study focused on the paving operation conducted between 6:00pm and 6:00am as a result of project selection limitations. Future study should assess the possibility of different levels of effectiveness for other scenarios not evaluated. There is a possibility that the level of effectiveness will be different based on the type, timing, and location of work conducted.

Given the identified potential of the intrusion alert technologies tested in the current study, future studies should consider assessing the usefulness of subsequent released intrusion alert technologies (see Section 10.8).

The current study focused its assessment primarily on the audio alarm feature of each technology. Given the documented impact of the visual alarms of the Intellicone® and the potential usefulness of haptic alert, future studies should consider quantifying the impact of visual and haptic alerts, and combinations thereof, on workers. Findings from such study can be used to calibrate the results of the present study by providing not only qualitative data, but quantitative data that could be used to create specifications for future products.

10.8 OTHER SUPPORTING TECHNOLOGIES AND NEWLY-DEVELOPED INTRUSION ALERT TECHNOLOGIES

This section of the report includes descriptions of additional technologies that support and improve the effectiveness of intrusion alert technologies, and new intrusion alert technologies that have been developed since the inception of the present research study. Future research exploring intrusion alert technologies should consider incorporating the technologies described below.

10.8.1 Safe Vest (InZoneAlert Vest)

The InZoneAlert vest is designed to provide a two-way warning between the worker and the driver of the intruding vehicle. The worker is required to wear a safety vest embedded with transmitters. When a collision is imminent, short-range communication is used to send a message to the motorist by means of connected vehicle technology. The vest also produces an audible sound to warn the worker of an imminent hazard. Results from initial testing indicate that the InZoneAlert vest successfully alerts the worker and driver (91% success rate). The InZoneAlert vest also provides a valuable 5-6 second reaction time for workers before any potential collision (Forsyth, Martin, and Bowman 2014).

The URL for the InZoneAlert website is: https://www.vt.edu/spotlight/innovation/2015-08-31-beacon/safetyvests.html.

10.8.2 Wrong Way Alarm (WWA)

Although primarily designed to notify drivers of wrongful entrance into a lane, the Wrong Way Alarm (WWA) could be adapted to function as a work zone safety intrusion alert technology. A WWA detects intruding vehicles using Doppler radar technology and a mesh-Net System. Warning is produced using high intensity LED Flasher bars. Currently, the WWA does not produce an audio warning. The device may be useful for taper intrusion but may not be as effective at catching intrusions via other points of entry.

The URL for the WWA website is: http://trafficalm.com/wrongwayalert-wrong-way-warning-system/.

10.8.3 Directional Audio System

The directional audio system (DAS) is designed to transmit high-intensity and directional warning sound that helps prevent distracted drivers from entering into the work zone. The DAS is mounted at the rear of a truck-mounted attenuator. When the system detects the possibility of an intrusion, it emits a high-intensity warning sound in the direction of the oncoming vehicle.

The URL for the Directional Audio System website is: https://library.modot.mo.gov/RDT/reports/TR201412/cmr15-011.pdf.

10.8.4Proximity Alarm for Visual Alarm

Published literature indicates that a significant number of fatalities are caused by equipment-pedestrian (worker) collisions. A few proximity warning systems have been developed and tested on work zone projects. BodyGuard Safety Solution’s Dual Zone pedestrian proximity warning system improves worker safety around mobile plants in highway maintenance and construction. Sensors, personal tags, and cab alert units are used to provide a safe perimeter within the work zone.

The URL for the BodyGuard Proximity Warning System website is: http://www.bodyguardsafety.com.au/.

10.8.5 AWARE System by Oldcastle

The Advanced Warning and Risk Evasion (AWARE) system is a vicinity monitoring device that provides advanced warning when hazardous conditions exist. The system comprises of a personal tracking unit, vicinity monitoring unit, and a base station. The vicinity monitoring unit can be mounted on a vehicle. The personnel tracking unit is connected to the vicinity monitoring unit and can be worn on a hard hat, vest, or strapped around a worker’s arm. The base station is primarily used to monitor activities going on in and around the work zone, e.g., worker’s location. The alarm is triggered when a non-construction vehicle deviates from its projected travel path into the work zone. When an intrusion occurs, the vicinity monitoring unit’s alarm triggers, producing both visual and audio warning. Workers deemed to be at-risk (within projected impact area) are warned through the personal tracking unit (haptic system). According to Advanced Real Time Information System (ARTIS), preliminary results from testing the AWARE show a low false alarm rate and high threat detection rate (ARTIS 2015).

The URL for the AWARE System website is: https://vimeo.com/135969644.

10.8.6 Smart Taper and Safelane by Highway Resource Solutions

The Intellicone® Smart Taper is a combination of the Intellicone® technology with Unipart Dorman Sequential Cone Lamps. By combining these two technologies, the Smart Taper is intended to improve drivers' experiences as they navigate the work zone (speed reduction) as well as provide intrusion alert capability supposing a vehicle breaches the perimeter.

The Safelane system could be used as a panic alarm or a checkpoint alarm in a work zone. The panic alarm provides workers with the opportunity to wirelessly alert other workers located further downstream in the work zone of an errant vehicle.

The checkpoint system replaces personnel assigned to monitor closure points by electronically monitoring closures. If an intrusion occurs, the portable site alarm triggers, simultaneously sending a signal to the alarm unit closest to the work area. This capability creates adequate warning and reaction time for workers.

The URL for the Smart Taper website is: http://www.intellicone.co.uk/smart-taper.

10.8.7 Wireless Sensor Network-Based Intrusion Alarm System

The Wireless Sensor Network-Based Intrusion Alarm System utilizes ultrasonic beams to detect errant vehicles. The system consists of two main elements: sensor nodes and individual warning devices worn by workers. Although results from field evaluations indicate that this intrusion technology is effective and useful, a commercial version is yet to be released.

The URL for the Wireless Sensor Network-Based Intrusion Alarm System website is: https://www.hindawi.com/journals/js/2016/7048141/.

10.8.8 TMA Mounted LED Panic Lights and Sound

The Missouri Department of Transportation (MoDOT) developed a manually-operated intrusion alert system by mounting six white LED panic lights to the rear side of a truck-mounted attenuator. The lights and audio alarm mechanism are connected to a switch inside the cab of the truck which is manually operated by the TMA driver. If a vehicle refuses to change lanes, the driver is instructed to activate the panic light and audio alarm to alert other workers in the area and the driver of the intruding vehicle (Missouri Department of Transportation 2015).

The URLs to websites showing and describing the TMA Mounted LED Panic Lights and Sound are: https://www.youtube.com/watch?v=bKo1ClwjjR8; and http://noboundaries-roadmaintenance.org/LED-Panic-Lights.html.

