STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA19-3038	N/A	N/A

4. TITLE AND SUBTITLE
Evaluation of Work Zone Intrusion Alarms

5. REPORT DATE
August 14, 2019

6. PERFORMING ORGANIZATION CODE
Sacramento State

7. AUTHOR(S)
Ghazan Khan, Shukurat Sanni, Steffen Berr, Kevan Shafizadeh

8. PERFORMING ORGANIZATION REPORT NO.
N/A

9. PERFORMING ORGANIZATION NAME AND ADDRESS
California State University Sacramento
Department of Civil Engineering
6000 J St. Sacramento, CA 95819-6029

10. WORK UNIT NUMBER
N/A

11. CONTRACT OR GRANT NUMBER
65A0643

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
P.O. Box 942873, MS #83
Sacramento, CA 94273-0001

13. TYPE OF REPORT AND PERIOD COVERED
Final Report
June 16, 2017 – August 14, 2019

14. SPONSORING AGENCY CODE
Caltrans

15. SUPPLEMENTARY NOTES

16. ABSTRACT
The main goal of this research was to evaluate the effectiveness of work zone intrusion alarm (WZIA) systems and assess their readiness to be deployed in California work zones. Four WZIA systems were selected for evaluation; one of which was subsequently dropped because of unavailability of the device. A detailed evaluation framework was developed to assess the performance of each system and understand their capabilities, issues, and limitations. Pilot testing was conducted resulting in some known issues from the literature, and other new issues and unexpected results; followed by supplemental testing to better assess the systems' capabilities and strengthen the conclusions derived. The final results showed that the Worker Alert System (WAS) performed well with certain limitations and differences observed from the manufacturer's specifications. The SonoBlaster system encountered several issues and limitations, most of which could not be resolved or corrected. The Intellicone system's intermittent issues observed during the pilot testing were resolved after extensive tests and consultation with the manufacturer and all subsequent trials were successful. Supplemental plans to the Caltrans standard work zone traffic control plans were developed which describe the deployment location, range distances, and setup of the Intellicone and WAS. Implementation of the Intellicone and WAS in California work zones could provide additional safety benefits, supplementing existing safety practices for the benefit of work zone workers and reducing work zone fatalities.

17. KEY WORDS
Work Zone Safety, Work Zone Intrusion Alarm, Testing and Evaluation

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	154	N/A

DISCLAIMER

EVALUATION OF WORK ZONE INTRUSION ALARMS

FINAL REPORT

Ghazan Khan, Ph.D.

Shukurat Sanni

Steffen Berr

Kevan Shafizadeh, Ph.D., P.E., PTOE, PTP

Department of Civil Engineering

California State University, Sacramento

August 14, 2019

ABSTRACT

The main goal of this research was to evaluate the effectiveness of work zone intrusion alarm (WZIA) systems and assess their readiness to be deployed in California work zones. Four WZIA systems were selected for evaluation, one of which was subsequently dropped because of unavailability of the device. A detailed evaluation framework was developed to assess the performance of each system and understand their capabilities, issues, and limitations. Pilot testing was conducted, resulting in some issues identified during the literature review, and other new issues and unexpected results. Supplemental testing was subsequently conducted to better assess the systems' capabilities and strengthen the conclusions. The final results showed that the Worker Alert System (WAS) performed well, with certain limitations and differences from the manufacturer's specifications observed. The SonoBlaster system encountered several issues and limitations, most of which could not be resolved or corrected. The Intellicone system's intermittent issues observed during the pilot testing were resolved after extensive tests and consultation with the manufacturer. All subsequent trials were successful. Supplemental plans to the Caltrans standard work zone traffic control plans were developed. These supplemental plans detail the deployment location, range distances, and setup of the Intellicone and WAS. Implementation of the Intellicone and WAS in California work zones could provide additional safety benefits, supplementing existing safety practices for the benefit of work zone workers and reducing work zone fatalities.

EXECUTIVE SUMMARY

Maintaining worker safety in work zones is of paramount concern to Caltrans and other highway agencies in the United States. Even though Caltrans maintains high worker safety standards through its operations and equipment standards, the need to find ways to further improve highway work zone safety persists. In this respect, a work zone intrusion alarm (WZIA) system is a set of equipment that provides highway workers with additional warning of unauthorized vehicles and errant motorists that enter a work zone. WZIA systems are designed to supplement best work zone practices and traffic control devices set by the Manual on Uniform Traffic Control Devices (MUTCD).

The main goal of this research was to evaluate the effectiveness of WZIA systems and assess whether such systems are ready to be deployed in California work zones. The objective was to provide recommendations to Caltrans on the effectiveness and practicality of implementing such systems and provide guidance on their implementation.

A detailed review of the literature and the market was conducted to compile comprehensive details on three types of systems/devices, ranging from commercially available intrusion alarm systems and emerging technologies to technologies that could be adapted/upgraded to mitigate work zone intrusions. Four WZIA systems listed below were selected in consultation with the Project Advisory Panel for detailed evaluation, one of which, the TAPCO Temporary Speed Bumps and Rumble Strips, was subsequently dropped because of unavailability of the device.

1. Traffic Guard Worker Alert System (WAS)
2. SonoBlaster
3. Intellicone
4. TAPCO Portable Rumble Strips

A detailed evaluation framework was developed to effectively assess the performance of each system and understand their capabilities, issues, and limitations. In view of the evaluation framework, pilot testing of the selected WZIA systems was conducted at the Caltrans Maintenance Equipment Training Academy (META) testing facility. Most of the tests revealed valuable data and information including some known issues from the literature review, new issues, and unexpected results, which were documented in this research. Given the preliminary findings of the pilot testing, supplemental testing was conducted to better assess the capabilities of the WZIA systems and strengthen the conclusions derived. Some of the issues documented during pilot testing were clarified after discussions with the manufacturers while others were resolved through newly devised tests.

The final results showed that the WAS performed well with certain limitations and differences observed from the manufacturer's specifications. Caltrans maintenance workers favored the simplicity and flexibility of the system in deployment, operation, and overall improvement of work zone safety. During supplemental testing, the SonoBlaster system encountered several issues and limitations similar to the ones observed during the pilot testing, most of which could not be resolved or corrected. Maintenance workers expressed a general lack of interest with the deployment and maintenance aspects of the device, especially the increased worker exposure time during deployment. In the survey of Caltrans maintenance staff, the SonoBlaster was the only device that was believed to decrease safety in a work zone. The Intellicone system's intermittent issues observed during the pilot testing were resolved after extensive tests and consultation with the manufacturer and all subsequent trials were successful.

Given the evaluation results and considering the capabilities and limitations, guidance on the practical deployment of the selected WZIA systems was developed in the form of supplemental plans to the Caltrans standard work zone traffic control plans. The supplemental plans detailed the deployment location, range distances, and setup of the Intellicone and WAS. No specific guidance was provided for the SonoBlaster system, given the issues and challenges observed during this research.

Based on the overall outcomes of this research, the Intellicone and WAS performed the best with consistent results of all evaluation tests upon resolution of the pilot testing issues. Implementation of the Intellicone and WAS in California work zones could provide additional safety benefits, supplementing existing safety practices for the benefit of work zone workers and reducing work zone fatalities. The development of a detailed evaluation framework and testing protocols in this research provides governing and regulatory agencies the ability to conduct systematic and objective tests in the future to make informed decisions in selecting and implementing applicable WZIAs. Although false alarms and deployment time are drawbacks to the implementation of WZIAs, the systems tested in this research generally appear effective in alerting workers of work zone intrusions.