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APPENDIX A

EXTENDED CATALOG OF AVAILABLE TECHNOLOGIES

APPENDIX A

APPENDIX A: EXTENDED CATALOG OF AVAILABLE TECHNOLOGIES

A.1 INTELLICONE®

Using a combination of both visual and audio alarms, the Portable Site Alarm (PSA) notifies workers and errant driver within a work zone of a likely breach of the wireless perimeter. Depending on the type of project, different PSA units could be deployed. Currently, there are three major types of PSA units:

- Y-Series - Large worksites with multiple work crews
- R-Series - Small to medium size temporary worksites
- O-Series - Safety critical projects

The audio alarm is designed to provide multiple audible tones over long distances, and consequently to provide warning that increases workers reaction time. The design of the PSA consists of a heavy-duty shell that protects the device from wear and tear. The rechargeable alarm unit has the capacity to produce different ranges and intensity of sound which is triggered by motor sensors with adjustable sensitivity levels. The PSA can be installed on a traffic cone or a flat surface around the work zone. Table A.1 highlights some key features of the different types of PSA Units.

Table A.1: Description of Intellicone® Alarm System Features (Highway Resource Solution 2015)

Component	Features	Specification/ Dimensions
Intellicone® Unipart Dorman ConeLITE	Intelligent wireless impact detection technology Lamp and sensor activation by fitting lap onto cone Deploys in any order and works day and night , even when the lamp turns off during the daytime (two-stage switching process) Communicates seamlessly with Intellicone® Portable Site Alarm and any Intellicone® integrated sensors	Maximum range between lamps: 50 meters

Intellicone® Sentry (motion sensor)	Easy to use self-calibrating technology Cone mountable Communicates seamlessly with Intellicone® equipment 3m ultrasonic beam technology Push button override Rechargeable batteries with 80- hours operation Status indicator Power supply provided Cone mountable External 12v battery	Placed within 30 meters of Intellicone® PSA or TMU
Intellicone® Unipart Dorman SynchroGUIDE	Intelligent wireless impact detection technology lamp and sensor activation by button operation deploys in any order and works day and night communicates seamlessly with other sensors and Intellicone® PSA Sequential flashing lamp	Maximum range between lamps: 50 meters
Intellicone® Traffic Management Unit	Versatile mounting system (to cone's, signage, barriers and other metallic surfaces) User friendly touch panel control interface with low battery and alarm status indicators Communicates seamlessly with Intellicone® Portable Site Alarms and any Intellicone® integrated sensors Intelligent wireless impact detection technology Once deployed the alarm will activate when the device is moved	Placed within 30 meters of Intellicone® enabled sensors

Portable Site Alarm Y-Series	3 tone siren, green and red LEDs Web enabled to create large sites with multiple devices connected GPS location tracking Web portal reporting Internal rechargeable battery Auxiliary output	Connects to Intellicone® sensors via short range RF: 50 meter range Text message alerts
Portable Site Alarm R-Series	3 tone siren, green and red LEDs Internal rechargeable battery Auxiliary output	Connects to Intellicone® sensors via short range RF: 50 meter range
Portable Site Alarm O-Series	3 tone siren, green and red LEDs Two way communication with sensors (self-monitoring system) Internal rechargeable battery Auxiliary output	Connects to Intellicone® sensors via short range RF: 200 meter range

The Intellicone® can be deployed on temporary lane closures, double lane closure, and partial or full exit ramp closure (Highway Resource Solution 2015). Motion sensors (sentry) would be mounted on traffic cones around the work zone to create a wireless network that identifies any unplanned vehicle entry into the work zone. The lamps, which are also motion sensors, are mounted on traffic cones and are automatically connected to the wireless network. When impacted by an errant vehicle, the tilt-alarm mechanism sets in, triggering the alarm system. Depending on the type of project, the staging requirement could differ. Nevertheless, the deployment procedure will substantially remain the same.

A.2 SONOBLASTER®

This system is a relatively easy-to-use work zone friendly technology that alerts both workers and errant drivers. The device is portable, affordable, requires no electrical power to function, and operates independently (KansasDOT 2011; Transpo Industries Inc. 2015a). A SonoBlaster® device is placed on traffic cones or barricades at a pre-established interval along the work zone to create a safety environment for field workers. It also can act as a deterrent to errant drivers. To trigger the CO2 cartridge powered alarm, the traffic cones on which the device is placed has to be tilted to an angle above 70 degrees. This action will release a loud alarm blast of about 125 decibels lasting approximately 15 seconds. Table A.2 provides additional information about this technology.

Table A.2: Description of SonoBlaster® Features (Transpo Industries Inc. 2015b; ELWC 2015)

Component	Features	Specification/ Dimensions
SonoBlaster® Alarm	Activation: impact or tilting When activated, alarm sounds at high tone Powered by safe, reliable CO_2 cartridges Critical alignment not needed as in beam-type devices Stable: resistant to normal roadway harmonics and vibration No receiver units required Holds multiple U.S. patents	Duration is 15 Seconds 125 dB @ 6 feet High-impact visible yellow body 70 to 90 degrees activation angle Pressure relief valve Barricade light-type mounting Control knob(for 'safe' and 'ready' status) 7.25" wide by 6" high by 2" deep 2 lbs. (1kg) 00 to +1100F (-180 to +430C) Unit Operating Temperature Cartridge Temperature Range - -300 to +1200F (-340 to +490C) Cartridge 'Shelf Life': Indefinite

A SonoBlaster® unit could easily be attached to traffic cones, A-frames, security fences, barrels and drums, barricades, and delineators. The spacing of each device depends on different factors such as the type of project, environmental constraints, and available resources. To activate the device, the unit must be cocked using a key chain tool then placed along a work zone on safe mode. The control knob is then rotated to get ready. This action arms the device.

A.3 INTELLISTROBE®

IntelliStrobe® was developed primarily to reduce the exposure of flaggers to live traffic during road construction and maintenance. Although mainly used for its flagging capability, IntelliStrobe® has the capacity to detect vehicle intrusion into the work zone. The IntelliStrobe® is equipped with a Lane Intrusion Alarm that creates a 125-decibel siren sound when traffic crosses the two pneumatic pressure sensitive hoses. Table A.3 provides additional information about the IntelliStrobe®.

Table A.3: Description of IntelliStrobe® Features (IntelliStrobe Safety Systems 2015)

Component	Features	Specification/ Dimensions
Flagger - W1-AG	25 feet safety pneumatic hose for detecting errant driver and triggering alarm Two color (Red and Yellow) LED light for alerting intruding drivers Alarm covers a 2000 feet range Pre-Installed Automated Gate	Automatic Safety Alarm System Dual 100 watt 125 Decibel Sirens Pressure sensitive activation hoses Manual activation option Cabinet Aluminum .090 18" x 24" x 36" 165 lbs per device

Remote Control Radio- FC 401-1	Arm and Flag	Gate Arm 7’ x 2 ½” x 1” Diamond grade reflective tape Alternating red & white stripes in 16” intervals horizontally Orange safety flag 18” x 18” Signals Lights: 12” LED’s 1 Red & 1 Yellow per device Battery: 12 Volt DC 55 amp AGM Spill Proof Batteries Battery Tender, 2 bank 1.25 amp Material: High impact ABS plastic with a non-slip coating Weight: 12 oz Voltage: 12-volt rechargeable Li-Ion battery Radio: 2watt transmitter/receiver UHF 453.325-468.00 MHz FCC: Complies with Part 90 Security: Spread Spectrum & Binary Coding Dimensions: 3” wide x 7” long x 2” deep

FWHA (2009) suggests that the IntelliStrobe® be set up on the shoulder of a roadway at either end of the work zone (e.g., north and south bound lanes). The two pneumatic tubes (red and blue) are spaced 18 to 24 inches apart and placed across the length of the road with the red hose on the exterior side. A worker can then control the flagger from a distance using the wireless remote. If a vehicle ignores the stop sign (red light) and pressures the pneumatic tube on its way into the work zone, the alarm is triggered.

A.4 WORKER ALERT SYSTEM (WAS)

The Traffic Guard Worker Alert System (WAS.) comprises of a lightweight, portable trip hose, and sensor assembly that wirelessly sends a signal to an alarm and flashing light when pressured. If an intrusion occurs, the alarm and flashing light are triggered by the pneumatic tube, which then alerts workers so they are able to safely and quickly move out of the way of an oncoming vehicle. Table A.4 provides additional details about the Worker Alert System.

Table A.4: Description of Worker Alert System Features (Astro Optics 2015)

Component	Features	Specification/ Dimensions
Consists of: Pneumatic hose, visual and audio alarm device, and personal vibrating device	Wireless 12 feet trip hose with sensor (AA batteries required) Rechargeable alarm/flashing light Available heavy duty carrying case Lifetime warranty (restrictions apply) 1,000 feet range Variable hose lengths Variable wireless distance triggering Personal safety vibration device Sequential siren box alerting	Specific information not available

Depending on the type of highway construction operation and the location of the work zone with respect to the direction of traffic, the trip hose could be placed before or after the work zone. Adequate distance that accounts for the travelling speed of vehicles should be kept between the trip hose and the workers to provide sufficient response time if an errant car intrudes into the work zone. The alarm and flashing light should be placed within close proximity of the workers (not more than 1,000 feet away from the trip hose) to ensure adequate warning.

APPENDIX B

INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

APPENDIX B

B.1 INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

OSU Oregon State University

Institutional Review Board
Office of Research Integrity | Oregon State University
B308 Kerr Administration Building, Corvallis, OR 97331-2140
Telephone (541) 737-8008
irb@oregonstate.edu | http://research.oregonstate.edu/irb

EXEMPT DETERMINATION

Date of Notification	09/23/2015		
Study ID	7056		
Study Title	Work Zone Intrusion Alert Technologies: Assessment and Practical Guidance		
Principal Investigator	Hyun Woo Lee		
Study Team Members	John Gambatese, Chukwuma Nnaji		
Submission Type	Initial Application	Date Acknowledged	09/23/2015
Level	Exempt	Category(ies)	2
Funding Source	Oregon Department of Transportation (ODOT)	Proposal #	SPR 790
PI on Grant or Contract	John Gambatese	Cayuse #	15-1830

The above referenced study was reviewed by the OSU Institutional Review Board (IRB) and determined to be exempt from full board review.

EXPIRATION DATE: 09/22/2020
*The exemption is valid for **5 years** from the date of approval.*

Annual renewals are not required. If the research extends beyond the expiration date, the Investigator must request a new exemption. Investigators should submit a final report to the IRB if the project is completed prior to the 5 year term.

Documents included in this review:

- ☒ Protocol
- ☐ Consent forms
- ☐ Assent forms
- ☒ Alternative consent
- ☐ Letters of support
- ☒ Recruiting tools
- ☒ Test instruments
- ☐ Attachment A: Radiation
- ☐ Alternative assent
- ☐ Grant/contract
- ☐ External IRB approvals
- ☐ Translated documents
- ☐ Attachment B: Human materials
- ☐ Other:

Comments:

Principal Investigator responsibilities:

- Certain amendments to this study must be submitted to the IRB for review prior to initiating the change. These amendments may include, but are not limited to, changes in funding, , study population, study instruments, consent documents, recruitment material, sites of research, etc. For more information about the types of changes that require submission of a project revision to the IRB, please see: http://oregonstate.edu/research/irb/sites/default/files/website_guidancedocuments.pdf
- All study team members should be kept informed of the status of the research. The Principal Investigator is responsible for ensuring that all study team members have completed the online ethics training requirement, even if they do not need to be added to the study team via project revision.
- Reports of unanticipated problems involving risks to participants or others must be submitted to the IRB within three calendar days.

OSU IRB FWA00003920 1 IRB Form | v. date July 2015

Figure B.1: Oregon State University Institutional Review Board Approval Letter

APPENDIX C

ONLINE SURVEY

APPENDIX C

C.1 STUDY TITLE: WORK ZONE INTRUSION ALERT TECHNOLOGIES: ASSESSMENT AND PRACTICAL GUIDANCE

You are invited to take part in this research study as you are identified as being actively involved in highway construction and/or maintenance projects. Participation in this study is voluntary. If you consent and understand the explanation of research attached to the survey, please complete the survey form. The purpose of this study is to provide Oregon DOT traffic control, construction, and maintenance staff with guidance on the use of intrusion alert systems in work zones. Participation or non-participation will not affect your relationship with the company or your job performance. There is no direct benefit to you as participant in the research; however, the research will be beneficial to the construction industry as a whole.

If you choose to take part in this survey, you will be asked to provide the following information:

- Perception on the impact of work zone safety technologies
- Perception on the impact of work zone intrusion alert technologies
- Personal attributes such as title, type of company/organization, years of experience, etc.

The survey is expected to take approximately 10 minutes to complete. The survey has minimal risks, and all information that you provide will be accessed only by the researchers. The survey data will be kept confidential and anonymous. When this study is published, no information regarding identity will be made public. For more information about this study, please contact Chukwuma Nnaji at nnajic@onid.oregonstate.edu or the principal investigators, Dr. John Gambatese and Dr. Hyun Woo Lee, by phone at 541-737-8913, 541-737-8539 or email at john.gambatese@oregonstate.edu, hw.chris.lee@oregonstate.edu respectively.