TABLE OF CONTENTS

ABSTRACT .... **I**

EXECUTIVE SUMMARY .... **II**

TABLE OF CONTENTS .... **IV**

LIST OF FIGURES .... **VII**

LIST OF TABLES .... **IX**

LIST OF ACRONYMS AND ABBREVIATIONS .... **X**

ACKNOWLEDGEMENTS .... **XI**

1 INTRODUCTION **1**

1.1 INTRODUCTION AND BACKGROUND 1
1.2 RESEARCH NEEDS 2
1.3 OBJECTIVES AND TASKS 3
1.4 REPORT ORGANIZATION 5

2 LITERATURE REVIEW **6**

2.1 TYPES OF WORK ZONE INTRUSION ALARM TECHNOLOGY SYSTEMS 6
2.2 SUMMARY OF WZIA SYSTEMS, RELEVANT TECHNOLOGIES, AND OTHER DEVICES 7
2.3 COMMERCIALLY AVAILABLE WORK ZONE INTRUSION ALARM SYSTEMS 8
2.3.1 Traffic Guard Worker Alert System 8
2.3.1.1 Description and Specifications 8
2.3.1.2 Setup/Installation and Operation 9
2.3.1.3 Related Literature 9
2.3.2 SonoBlaster 10
2.3.2.1 Description and Specifications 10
2.3.2.2 Setup/Installation and Operation on a Traffic Cone 11
2.3.2.3 Related Literature 11
2.3.3 Intellicone System 12
2.3.3.1 Description and Specifications 12
2.3.3.2 Setup/Installation and Operation 13
2.3.3.3 Related Literature 14
2.3.4 General Findings from Literature for Currently Available WZIA Systems 14
2.4 EMERGING WORK ZONE INTRUSION ALARM SYSTEMS 15
2.4.1 Advanced Warning and Risk Evasion 15
2.4.1.1 Description and Specifications 15
2.4.1.2 Operation 16
2.4.1.3 Related Literature 17
2.4.2 Intellistrobe W1-AG 17
2.4.2.1 Description and Specifications 17

2.4.3 *AutoFlagger* *18*
2.4.3.1 Description and Specifications 18
2.4.3.2 Operation 20
2.4.3.3 Related Literature 20
2.5 Systems and Devices Related to Work Zone Management and Safety 20

3 WZIA SYSTEMS PROCUREMENT AND TESTING PROTOCOLS 21

3.1 System Procurement and Specifications 21
3.2 Evaluation Framework, Methodology, and Testing Protocols 24
3.2.1 *Development of Testing Protocols* *25*
3.2.2 *Development of a Work Zone Workers Survey* *26*

4 PILOT TESTING OF WZIA SYSTEMS 27

4.1 Pilot Testing Location and Schedule 27
4.2 Pilot Testing Results: the Worker Alert System 27
4.2.1 *Functional Characteristics - Deployment* *29*
4.2.2 *Relationship Between Sound Level and Distance* *30*
4.2.3 *Functional Characteristics - Operation* *33*
4.2.4 *Observations and Feedback* *36*
4.3 Pilot Testing Results: SonoBlaster 37
4.3.1 *Functional Characteristics - Deployment* *37*
4.3.2 *Relationship Between Sound Level and Distance* *40*
4.3.3 *Functional Characteristics – Operation* *44*
4.3.4 *Observations and Feedback* *45*
4.4 Pilot Testing Results: Intellicone 47
4.4.1 *Functional Characteristics - Deployment* *47*
4.4.2 *Relationship Between Sound Level and Distance* *49*
4.4.3 *Functional Characteristics - Operation* *51*
4.4.4 *Observations and Feedback* *54*

5 SUPPLEMENTAL TESTING OF WZIA SYSTEMS 56

5.1 Supplemental Testing Background and Details 56
5.2 Supplemental Testing Location and Schedule 58
5.3 Worker Alert System Supplemental Testing Results 59
5.3.1 *Functional Characteristics – Operation and Range Test Trials* *59*
5.4 SonoBlaster Supplemental Testing Results 61
5.5 Intellicone Supplemental Testing Results 62
5.6 Work Zone Maintenance Workers Training, Deployment, Operation, and Feedback Session 64
5.6.1 *Effectiveness of Mitigating Collisions and Improving Work Zone Safety 65*
5.6.2 *Device Effectiveness* *66*
5.6.3 *Deployment and Operation* *68*
5.6.4 *Durability of Devices* *70*

5.6.5 Distinctiveness of Sound ... *72*
5.6.6 Summary of Survey Comments, Feedback, and Recommendations. *73*

6 WZIA SYSTEMS EVALUATION DISCUSSION AND GUIDANCE ON PRACTICAL IMPLEMENTATION ... 75

6.1 OVERALL EVALUATION OF WZIA SYSTEMS – DISCUSSION AND OUTCOMES ... 75
6.1.1 Overall Evaluation of the Worker Alert System ... *75*
6.1.2 Overall Evaluation of the SonoBlaster ... *79*
6.1.3 Overall Evaluation of the Intellicone System ... *80*
6.2 GUIDANCE ON PRACTICAL DEPLOYMENT IN WORK ZONES ... 83
6.2.1 Worker Alert System – Recommended Deployment Plans ... *84*
6.2.2 SonoBlaster – Recommended Deployment Plans ... *86*
6.2.3 Intellicone – Recommended Deployment Plans ... *86*
6.2.4 Additional Guidance on WZIA Systems Deployment ... *88*
6.3 COST BENEFIT ANALYSIS OF SELECTED WZIA SYSTEMS ... 88
6.3.1 Cost Analysis ... *89*
6.3.1.1 Worker Alert System ... 89
6.3.1.2 SonoBlaster and Intellicone ... 89
6.3.2 Benefit Analysis ... *90*

7 CONCLUSIONS AND FUTURE RESEARCH ... 91

7.1 SUMMARY OF WZIA SYSTEMS, RELATED DEVICES, AND RELEVANT TECHNOLOGIES ... 91
7.2 DEVELOPMENT OF TESTING PROTOCOLS FOR EVALUATING WZIA SYSTEMS ... 91
7.3 PILOT TESTING OF SELECTED WZIA SYSTEMS ... 92
7.3.1 Worker Alert System ... *93*
7.3.2 SonoBlaster ... *93*
7.3.3 Intellicone System ... *94*
7.4 SUPPLEMENTAL TESTING OF SELECTED WZIA SYSTEMS ... 94
7.4.1 Worker Alert System ... *95*
7.4.2 SonoBlaster ... *95*
7.4.3 Intellicone ... *96*
7.5 GUIDANCE ON PRACTICAL IMPLEMENTATION OF SELECTED WZIA SYSTEMS ... 96
7.6 FUTURE RESEARCH ... 97

8 REFERENCES ... 100

APPENDIX A ... 105

APPENDIX B ... 112

APPENDIX C ... 118

APPENDIX D ... 122

APPENDIX E ... 126

APPENDIX F ... 132

APPENDIX G ... 138

LIST OF FIGURES

FIGURE 2.1 TRAFFIC GUARD WORKER ALERT SYSTEM COMPONENTS 8
FIGURE 2.2 SONOBLASTER SYSTEM COMPONENTS 10
FIGURE 2.3 INTELLICONE SYSTEM 12
FIGURE 2.4 COMPONENTS OF THE AWARE SYSTEM 16
FIGURE 2.5 AWARE DETECTION OPERATION 17
FIGURE 2.6 INTELLISTROBE W1-AG 18
FIGURE 2.7 AUTOFLAGGER AF-54 19
FIGURE 2.8 AUTOFLAGGER 76X 19
FIGURE 3.1 TRAFFIC GUARD WAS RT ALARM UNIT ON THE LEFT AND CAL UNIT ON THE RIGHT 22
FIGURE 3.2 INTELLICONE SYSTEM PSA AND LAMPS 23
FIGURE 3.3 TWO SONOBLASTER UNITS INSTALLED ON TWO STANDARD TRAFFIC CONES 23
FIGURE 3.4 METHODOLOGY FRAMEWORK 24
FIGURE 4.1 WAS DEPLOYMENT LAYOUT DURING PILOT TESTING 28
FIGURE 4.2 PHOTO OF WAS DEPLOYMENT DURING PILOT TESTING 28
FIGURE 4.3 WAS PRESSURE SENSOR LED LIGHT 29
FIGURE 4.4 WAS SOUND LEVEL MEASUREMENTS DOWNSTREAM OF WORK AREA 32
FIGURE 4.5 WAS SOUND LEVEL MEASUREMENTS UPSTREAM OF WORK AREA 32
FIGURE 4.6 PHOTO OF WAS OPERATIONAL TRIALS 34
FIGURE 4.7 STACKED TRAFFIC CONES WITH INSTALLED SONOBLASTER 38
FIGURE 4.8 INSUFFICIENT SPACE IN CONE BODY TRUCK FOR TWO ROWS OF SONOBLASTER CONES 38
FIGURE 4.9 DEPLOYING A SONOBLASTER MOUNTED CONE FROM A STANDARD CALTRANS CONE BODY TRUCK 38
FIGURE 4.10 PHOTO OF SONOBLASTER SOUND TEST WITH HORN POINTING DOWNWARD 41
FIGURE 4.11 SONOBLASTER SOUND LEVEL MEASUREMENTS DOWNSTREAM OF WORK AREA 43
FIGURE 4.12 SONOBLASTER SOUND LEVEL MEASUREMENTS UPSTREAM OF WORK AREA 43
FIGURE 4.13 DEPLOYMENT LAYOUT OF INTELLICONE SYSTEM DEPLOYMENT DURING PILOT TESTING . 47
FIGURE 4.14 SOUND LEVEL MEASUREMENTS UPSTREAM AND DOWNSTREAM OF WORK AREA FOR INTELLICONE 51
FIGURE 4.15 PHOTO OF INTELLICONE OPERATIONAL AND LAMP SENSITIVITY TEST 53
FIGURE 4.16 PHOTO OF INTELLICONE PSA VISUAL ALERT TEST AT NIGHT 53
FIGURE 5.1 WAS ALARM UNIT ATTACHED TO A VEHICLE IN THE WORK ZONE (4 FEET ABOVE THE GROUND) 59
FIGURE 5.2 DEPLOYMENT LAYOUT OF WAS RANGE TESTS DURING SUPPLEMENTAL TESTING 61
FIGURE 5.3 PHOTO OF INTELLICONE LAMP SENSITIVITY TESTS USING HIGH SPEED VIDEO 63
FIGURE 5.4 PHOTO OF INTELLICONE OPERATION TESTS WITH LAMPS DEPLOYED ON A TANGENT-CURVE COMBINATION 64
FIGURE 5.5 CALTRANS MAINTENANCE SUPERVISORS TRAINING AND FEEDBACK SESSION 65
FIGURE 5.6 EFFECTIVENESS OF WZIA DEVICES IN MITIGATING WORK ZONE COLLISIONS 66
FIGURE 5.7 EFFECTIVENESS OF WZIA DEVICES IN IMPROVING WORK ZONE SAFETY 66
FIGURE 5.8 GENERAL EFFECTIVENESS OF THE WORKER ALERT SYSTEM 67