Thank you,

Chukwuma “Chuma” Nnaji

Ph.D. Student Researcher

nnajic@onid.oregonstate.edu

(541) 908 0475

Work Zone Intrusion Alert Technologies: Assessment and Practical Guidance

1.1 Please select your role:

- ☐ Owner Agency (e.g. Oregon DOT, etc.)
- ☐ General Contractor
- ☐ Sub-Contractor
- ☐ Vendor
- ☐ Other: ____________________

1.2 Select the job title that best describes what you do:

- ☐ Project Manager
- ☐ Project Engineer
- ☐ Traffic Control Designer
- ☐ Safety Officer
- ☐ Safety Equipment Supplier
- ☐ Road Maintenance Crew
- ☐ Traffic Control Crew
- ☐ Other: ____________________

1.3 How many years of industry experience do you have?

- ☐ Less than 1 year
- ☐ 1 - 5 years
- ☐ 5 - 10 years
- ☐ 10 - 20 years
- ☐ More than 20 years

1.4 What state do you primarily work in?

- ☐ ____________________

2.1 What type(s) of work zone safety technologies are commonly used on your projects? (Select all that apply.)

- ☐ Portable Rumble Strip
- ☐ Portable Changeable Message Sign
- ☐ Work Zone Intrusion Alert System
- ☐ Automated Flaggers
- ☐ Drone Radar Speed Detection
- ☐ Others: ____________________
- ☐

2.2 Rate the accident prevention effectiveness of the technologies listed below on a scale of 1 to 5, where 1 = minimally effective and 5 = highly effective

	1	2	3	4	5	I don't Know
Portable Rumble Strip						
Portable Changeable Message Sign						
Work Zone Intrusion Alert System						
Automated Flaggers						
Drone Radar Speed Detection						
Others:						

2.3 Do you currently use any work zone intrusion alert system or have plans to use any in the future?

☐ Yes
☐ No

2.4 What type(s) of work zone intrusion accidents have you observed in the past?

☐ Full intrusion (Accidents resulting from vehicle intrusion into the work zone through the taper)
☐ Buffer intrusion (Accidents resulting from contact with vehicle outside the work zone, e.g., sideswipe contact accidents)
☐ Moving operation (When flaggers and/or work vehicles are used in lieu of channelizing devices)
☐ Access related accidents (Vehicles moving through the work zone to gain access to or from a driveway or other roadside area)
☐ Struck by debris or traffic control device thrown into the work zone by passing vehicle
☐ None
☐ Others: ____________________

2.5 How knowledgeable are you about work zone intrusion alert systems?

☐ Very knowledgeable
☐ Knowledgeable
☐ Not so knowledgeable
☐ Never used one

2.6 What type(s) of work zone intrusion alert systems are you familiar with (i.e., have used or heard of in the past)? Please select all that apply.

☐ Pressure Triggered Pneumatic Tube Alarms (e.g., Watch Dog, WAS, Intellistrobe®, etc.).
☐ Infrared Beam Intrusion Alert Systems (e.g., Rockwell Automation).
☐ Microwave Intrusion Alert Systems (e.g., Safety Sentinel).
☐ Impact and Tilt Activated Safety Systems (e.g., SonoBlaster®).

2.7 In your opinion, do you think the work zone intrusion alert systems currently available are beneficial to work zone safety?

- ☐ Yes
- ☐ No
- ☐ Please explain your answer _____________________

For subsequent questions, your response should be based on one intrusion alarm technology that you are most familiar with. Kindly name the technology and brand if possible.

- ☐ Technology (e.g., Pneumatic tube, Impact Tilt.). _____________________
- ☐ Brand (e.g., SonoBlaster®, WAS, Intellistrobe®, Watch Dog). _____________________

3.1 Where do you typically deploy the work zone intrusion alert system identified above?

- ☐ At the taper
- ☐ At the taper and along the work zone
- ☐ Along the zone but not at taper
- ☐ Other location: _____________________

3.2 Rate the cost effectiveness of the identified alert system on a scale of 1 to 5, where 1 = minimally effective and 5 = highly effective

	1	2	3	4	5
Alert System: ___________________					

3.3 Based on your experience, what benefit(s) come with deploying the identified work zone intrusion alert system? (Select all that apply.)

- ☐ Provides adequate reaction time for workers
- ☐ Easy to use and maintain
- ☐ Alarm produced is distinctive
- ☐ Easy to deploy and retrieve
- ☐ Others: _____________________

3.4 Based on your knowledge, what are the barriers associated with the highlighted work zone intrusion alert system?

- ☐ Inaccurate alarm (false-positive and false-negative)
- ☐ Expensive
- ☐ Difficult to operate and maintain
- ☐ Difficult to deploy and retrieve
- ☐ Less distinctive alarm produced by device (e.g., inaudible alarm)
- ☐ Inadequate work zone coverage
- ☐ Other: _____________________

3.5 Please share any opinions that you have for implementing intrusion alert technologies in work zones:

☐ Opinion: ____________________

If available for further questions, please provide your contact.

☐ ____________________

☐

APPENDIX D

DEVICES USED FOR PRELIMINARY INVESTIGATION

APPENDIX D

D.1 DOSIMETER

To collect the level of noise to which field workers are exposed, two Etymotic 2R-220 w8 noise dosimeters were used. The dosimeter is designed to be a carry-on device that has little or no impact on a worker's regular activities. The Etymotic dosimeter records noise level every 20 seconds but logs data every 3.75 minutes using the average noise level observed within the logging time frame.

The technical specifications of the Etymotic 2R-220 w8 dosimeter are listed in Table D.1.

Table D.1: Technical Specifications of Noise Dosimeter

Criteria	Value
Calibration Accuracy	± 2.5 dB
Threshold Level	Programmable
Run Length	Programmable
Frequency Weighting	A
Response	Slow
Temperature Range of Operation	-10°C to 45°C (14°F to 113°F)
Omni-directional Microphone	Flat from 100 Hz to 15 kHz
Power Supply	Three AAAA batteries
RMS Detector	Dynamic range 60 dB (70 to 130 dB)
Battery Life	200 hours continuous use

D.2 LIGHT METER

Considering that two of the available alert technologies (WAS and Intellicone®) can trigger visual alarms, it has become important to measure the level of light workers are exposed to within the work zone. An Extech 401036 light meter was used to collect data on light intensity in the work zone. Figure D.1 depicts the light meter used for the data collection.