Figure 5.9 General Effectiveness of the SonoBlaster..67
Figure 5.10 General Effectiveness of the Intellicone System 68
Figure 5.11 Difficulty/Ease of Deploying and Operating the Worker Alert System........69
Figure 5.12 Difficulty/Ease of Deploying and Operating the SonoBlaster.....................69
Figure 5.13 Difficulty/Ease of Deploying and Operating the Intellicone........................70
Figure 5.14 Durability of the Worker Alert System 71
Figure 5.15 Durability of the SonoBlaster 71
Figure 5.16 Durability of the Intellicone System..72
Figure 5.17 Sound Distinctiveness of the Worker Alert System 72
Figure 5.18 Sound Distinctiveness of the SonoBlaster 73
Figure 5.19 Sound Distinctiveness of the Intellicone System...73
Figure 6.1 Worker Alert System Layout for Reaction Time Calculations 78
Figure 6.2 Intellicone System Layout for Reaction Time Calculations 82
Figure 6.3 Recommended Deployment Plan for Worker Alert System on a Standard T-13 Closure 85
Figure 6.4 Recommended Deployment Plan for Worker Alert System on a Standard Ramp Closure...85
Figure 6.5 Recommended Deployment Plan for Intellicone on a Standard T-13 Closure 87
Figure 6.6 Recommended Deployment Plan for Intellicone on a Standard Ramp Closure 88

LIST OF TABLES

Table 2.1 List of Commercially Available WZIA Systems 7
Table 2.2 List of Emerging WZIA Systems 7
Table 2.3 Applications of Intellicone Portable Site Alarm (PSA) Systems 14
Table 3.1 Possible WZIA Evaluation Trial Outcomes 25
Table 4.1 WZIA Systems Pilot Testing – Schedule and Field Conditions 27
Table 4.2 Worker Alert System – Pre-Deployment Functional Characteristics 29
Table 4.3 Worker Alert System – Work Zone Deployment Functional Characteristics 30
Table 4.4 Worker Alert System – Sound Test Details Relative to Alarm Orientation and Distance 31
Table 4.5 Worker Alert System – Operation Functional Characteristics 33
Table 4.6 Worker Alert System – Results of Operational Trials During Pilot Testing 35
Table 4.7 Worker Alert System – Miscellaneous Observations and Feedback 36
Table 4.8 SonoBlaster – Pre-Deployment Functional Characteristics 39
Table 4.9 SonoBlaster – Work Zone Deployment Functional Characteristics 39
Table 4.10 SonoBlaster - Details of Sound Tests Relative to Alarm Orientation and Distance 41
Table 4.11 SonoBlaster – Results of Operational Trials during Pilot Testing 44
Table 4.12 SonoBlaster – Operation Functional Characteristics 45
Table 4.13 SonoBlaster – Miscellaneous Observations 46
Table 4.14 SonoBlaster – Feedback from Maintenance Workers 46
Table 4.15 Intellicone – Pre-Deployment Functional Characteristics 48
Table 4.16 Intellicone – Work Zone Deployment Functional Characteristics 49
Table 4.17 Intellicone - Details of Sound Tests Relative to Alarm Orientation and Distance 50
Table 4.18 Intellicone – Operation Functional Characteristics 52
Table 4.19 Intellicone – Miscellaneous Observations 55
Table 4.20 Intellicone – Feedback from Maintenance Workers 55
Table 5.1 WZIA Systems Supplemental Testing – Schedule and Field Conditions 58
Table 5.2 Worker Alert System – Range Tests 60
Table 5.3 Worker Alert System – Results of Operational Trials during Supplemental Testing 61
Table 5.4 Summary of Written Comments by Maintenance Staff on WZIA Systems 74
Table 6.1 Worker Alert System Reaction Time for Workers with Minimal Setup 77
Table 6.2 Intellicone System Reaction Time for Workers with Minimal Setup 83

LIST OF ACRONYMS AND ABBREVIATIONS

AFAD	automated flagger assistance device
AWARE	Advanced Warning and Risk Evasion
BWZA	Be Work Zone Alert
Caltrans	California Department of Transportation
CBA	cost-benefit analysis
CO_2	carbon dioxide
dBA	A-weighted decibels
DRISI	Caltrans Division of Research, Innovation and System Information
FHWA	Federal Highway Administration
fps	frames per second
GPRS/GSM	General Packet Radio Service/Global System for Mobile
GPS	global positioning system
META	Maintenance Equipment Training Academy
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
PAC	portable alarm case
PCMS	portable changeable message signs
PI	preliminary investigation
PSA	portable site alarm
PSD	personal safety device
RF	radio frequency
SIM	Subscriber Identity Module
SHRP	Strategic Highway Research Program
SMS	short message service
TMU	Traffic Management Unit
TTI	Texas Transportation Institute
VDOT	Virginia Department of Transportation
WAS	worker alert system
WZIA	work zone intrusion alarm

ACKNOWLEDGEMENTS

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Arvern Lofton, Justin Unck, and Joe Horton with the Division of Research, Innovation and System Information, and Theresa Drum, Patti-Jo Dickinson, Tim Lang, Marvin Guinez, David Frame, William Farnbach, and Joel Allen with the Division of Maintenance. The authors thank Atifa Ferouz and Nestor Cuellar with the Division of Traffic Operations, and Ed Yarbrough and Kim Smith with the Division of Construction (District 3) for their valuable participation, support, and contributions.

The authors express their gratitude to the staff at the Caltrans Maintenance Equipment Training Academy (META), especially Larry Schwartz, for their active and excellent support in setting up the lane closures for field testing at the META facility. We also thank the numerous participants of the work zone training program and the maintenance supervisors who shared their valuable insights on the work zone intrusion alarm systems and participated in the feedback survey during field testing. The authors thank Timothy Shaw, Geno Cervantes, and Jeff Adams for their efforts in providing the test vehicle for field testing. The authors acknowledge the dedicated efforts of the research team at Sacramento State including Cynthia Ruiz, Shukurat Sanni, Steffen Berr, and Dr. Kevan Shafizadeh who have made this work possible.

1 INTRODUCTION

1.1 INTRODUCTION AND BACKGROUND

California relies on its transportation infrastructure for its $2.7 trillion economy and mobility of its citizens. The California Department of Transportation (Caltrans) maintains and repairs California's 50,000 highway lane miles, 12,000 bridges, 205,000 culverts and drainage systems, 87 roadside rest areas, and 30,000 acres of roadside landscaping (Be Work Zone Alert [BWZA], 2018). Local municipalities also maintain significant infrastructures that are essential to the state's economy. Work zones play a vital role in construction personnel and government agencies' ability to maintain and preserve transportation infrastructure. As the transportation infrastructure ages, there is an increase in maintenance and construction activities resulting in increased workers' and motorists' exposure to work zone hazards.

A work zone is an area of a traffic way with highway construction, maintenance, or utility-work activities typically marked by signs, channeling devices, barriers, pavement markings, and/or work vehicles. The work zone extends from the first warning sign or flashing lights on a vehicle to the "End of Road Work" sign or the last traffic control device (Federal Highway Administration [FHWA], 2017). Work zone strategies include, but are not limited to, lane constrictions, flagging practices, ramp closures, lane closures, complete closures, reduced shoulder-width, off-site detours, signage, and work hour restrictions. Even when used in combination, the limitations of these strategies cannot eliminate all safety risks for workers and the travelling public. The risks are further heightened by errant motorists who may overlook the cautionary traffic control devices placed on or near work zones and intrude into the work zone area, thus resulting in collisions, property damage, injuries, and fatalities.

The Virginia Department of Transportation (VDOT, 2018) reported that speed, alcohol, and motorist distraction are major causes of work zone collisions. Nationwide, 85 percent of drivers are believed to be distracted by cell phone usage; the average distraction time of texting while driving is five seconds (VDOT, 2018). With work zone personnel only a few feet away from the travel way, distracted motorists create one of the most challenging work zone hazards. Closing a roadway for work zone activities for an extended period may not be feasible, hence maintaining a balance between mobility needs and safety of workers in a work zone is challenging.

According to estimates, more than 20,000 workers are injured in work zones each year with 12 percent of those due to traffic incidents. FHWA estimates that one work zone fatality occurs for every $112 million worth of roadway construction expenditures (FHWA, 2018). Work zone fatalities in the United States increased from 782 in 2016 to 799 in 2017. The *Be Work Zone Alert* (BWZA) campaign reported that 45 percent of highway work zones in California in 2013 experienced vehicle crashes and 6,525 work zone collisions occurred on California highways in 2014 (BWZA, 2018). As of 2018, 189 Caltrans employees have been killed on the job since 1921 (Caltrans, 2018).

Maintaining worker safety in work zones is of paramount concern to Caltrans and other highway agencies in the United States. There are several ways to promote the safety of highway workers in work zones, e.g. using safe work practices and additional safety measures such as temporary work zone signage including portable changeable message signs (PCMS), automated flagging assistance, etc. Even though Caltrans maintains high worker safety standards through its operations and equipment standards, the need to find ways to further improve highway work zone safety persists.

In response to work zone safety concerns, the Strategic Highway Research Program (SHRP) introduced work zone intrusion alarm (WZIA) systems in 1995 (Awolusi & Marks 2019). A WZIA system is a set of equipment that provides highway workers with additional warning of unauthorized vehicles, including errant motorists that enter a work zone. WZIA systems are designed to supplement best work zone practices and traffic control devices set by the *Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD),* published by FHWA. Concurrently, WZIA systems could also alert motorists of the intrusion, giving them a chance to mitigate the intrusion (Gambatese et al., 2017). WZIA systems usually include a detector, transmitter, and auditory alert unit. Additionally, some systems have visual and personal safety device options.

1.2 RESEARCH NEEDS

WZIA systems can improve work zone safety by warning workers of work zone intrusions and are a cost-effective work zone safety practice (Gambatese et al., 2017). To further improve work zone safety, Caltrans is considering the use of WZIA systems to augment current Caltrans Standard Plans for traffic control in work zones. In this respect, a preliminary investigation (PI) was completed by the Caltrans Division of Research, Innovation and System Information (DRISI) to explore commercially available WZIA systems (Fyhrie, 2016).

However, since the introduction of WZIA systems over 20 years ago, consensus has not been reached on implementation, due to a lack of actual usage and a uniform set of standards for comparison. There are limited results that could promote the integration of WZIA systems into policy and practice. Furthermore, there are various types of WZIA systems based on different technologies available commercially. A few studies on the feasibility of these devices have been conducted, most recently in Texas, Kansas, and Oregon, yielding varying and inconclusive results on their effectiveness and use.

1.3 OBJECTIVES AND TASKS

The main objective of this research was to assess the effectiveness of selected WZIA systems through a comprehensive set of field tests and evaluations to validate manufacturer specifications and the findings of other research studies. Furthermore, this research intended to provide Caltrans with recommendations on specific WZIA systems with regards to their capabilities, deployment, practicality, effectiveness, and reliability. The research objective also included documenting and evaluating promising commercially available WZIA systems and related technologies for effectiveness, benefits, and shortcomings. In view of the objectives, the following list of tasks were completed in this research.

Task 1: Project Management

Project management included management of research tasks, budgeting, submission of progress reports, and scheduling meetings with Caltrans staff.

Task 2: Stakeholder Identification and Project Advisory Panel Setup

A Project Advisory Panel was established, consisting of members from Caltrans, to provide guidance and input at various stages in this research.

Task 3: WZIA Systems Assessment and Literature Review

A review of the current and emerging literature was conducted to identify new research, evaluate current practices in other states, and determine availability of various technologies, products, and systems related to WZIA. Vendors of WZIA technologies were contacted to obtain detailed information about each system. Consultation with the Project Advisory Panel was conducted to select the most appropriate systems and discard any systems that may not be suitable for Caltrans needs.

Task 4: Procuring WZIA Systems

WZIA systems identified as suitable for testing in this research were procured in consultation with the Project Advisory Panel and vendors.

Task 5: Developing Preliminary Testing Plans and Protocols

A set of testing protocols was developed in consultation with the Project Advisory Panel to evaluate the performance and implementation of selected WZIA systems. Based on the characteristics of specific systems, clear criteria were developed for evaluating the systems' deployment, installation, operation, effectiveness, and limitations. Additional checklists were developed to evaluate the performance of WZIA systems in the case of a detected or undetected vehicle entry into the work zone. A list of worker survey questions was also developed to obtain data for the performance evaluation of specific WZIA systems. Supplements to the Caltrans Standard Plans for traffic control in work zones were developed to show proposed setup and implementation details of selected WZIA systems focusing on T-10 through T-13 Caltrans Standard Plans for traffic control in work zones.

Task 6: Pilot Testing and Evaluation

Based on the testing protocols, initial testing of WZIA systems was conducted at a closed facility (not on a roadway) to understand the deployment, practical implementation, system capabilities, and limitations. Detailed data collected during pilot testing was analyzed and presented to the Project Advisory Panel showcasing outcomes, issues, and limitations of each selected system.

Task 7: Supplemental Testing

The original research proposal included testing and evaluating selected WZIA systems in an active work zone as part of Task 7. However, in view of the pilot testing results and in consultation with the Project Advisory Panel, active work zone testing was replaced with additional supplemental tests due to concerns that the systems were not ready for on-highway/live roadway testing, and to allow for resolving questions and issues discovered during the pilot testing. Vendors were contacted to discuss the issues identified during the pilot testing to determine remedies and changes to the systems to make them effective. The research team worked with maintenance staff to provide training and guidance on the deployment and usage of WZIA systems. Furthermore, a survey was conducted of selected work zone staff from Caltrans to obtain input on each selected WZIA system.

Task 8: Documentation and Final Report

A final report was prepared documenting all findings of the research and final recommendations to Caltrans. A discussion on the cost-benefit analysis (CBA) of the tested WZIA systems was provided to determine if the implementation of the systems will be beneficial or not. Supplements to Caltrans Standard Plans (T-10 through T-13) were provided for the deployment and implementation of selected WZIA systems.

1.4 REPORT ORGANIZATION

All aspects of the research activities are presented in detail in this report in the subsequent chapters and are organized as follows:

- Chapter 1 presents an introduction, background, research needs, objectives, and tasks.
- Chapter 2 presents the types of WZIA devices and related technologies and identifies emerging and commercially available systems in detail.
- Chapter 3 presents details of the selected WZIA systems procured during this research. Chapter 3 also presents the development and details of a comprehensive evaluation framework (methodology) and testing protocols including checklists and detailed survey used to evaluate the systems.
- Chapter 4 presents details of pilot testing activities and evaluation results.
- Chapter 5 presents details of the supplemental testing activities and evaluation results.
- Chapter 6 presents a detailed discussion of the overall evaluation and provides guidance on the practical deployment of the selected WZIA systems.
- Chapter 7 presents conclusions and future recommendations.

2 LITERATURE REVIEW

This chapter describes the types of WZIA systems and presents a review of literature including a list of available, emerging, and other technologies that have the capability to be adapted to include work zone detection technology.