Figure D.1: Data Logging Light Meter

Table D.2: Technical Specifications of Data logging Light Meter

Criteria	Value
Light Intensity: 0-20 0-200 0-2,000 0-20,000	Resolution: 0.01 0.1 1 10
Accuracy	±(3% reading + 5 digits)
Operating Temperature	32 to 104°F (0 to 40°C)
Operating Humidity	Less than 80%
Power source	9V battery (included); 50 hour battery life
Applicable Standards	JIS C1609-1993; CNS 5119-1998; Standard illuminant 'A'
Dimensions	5.7 x 2.8 x 1.2" (145 x 72 x 31mm)
Weight	7.5 oz. (235)

D.3 SOUND LEVEL METER

An Extech HD 600 sound level meter was used to measure sound levels around the work zone. The sound meter supports not only spot measurements but also extensive data logging for sound levels ranging from 30 to 130 decibels. Given that construction equipment could produce sound level between 60 and 102 decibels (FHWA 2015), the sound meter was deemed appropriate for the research study.

The technical specification of the Extech HD 600 sound level meter are summarized in Table D.3.

Table D.3: Technical Specifications of Sound Level Meter

Criteria	Value
Range	30 to 130dB
Basic accuracy	±1.4dB
Weighting	A and C
Response Time	Fast/Slow
Analog Output	AC/DC
Data logging	20,000 points
PC Interface	USB
Dimensions	10.9 x 3 x 2" (278 x 76 x 50mm)
Weight	12.3oz (350g)

APPENDIX E

NIGHTTIME OBSERVATION RESULTS

APPENDIX E

E.1 NIGHTTIME OBSERVATION RESULTS

Figure E.1: Sound Level of Workers around Paver and Roller

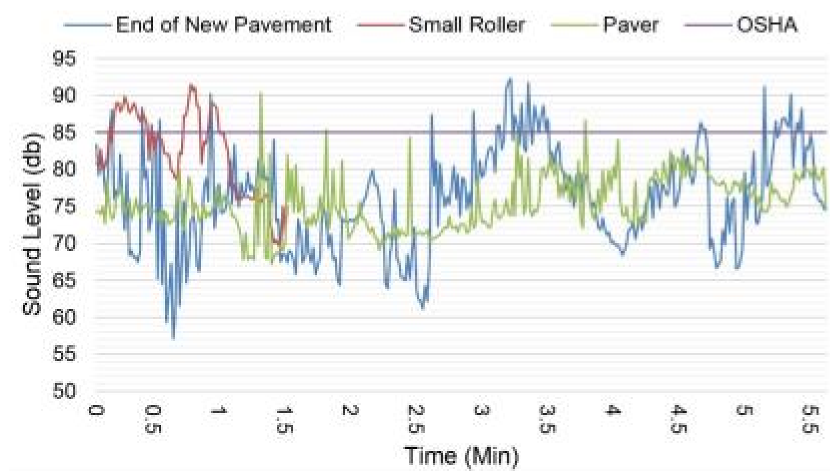

Figure E.2: Sound Level in Close Proximity to Rollers and Paver

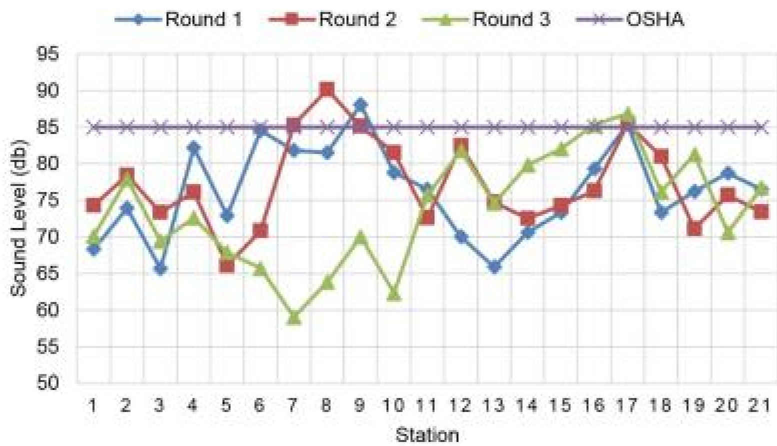

Figure E.3: Sound Level along Grid-Line 1

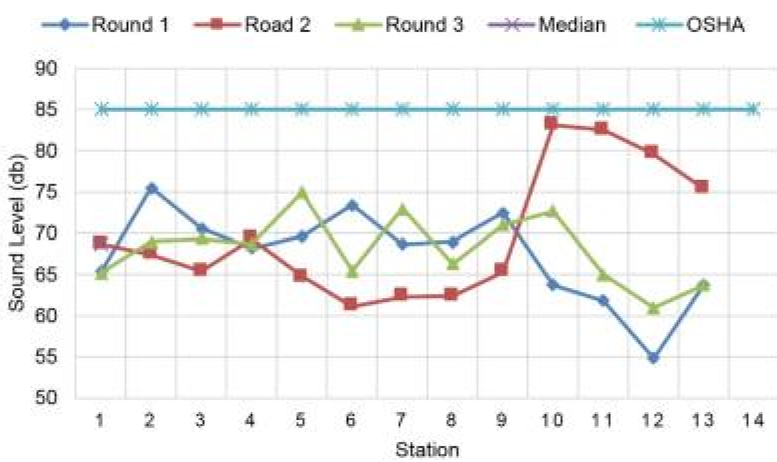

Figure E.4: Sound Level along Grid-Line 2

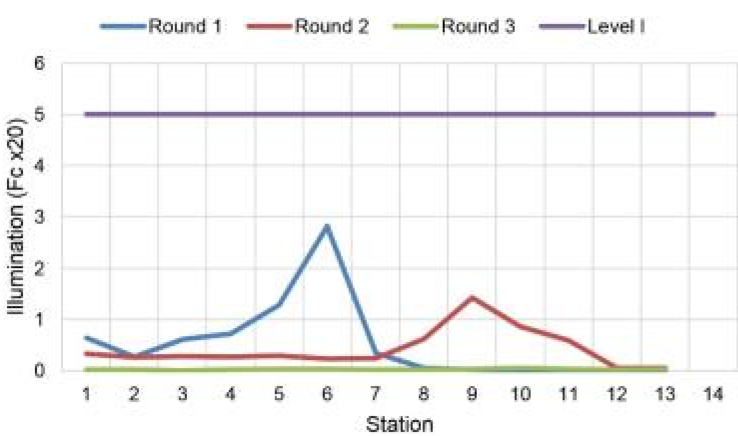

Figure E.5: Illumination Level along Grid-Line 2

APPENDIX F

WORKER ALARM REACTION TIME

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APPENDIX F

F.1 SCREED DRIVER

SonoBlaster®

Figure F.1: Screed Driver Response Time (SonoBlaster®)