2.1 TYPES OF WORK ZONE INTRUSION ALARM TECHNOLOGY SYSTEMS

WZIA systems are often categorized into six types of intrusion technology systems described as follows (Fyhrie, 2016; Marks et al., 2017):

1. **Kinematic Intrusion Technology Systems:** Kinematic systems are impact activated. Devices with kinematic systems detect intruding vehicles when struck by a vehicle. These devices are typically attached to a traffic control device (Fyhrie, 2016).
2. **Infrared-Based Intrusion Technology Systems:** Infrared systems use beams of infrared light to connect device units that are typically deployed on separate cones or barrels. Such systems require precise alignment of the infrared beam between the source and the receptor. The system is triggered by an object interrupting the beam that activates an alarm placed around the work zone (Carlson et al., 2000).
3. **Pneumatic Intrusion Technology Systems:** Pneumatic systems utilize pneumatic tubes that are connected to a transmitter. The tube activates an alert mechanism such as a siren or a strobe light. The tubes are typically placed on the roadway perpendicular to the flow of traffic at the beginning of a work zone. The alert mechanisms are activated when an intruding vehicle passes over tube (Carlson et al., 2000).
4. **Microwave Intrusion Technology Systems:** Microwave systems feature a transmitter, a receiver, and a siren connected together (Carlson et al., 2000). Microwave signals are used to connect to the base unit and activate an alert when a vehicle intrudes the work zone (Wang et al., 2011). Devices with microwave technology are typically mounted on traffic barriers (Fyhrie, 2016).
5. **Radar-Based Intrusion Technology Systems:** Radar-based systems such as the Advanced Warning and Risk Evasion (AWARE) system include electronically scanned radar, high-precision differential global positioning system (GPS), accelerometers, gyroscopes, and magnetometers for position and orientation sensing. This system monitors work zone vicinity and assesses vehicle's approaching speed and trajectory to determine

the possibility of work zone intrusion and subsequently warns workers and motorists by activating warning lights and audible alarm (Theiss et al., 2017).

6. **Radio-Based Intrusion Technology Systems:** Radio-based intrusion systems use radio waves to facilitate communication between sensors and an alarm unit. The Intellicone system is an example of a radio-based (and kinematic) system where the sensors detect an intrusion and communicate with the alarm unit using a radio-based signal.

2.2 SUMMARY OF WZIA SYSTEMS, RELEVANT TECHNOLOGIES, AND OTHER DEVICES

An extensive review of the literature on work zone intrusion technologies was conducted to identify the spectrum of WZIA systems and related technologies as listed in Table 2.1 and Table 2.2.

Table 2.1 List of Commercially Available WZIA Systems

Device	Type	Audible Alert Mechanism	Visual Alert Mechanism	Vibratory Alert Mechanism
Traffic Guard Worker Alert System (WAS)	Microwave and Pneumatic	✓	✓	✓
SonoBlaster	Kinematic	✓	×	×
Intellicone	Kinematic and Radio-based	✓	✓	×

Key. ✓= present ×= not present

Table 2.2 List of Emerging WZIA Systems

Device	Type	Audible Alert Mechanism	Visual Alert Mechanism	Vibratory Alert Mechanism
AWARE	Radar-based	✓	✓	✓
Intellistrobe W1-AG	Microwave and Pneumatic	✓	✓	×
AutoFlagger 54 & 76X	NA	×	✓	×

Key. ✓= present ×= not present

Table 2.1 lists current commercially available WZIA systems and Table 2.2 lists emerging WZIA systems that should be available commercially in the future. Table 2.1 and Table 2.2 also includes a brief summary of the detection technology and the alert mechanisms of each device. A third category of systems and devices that are not directly related to work zone safety but have the capability of being adapted to include intrusion detection technology and alert features were also reviewed. A detailed description, specifications, operation, and related information from the literature review are presented in subsequent sections and in Appendix A.

2.3 COMMERCIALLY AVAILABLE WORK ZONE INTRUSION ALARM SYSTEMS

The following sections present detailed information on WZIA systems available on the market as of June 2019.

2.3.1 Traffic Guard Worker Alert System

2.3.1.1 Description and Specifications

Traffic Guard Worker Alert System (WAS), shown in Figure 2.1, is a pneumatic and microwave-based system with an auditory, visual, and haptic alarm that is wirelessly triggered when a vehicle crosses over a positioned pneumatic hose in a work zone. The components of WAS include the following:

- Portable alarm case (PAC) with pulsing sound blast and flashing light; henceforth known as the alarm unit
- Portable trip hose (a pneumatic tube) with pressure sensor and wireless transmitter
- Personal safety device (PSD) with audible and vibrating alarms

Figure 2.1 Traffic Guard Worker Alert System Components
(Source: trafficsafetywarehouse.com 2017)

2.3.1.2 Setup/Installation and Operation

The WAS uses a rechargeable battery to power the alarm unit, trip hoses of various lengths, and the option to connect multiple alarm units to the same trip hose. The WAS is installed by laying out the trip hose transverse to the anticipated intrusion direction of traffic into the work zone. Specific deployment steps are outlined in detail below.

1. Deploy trip hoses across the lane. Press the power button on the hose pressure sensor box. A light emitting diode (LED) will flash several times until the tube pressure is calibrated.
2. The alarm unit has a magnet, so it can be attached to a vehicle, structure, or equipment in a work zone. Set the alarm unit in a suitable location and press the power button under the handle, ensuring the green LED on the side of the unit is visible.
3. Turn on all workers' PSDs and verify the green LEDs are visible.
4. Step on a trip hose to activate the alarm to test that the system is functioning properly.

The WAS activates when a vehicle passes over the trip hose. The pressure sensor can send a signal wirelessly to the alarm unit and PSDs up to 1,000 feet away, according to manufacturer specifications (note: field testing does not support this claim). The audio alarm and flashing light are activated on the alarm unit alerting everyone in the work zone.

2.3.1.3 Related Literature

Gambatese conducted a study for the Oregon Department of Transportation, which found the duration of the WAS alarm to be consistently six seconds. The device produced a higher level of sound when the alarm was oriented towards the sound meter. A lag time of no more than one second was observed between the time the "pneumatic tube is pressured and when the alarm triggered." The transmission range from the trip hose to the alarm unit and PSDs, was 300 feet and 50 feet, respectively. The study recommended the WAS system for small-scale operations such as city streets or slow traffic. The researchers recommended deactivating the system to avoid false alarms during handling and placement of the device. The PSD's vibration feature provides an extra alert mechanism for workers; however, the PSD produced inconsistent vibration and audio alarms. The lack of distinctiveness of the alarm sound was a concern because it might not alert workers working too close to noisy equipment. A low battery in the alarm unit affected the audio transmission capabilities of the device and produced a weak visual alarm (Gambatese et al., 2017).

2.3.2 SonoBlaster

2.3.2.1 Description and Specifications

The SonoBlaster system, shown in Figure 2.2, is a kinematic work zone intrusion device. It is a mechanical system that emits an auditory alarm on impact in a work zone. The SonoBlaster comprises of a disposable carbon dioxide (CO_2) cartridge and an alarm unit. When impacted, the escaping gas from the punctured CO_2 cartridge produces sounds through an air-pressure horn. The device can be mounted on traffic cones, drums, delineators, A-frames, and other barricades. The main components of the SonoBlaster are:

- SonoBlaster alarm unit
- Disposable CO_2 cartridge
- Mounting bracket for mounting to a traffic cone

Figure 2.2 SonoBlaster System Components
(Source: Transpo Industries Inc., 2017)

2.3.2.2 *Setup/Installation and Operation on a Traffic Cone*

The following steps are to be followed in setting up and operating the SonoBlaster on a traffic cone.

1. Install the mounting bracket to the base of the cone, attach the device to the mounting bracket, and turn the knob to the unlock position.
2. Cock the SonoBlaster unit using a keychain tool.
3. Turn the knob to the locked position and install a CO_2 cartridge in the red compartment.
4. Place the traffic cone with the mounted SonoBlaster on the roadway while in "safe" mode.
5. Rotate the control knob from the locked position to the unlocked position.

SonoBlaster is an impact-tilt activated alarm system that alerts workers in the work zone at an audio level of 125 decibels (dBA) for at least 15 seconds. The system is mounted on cones and activates an alarm upon impact when the cone is tilted by more than 70 degrees. The system uses a disposable CO_2 cartridge and does not require a battery or power source.

2.3.2.3 *Related Literature*

A study conducted by Novosel for the Kansas Department of Transportation found the SonoBlaster alarm duration to be inconsistent, ranging from three to 80 seconds in duration. Irrespective of the orientation, the peak sound level occurred within the first second of firing and subsequent sound levels dropped off unevenly. Distinguishing the alarm from the backhoe noise was difficult while inside the backhoe (Novosel, 2014). A major concern with the SonoBlaster system was that in cold weather conditions and after the first activation, the compressed CO_2 cartridge used to operate the air horn alarm can become cold enough during firing that ice begins to condense on the cartridges. Novosel found that accumulated ice between the CO_2 cartridge and the firing pin resulted in the system not working properly. Furthermore, replacing the CO_2 cartridge in cold or wet weather conditions where water may come in contact with the nozzle could also be an issue (Novosel, 2014).

The study conducted by Gambatese found similar results to the Novosel study. The SonoBlaster yielded false negatives (system triggered but the alarm did not activate) and produced shorter bursts of sound after it had been used and the cartridge had been replaced. Gambatese deduced that the SonoBlaster was not designed to be reused and the consensus was that it should be discarded once it has been activated by an intrusion. Ice accumulation was also observed after activating the SonoBlaster in cold weather, which could cause delay in replacing the cartridge. The SonoBlaster sound level and duration was found to be inconsistent (Gambatese et al., 2017).

2.3.3 Intellicone System

2.3.3.1 Description and Specifications

The Intellicone system, shown in Figure 2.3, is a kinematic and radio-based system with a motion sensitive cone lamp and web enabled alarm unit equipped with General Packet Radio Service/Global System for Mobile (GPRS/GSM) communications and GPS sensors. The system offers a variety of communication options between the system components in the field and a central command location (some communication features are currently unavailable in the United States). The system includes a portable site alarm (PSA) and a traffic management unit (TMU). All devices, except for the TMU, can be mounted on a standard traffic cone. The electronic system transmits a warning signal when impacted, by producing auditory and visual alarm in a work zone.

Figure 2.3 Intellicone System
(Source: transcanadatraffic.ca 2019)

The main components of the Intellicone system are listed below, details of which are presented in Appendix A.

- PSA
    - Y-Series: Connects to Intellicone sensors via short range radio frequency (164-foot range)
    - R-Series: Connects to Intellicone sensors via short range radio frequency (164-foot range)
    - O-Series: Connects to Intellicone sensors via short range radio frequency (656-foot range)
- TMU
- Unipart Dorman ConeLITE® (lamp with impact sensor)
- Sentry (motion sensor)

2.3.3.2 Setup/Installation and Operation

The following steps are to be followed in setting up and operating the Intellicone system.

1. Deploy the Intellicone enabled lamps and/or Sentry unit on cones in the work zone.
    a. Lamps will provide an alert if they are pushed, impacted, or tilted.
    b. The Sentry unit provides a continuous ultrasonic beam and can be used to cover manned or unmanned work zone entrance points.
2. Fasten the TMU to a cone, sign, frame, or other work zone features. The Intellicone TMU is an optional device that should be placed within 164 feet of an Intellicone enabled barrier (lamps or Sentry). The TMU connects to the Intellicone web server, enabling the PSA to receive a remote signal.
3. Deploy one or more PSAs on cones around the work zone. A simple two-button operation will turn on the system. The PSA has a remote resetting function, which allows additional PSAs within the work zone to remotely reset the unit when activated.

The Intellicone system activates when a cone with lamp sensors is impacted or tilted beyond 45 degrees. The Sentry unit uses an ultrasonic beam which, when breached, will activate an alarm. The lamps and Sentry unit can transmit signals to the PSA, which activate an audio alert of 55 to 60 dBA at 400 feet (Novosel, 2014) and emit a flashing LED alarm. The lamps flash in steady intervals when activated and have a non-alarm related capability to function as sequential lighting. Table 2.2 shows the typical applications of the different types of Intellicone PSA systems.

Table 2.3 Applications of Intellicone Portable Site Alarm (PSA) Systems

PSA	Y-Series	R-Series	O-Series
Application	Large worksites with multiple work crews	Small to medium size temporary worksites	Safety critical
Sectors	Highway maintenance, construction, mining	Road maintenance, street works, incident response, heavy industry	Rail maintenance, heavy industry

(Source: Adapted from Trans Canada Traffic Inc., 2018)

2.3.3.3 Related Literature

A study conducted by Gambatese reported false positives with the Intellicone system resulting from operator error of mishandling the units during placement (Gambatese et al., 2017). The study recommended deactivating the audio alarm by muting the audio capability or shutting off the command unit to prevent false positives during deployment. The research found the sound level to be higher when two speakers were oriented towards the sound meter. The maximum range between a lamp and the PSA was up to 250 feet and the alarm duration was consistent at 32 seconds. Construction personnel that were surveyed indicated the system held greater promise if changes were made to the sound level, quality, and light intensity (Gambatese et al., 2017).

Similarly, Novosel found that even though engine and mechanical noises from construction vehicles in a work zone were louder than the Intellicone alarm levels, the alarm sound could be distinguished because of its high frequency and three tones (Novosel, 2014). However, distinguishing the alarm sound from the inside of a work zone vehicle (a backhoe) at 100 to 200 feet away, was difficult. The maximum sound level was around 90 dB at 10 feet and decreased to around 55 to 60 dB at 400 feet. The field testing of the Intellicone system resulted in one false negative (no alarm activated when there was an intrusion) and one false positive (alarm activated when there was no intrusion). The false positive occurred when one of the traffic cones moved because of air flow/pressure due to a fast-moving truck. Workers found the audible alarm on the Intellicone system difficult to hear due to the low sound volume (Novosel, 2014).

2.3.4 General Findings from Literature for Currently Available WZIA Systems

This section presents a summary of general findings from the literature on the evaluation of WZIA systems, a comparison of various systems, and additional information with respect to work zone safety. Marks conducted a study for the Alabama Department of Transportation, which observed that the WAS and

Intellicone alarms lasted for five and 60 seconds, respectively (Marks et al., 2017). Intellicone and WAS sound levels were similar at various distances, and the reaction time of workers was faster for the Intellicone than for the WAS, possibly because of the louder and amplified sound from the Intellicone PSA. The closer the worker was to the alarm, the faster the reaction time was observed. The WAS PSD was found to be ineffective because the vibratory alert had delays ranging from one to 2.5 seconds with an average delay of 0.37 seconds over the 15 trials performed. Workers took an average of 0.45 seconds to respond to the Intellicone alarm. The study recommended implementing the Intellicone for longer tapers in construction highway work zones, where traffic barrels or other temporary devices are implemented. The WAS was recommended for short tapers and short term or mobile highway work zone projects.

Gambatese recommended the WZIA devices be positioned close to the workers to ensure that those in the proximity of loud construction equipment can hear the alarm. The Intellicone and the WAS alarm sound from a single alarm unit was not audible beyond a distance of 250 feet and 300 feet, respectively. Therefore, multiple alarms may be required to adequately cover larger work areas. The orientation of the devices had a significant influence on the sound level, and, although the SonoBlaster produced the highest sound level, the Intellicone alarm was more consistent in volume and duration (Gambatese et al., 2017).

2.4 EMERGING WORK ZONE INTRUSION ALARM SYSTEMS

The following sections present information on WZIA systems or related technologies and devices that are either under development or have the potential to be retrofitted to be used as a WZIA system in the future. The purpose of reviewing these systems and technologies was to understand their potential to be used as WZIA systems and possibly initiate discussions with the manufacturers for retrofitting the devices for WZIA uses.

2.4.1 Advanced Warning and Risk Evasion

2.4.1.1 Description and Specifications

The AWARE system, shown in Figure 2.4, is a radar-based system that utilizes a target threat detection and tracking technology to assess approaching vehicle speed, location, and possible trajectory. Subsequently, the AWARE system can monitor possible work zone intrusions to alert workers in the work zone. AWARE is currently in development stages and is not commercially available. The system is one of two with a personal safety device for individual workers (the other being the WAS) and is recommended by the manufacturer for long duration highway work zone projects (Marks et al., 2017). The main components of the AWARE system are:

- The Raven (Radar Sensor)
- WorkTRAX (GPS based personal alarm unit)
- Visible and audible threat deterrent unit
- Base station (mobile app accessible)

Figure 2.4 Components of the AWARE System
(Source: Oldcastle Video Team, 2015)

2.4.1.2 Operation

AWARE radar sensor mounted in the back of a truck can detect vehicles in two flat fan-shaped protected regions covering a long and short range (Figure 2.5). The long-range detection area extends 500 feet upstream with a width of 10 degrees on either side of the radar sensor, totaling in a detection angle of 20 degrees. The short-range detection area covers 200 feet upstream with a total detection angle of 90 degrees. The AWARE radar sensor can monitor an active work zone by tracking the speed and heading of vehicles within the radar coverage area and uses stopping sight distance calculations to determine the appropriate response. If the trajectory of the vehicle is computed to intrude into the work area (or to be exceeding a reasonable speed approaching the work zone), the AWARE system is activated. The system provides an auditory and visual alert to the driver through a message and/or audio/visual alert mounted in the back of the truck. Additionally, workers are warned of the intrusion threat through the WorkTRAX personal tracking unit that produces a haptic alert (Theiss et al, 2017).