Intellicone

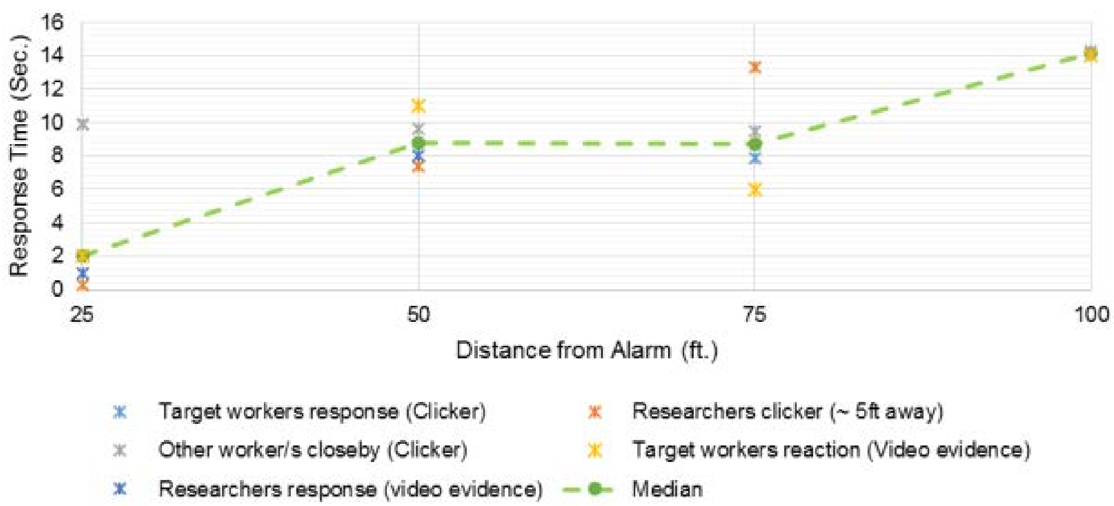

Figure F.2: Screed Driver Response Time (Intellicone®)

Worker Alert System (WAS)

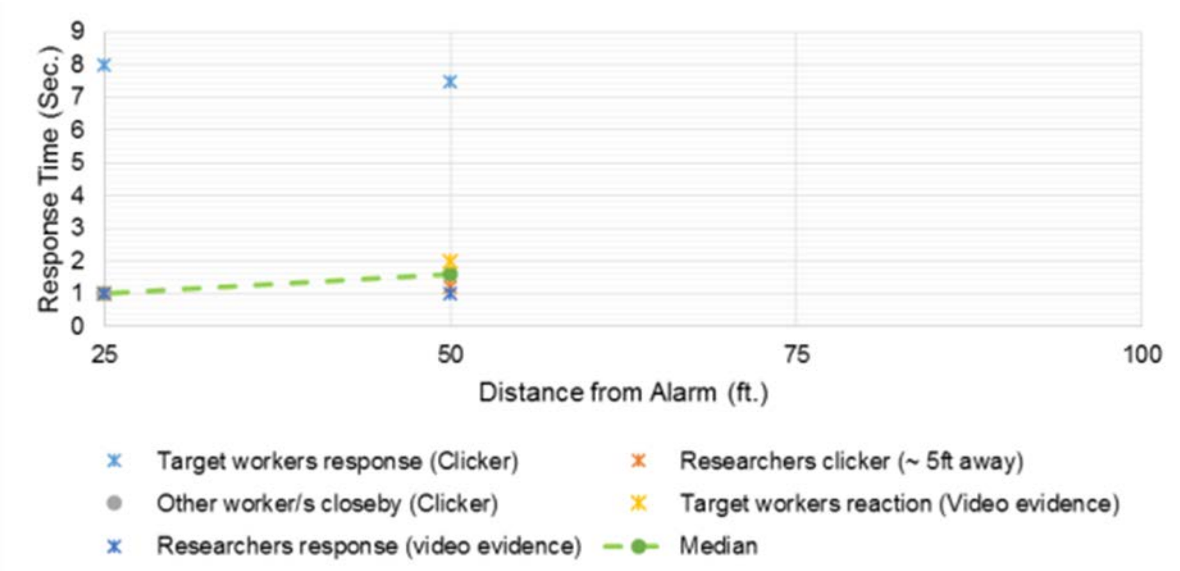

Figure F.3: Screed Driver Response Time (WAS)

F.2 SCREED OPERATOR

SonoBlaster®

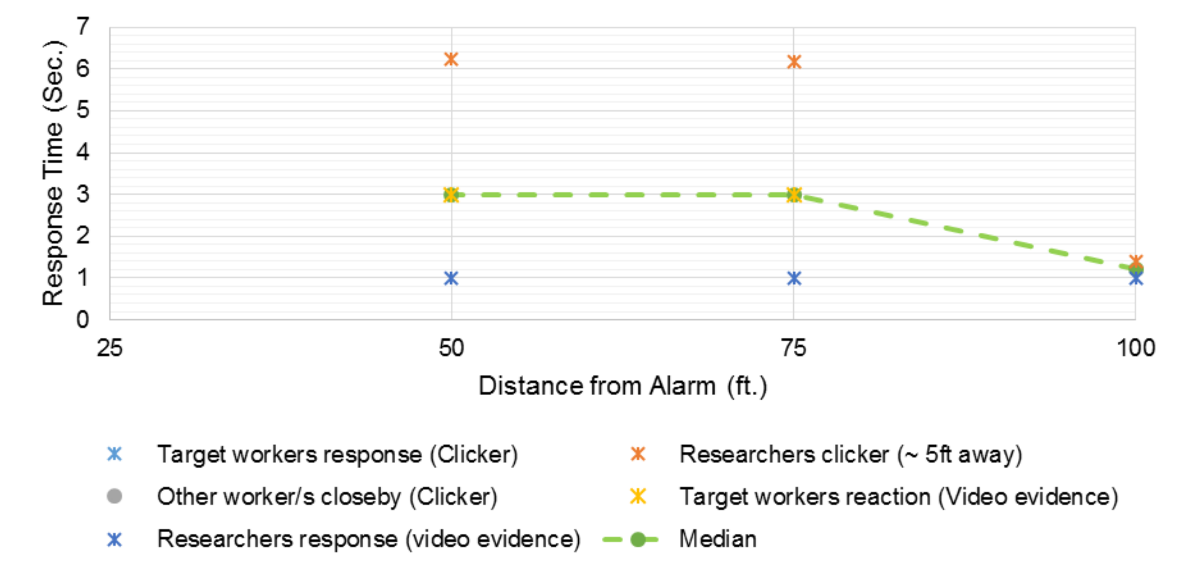

Figure F.4: Screed Operator Response Time (SonoBlaster®)