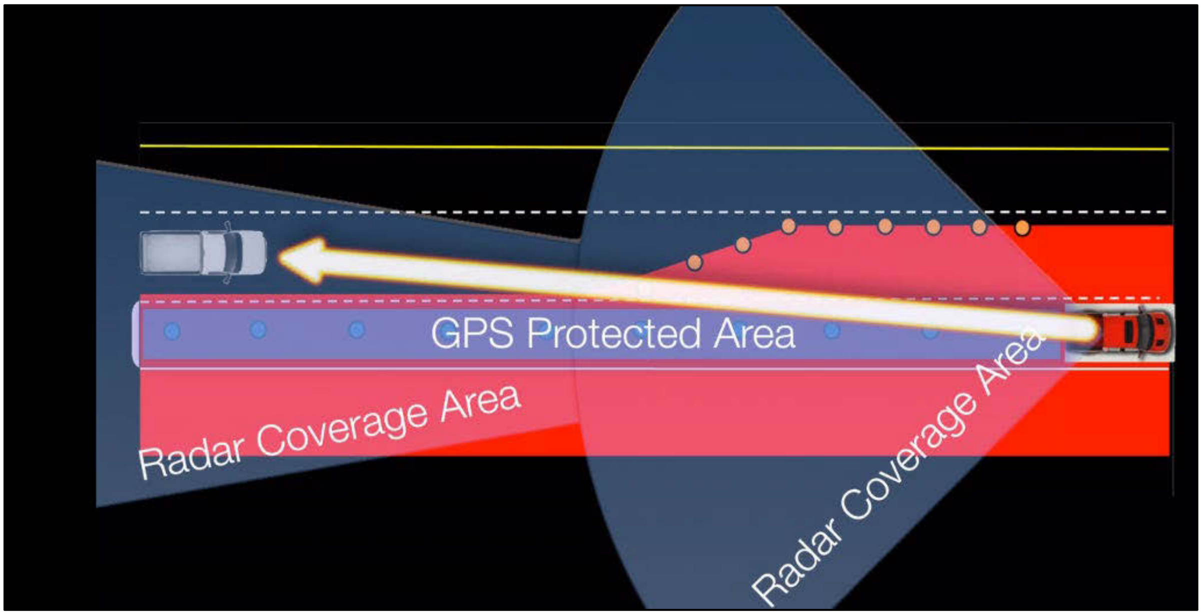


Figure 2.5 AWARE Detection Operation
(Source: Oldcastle Video Team, 2015)

2.4.1.3 Related Literature

Although the AWARE system is not yet commercially available (as of March 2019), the Texas Transportation Institute (TTI) conducted an evaluation of the system for the manufacturer (Theiss et al., 2017). TTI evaluated the AWARE system in various test scenarios, including multiple types of lane closures (closures on a tangent, right, and left curves). The activation distance was longer in the right versus the left curve testing scenario. The device had a 500-foot detection range, whereas the personal body alarm device (WorkTRAX) was found to consistently produce vibratory and audible alerts when the main alarm system was activated within a range of 300 feet. The AWARE's internal stopping sight distance calculations were precise to predict the timing of the alert.

2.4.2 Intellistrobe W1-AG

2.4.2.1 Description and Specifications

The Intellistrobe W1-AG, shown in Figure 2.6, is a pneumatic and microwave-based remotely-activated automated flagger assistance device (AFAD). It is remotely controlled by an operator and designed to protect work zones and replace human flaggers (Brown et al., 2017). The operator manually activates yellow or red signals, on devices positioned at either end of the work zone, to manage the entry into and through the work zone. The system also includes a pneumatic tube placed near each device to automatically detect any violations of the signal, resulting in a loud audio alarm (125 dBA) to the workers and motorists. The system is suitable for low speed work zones due to the alarm system being close to the device but would provide inadequate warning time to workers in high-speed work zone applications. The system is relatively new to the market; therefore, no relevant literature was found related to the device.

Figure 2.6 Intellistrobe W1-AG
(Source: intellistrobe.com, 2017)

2.4.3 AutoFlagger

2.4.3.1 Description and Specifications

AutoFlagger AF-54 (red/yellow lights) and AF-76X (stop/slow signs) are remotely operated AFAD devices. However, unlike the Intellistrobe AFAD, the AF-54 and AF-76X do not have alarm capability. The AF-54 includes a steady circular red light and a flashing circular yellow light during flagging operation. Alternatively, the AF-76X includes a sign with Stop and Slow faces. Both devices include a gate arm for added traffic control. Figure 2.7 and Figure 2.8 show the AutoFlagger AF-54 model and AF-76X, respectively, with their main components.

Figure 2.7 AutoFlagger AF-54
(Source: autoflagger.com, 2019)

Figure 2.8 AutoFlagger 76X
(Source: Caltrans District 3, 2018)

2.4.3.2 Operation

A pair of either the AF-54 or AF-76X devices can be remotely operated by a single worker during flagging operation. The system's smart technology prevents both the paired devices from displaying the same message to both directions of traffic. The high-visibility signs and overall mast height alert motorists that flagging is in effect. The devices do not have an automatic alarm mechanism to alert workers to possible intrusions. Instead, a visual strobe light alert can be initiated by the operator remotely using a hand-held remote.

2.4.3.3 Related Literature

A Minnesota study evaluated the AF-54 and AF-76X devices and found that both devices took 40 minutes to deploy and 40 minutes to demobilize – significantly more effort compared to traditional flagging (Terhaar, 2014). When compared with traditional flaggers, both devices lowered vehicle approach speeds overall and encouraged vehicle drivers to stop further away from the devices than traditional flaggers. The study recommended using the devices on two-lane roads, specifically the AF-54 at locations with narrow shoulders and the AF-76X at locations with wide shoulders. A driver intercept survey showed that 54 percent of respondents preferred the AFADs over traditional flaggers. The study revealed that the drivers' reaction time in the presence of AFADs was significantly longer as compared with traditional flagger operations; the exact reason for this could not be ascertained. Survey respondents raised and identified concerns about the AFADs, including reduced visibility due to sun glare and potential confusion in the event of a system malfunction (Brown et al., 2017).

2.5 SYSTEMS AND DEVICES RELATED TO WORK ZONE MANAGEMENT AND SAFETY

During the literature review, a few systems and devices were identified that have the capability of being adapted to include intrusion detection technology and alert features (Kochevar, 2002). The purpose of presenting this information was to support future discussions with the manufacturers for retrofitting such technologies for potential use as WZIA systems. A list of such systems and devices identified in the literature review is presented below with detailed information presented in Appendix A.

- Wrong Way Alert System and Wrong Way Warning Blinker Sign System
- Ver-Mac Smart Work Zone System and SP-3248V SpeedCam System
- iCone System
- Temporary Speed Bumps and Rumble Strips

3 WZIA SYSTEMS PROCUREMENT AND TESTING PROTOCOLS

This chapter presents details on the systems selected by the Project Advisory Panel and the development of a comprehensive evaluation framework that guided the evaluation of the selected WZIA systems. Although Chapter 2 presents some information with respect to the abovementioned systems, details specific to the systems procured in this research are discussed in the following section.

3.1 SYSTEM PROCUREMENT AND SPECIFICATIONS

In consultation with the Project Advisory Panel and in view of Caltrans' need for a system that can alert workers in a work zone for intruding vehicles, the following four systems were selected and procured:

1. Traffic Guard WAS
2. SonoBlaster
3. Intellicone
4. TAPCO Portable Rumble Strips

Two sets of WAS were used in this research, with each including the following components:

- One alarm unit with a base magnet
- One PSD
- One 12-foot or 33-foot trip hose with a pressure sensor at one end
- One hand-held remote trigger for flagging operations

The first set received was already owned by Caltrans (an older version of the system) and henceforth known as the "CAL" system (Manufacturer specifications were not available for the CAL system). The research team purchased the second system directly from the manufacturer, henceforth known as the "RT" system. Although the PSD and trip hoses functioned the same for both systems, the main observable (physical) difference was in the method for turning on the alarm units, as shown in Figure 3.1 (flip switch vs. toggle button). Both systems were evaluated in detail based on the same set of testing protocols. Functional differences were identified during testing and are discussed later.

Figure 3.1 Traffic Guard WAS RT Alarm Unit on the Left and CAL Unit on the Right

The Intellicone system is not yet commercially available in the United States; however, the United Kingdom-based manufacturer has plans to introduce the system to the United States in the near future. The Intellicone manufacturer offers various system components that are customized according to the specific needs of agencies and characteristics of the work zones where systems are deployed (as discussed in Chapter 2.) Since this research intended to evaluate WZIA systems from a general perspective of deployment in all types of work zones in California, extensive discussions were conducted with the manufacturer to specify the details of the Intellicone System suitable for this research. Eventually, the Y-series Intellicone PSA and the Intellicone Dorman ConeLITE lamps were determined to be best suited for Caltrans' needs, given the unavailability of the support and communication infrastructure required to operate other solutions offered by the manufacturer. According to the manufacturer, evaluations of the Intellicone system as observed in the literature (Chapter 2) were based on a previous generation system, whereas the system evaluated in this research was the latest version of the equipment.