Intellicone®

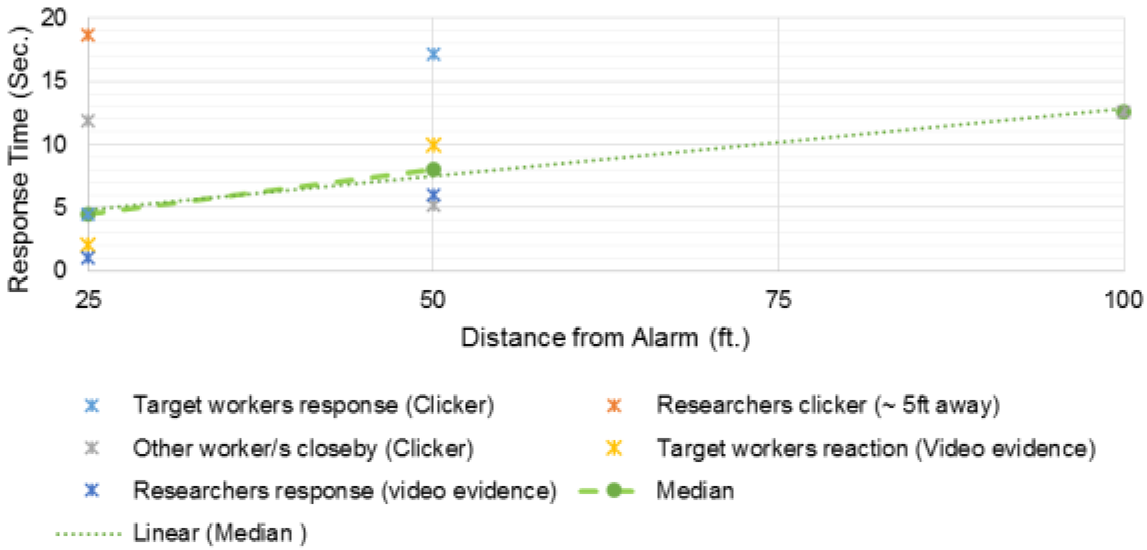

Figure F.5: Screed Operator Response Time (Intellicone®)

Worker Alert System (WAS)

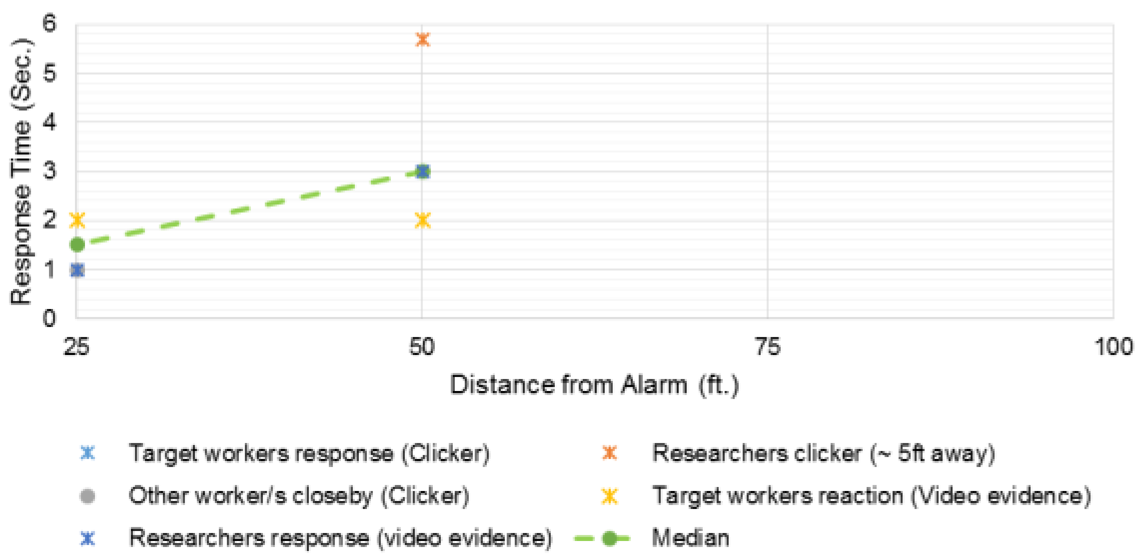

Figure F.6: Screed Operator Response Time (WAS)

F.3 SCREED WORKERS

SonoBlaster®

Figure F.7: Screed Worker Response Time (SonoBlaster®)

Intellicone®

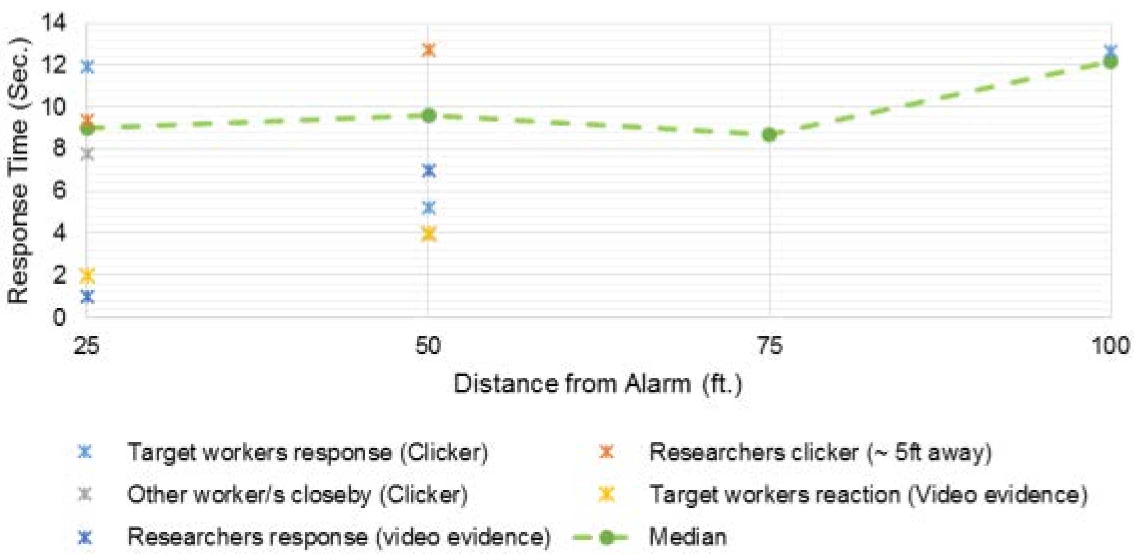

Figure F.8: Screed Worker Response Time (Intellicone®)

Worker Alert System (WAS)

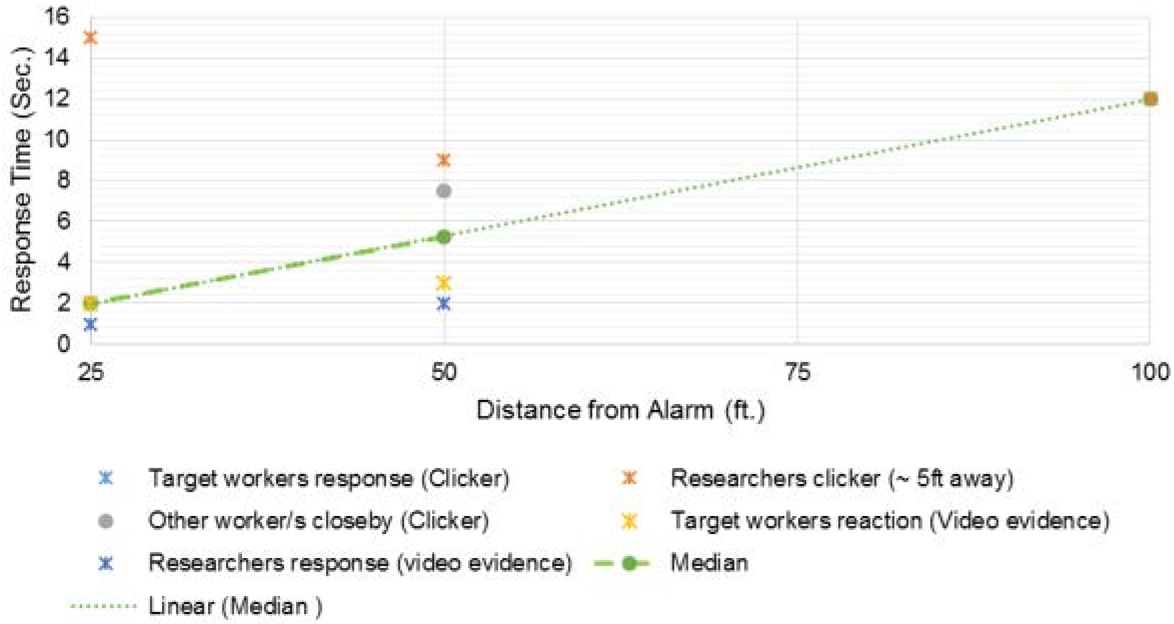

Figure F.9: Screed Worker Response Time (WAS)

APPENDIX G

WORKER PERCEPTION REGARDING ALERT DEVICES

APPENDIX G

G.1 CUMMULATIVE (ALL CASE STUDY PROJECTS)

SonoBlaster®

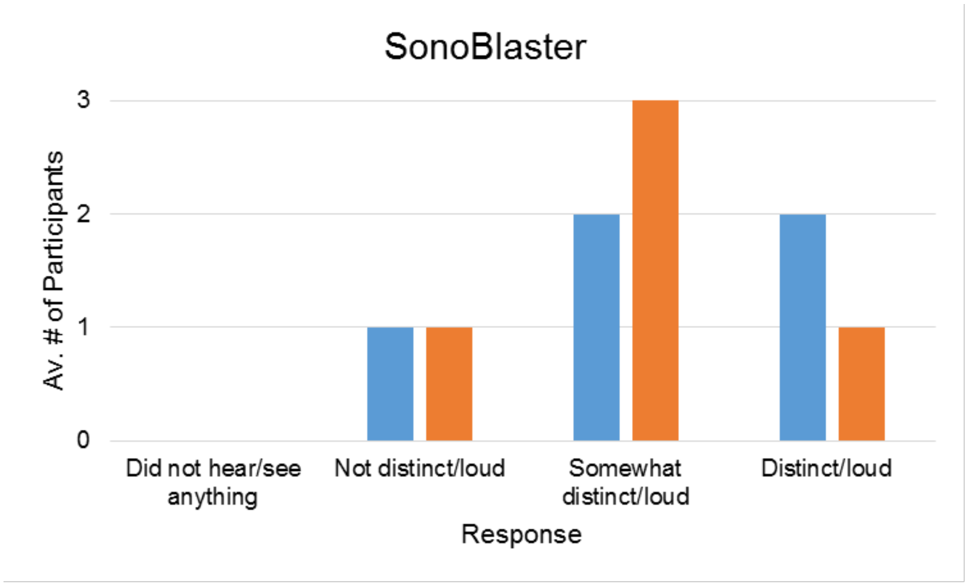

Figure G.1: Combined (Paving Crew and Inspector) Perception of SonoBlaster® Distinctiveness and Loudness

Worker Alert System (WAS)

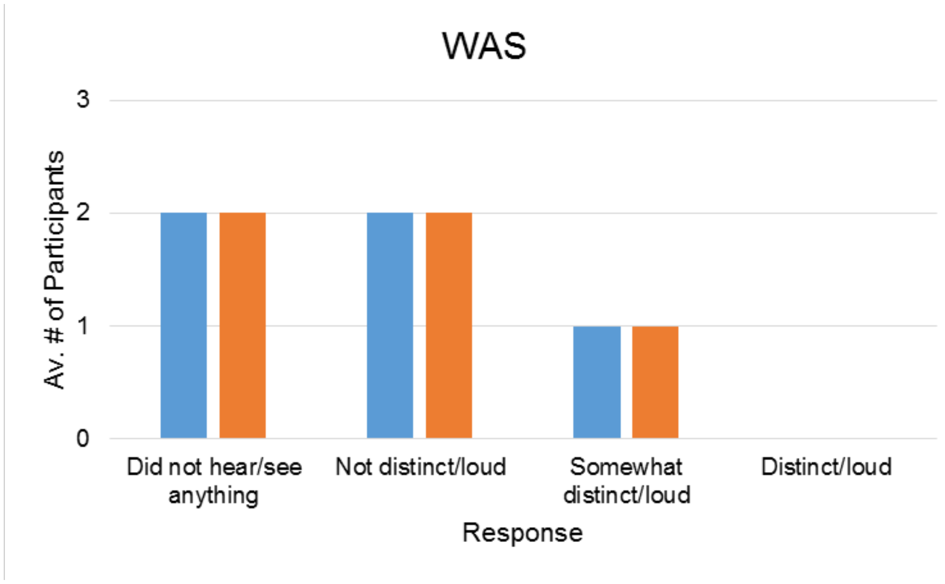

Figure G.2: Combined (Paving Crew and Inspector) Perception of WAS Distinctiveness and Loudness