The Intellicone system is triggered when a traveling vehicle strikes a cone with an installed lamp. Each lamp is equipped with a motion sensor that emits a radio frequency (RF) alert when a lamp is impacted or moved. The maximum transmission range of a sensor can be programmed from 98 to 328 feet (30 to 100 meters) depending on the work zone requirements and battery considerations. The motion sensor with its signal hopping capability can pass an alert on to other lamps in range until it is received by a PSA. A PSA can communicate with a secondary PSA at ranges of 98 to 328 feet using an RF signal and an unlimited distance using a cellular network (this function is currently available in the US). The PSA has two alarms: a red alarm for intrusion alert and a blue alarm for warning of incoming vehicles (manual activation). Three Y-series PSA units were procured for this research (one for backup and two for field testing), as shown in Figure 3.2 along with rest of the components.

Figure 3.2 Intellicone System PSA and Lamps

Intellicone lamps can be programmed for different sensitivity levels to prevent false alarms due to vibrations and high-speed traffic effects. Ten lamps were procured, two each of varying sensitivities: “very high,” “high,” “medium,” “low,” and “very low.”

The SonoBlaster is an impact activated system and can be mounted on barriers, barricades, cones, drums, delineators, and A-frames as shown in Figure 3.3. The kinetic device relies on its disposable CO_2 cartridges to provide an auditory alert upon impact. The SonoBlaster system procured from the manufacturer was the same as described in Chapter 2. Thirty SonoBlaster units and 100 CO_2 cartridges were procured in this research.

Figure 3.3 Two SonoBlaster Units Installed on Two Standard Traffic Cones
(Source: Transpo Industries Inc., 2017)

During the procurement process, the manufacturer indicated that the production of the TAPCO Portable Rumble Strips had been halted due to unforeseen circumstances. In the absence of a clear time frame on the availability, the Portable Rumble Strips were dropped from further evaluation in this research.

3.2 EVALUATION FRAMEWORK, METHODOLOGY, AND TESTING PROTOCOLS

To evaluate the selected WZIA systems, a detailed methodology framework was developed as shown in Figure 3.4 that guided the steps undertaken in this research.

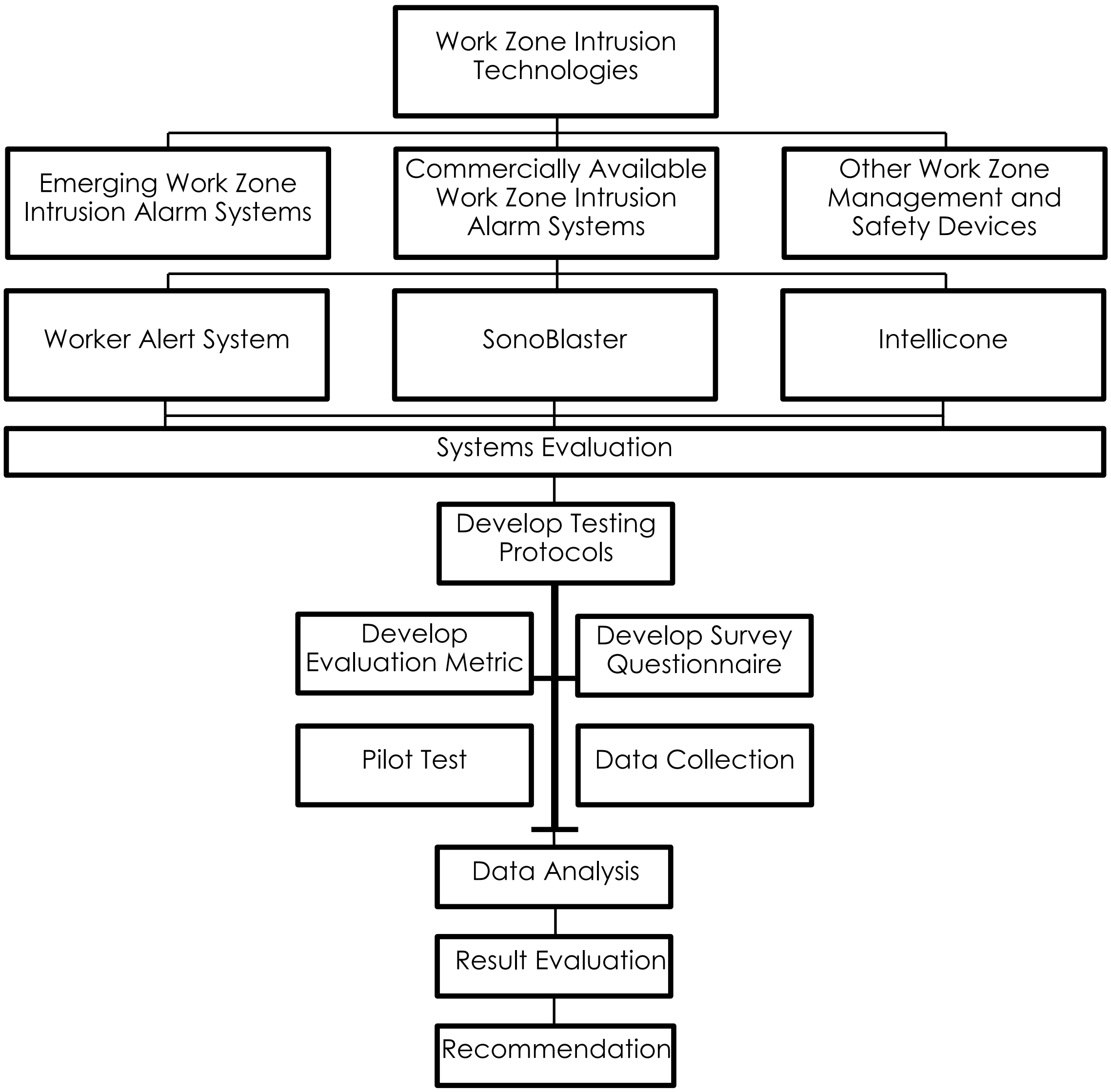


Figure 3.4 Methodology Framework

3.2.1 Development of Testing Protocols

The research framework presented in Figure 3.4 led to the development of a detailed set of goals, objectives, evaluation criteria, and data collection sources to conduct evaluation tests of the selected WZIA systems. Three main goals were defined for the purpose of evaluating WZIA systems during system testing. Goal 1 focused on documenting device information and the general work zone conditions where tests were conducted. Goal 2 focused on documenting the functional characteristics of the devices with consideration for the practicality of deployment, effectiveness, reliability, worker exposure to traffic hazards, and ease of removing devices from the work zone. Goal 3 focused on documenting feedback from maintenance personnel present during the testing. Details of the testing protocols pertaining to each of the goals and the field data collection forms are presented in Appendix B. The goals and objectives were developed with a view towards conducting evaluation tests in both closed-to-traffic and active work zone conditions. Therefore, some of the objectives may only be relevant to one of the specific test conditions. The research team identified two methods of collecting data during the evaluation tests:

- Field data as identified in the goals and objectives tables (Appendix B)
- Feedback (survey data) from maintenance staff observing testing through a survey provided at the end of testing

One of the most significant issues highlighted in the literature and identified by the Project Advisory Panel was that of false results. There are two types of false results of particular concern – "false negatives" and "false positives." A false negative occurs when a vehicle intrudes in the work zone, but an alarm does not activate; a false positive occurs when no vehicle intrudes in the work zone, but an alarm is mistakenly activated. False negatives are a more serious concern as they jeopardize worker safety. If frequent, false positives will deter workers from paying attention to alerts and can be a significant barrier in the acceptance and adoption of WZIA systems. Table 3.1 shows the four possible outcomes of an evaluation test of WZIA systems.

Table 3.1 Possible WZIA Evaluation Trial Outcomes

	Alarm Activated	**No Alarm Activated**
Vehicle Intrusion	True Positive – Alarm activated as designed.	False Negative – Alarm fails to activate during a vehicle intrusion.
No Vehicle Intrusion	False Positive – Alarm is activated when no vehicle intrusion occurs.	True Negative – Alarm at rest as designed (not activated). This is the normal, "ready" operating state.

3.2.2 Development of a Work Zone Workers Survey

An important aspect of the evaluation of WZIA systems was to obtain feedback from work zone workers on various aspects of the selected systems. The purpose of the survey was to better understand their needs, thoughts, and concerns regarding WZIA systems. The target population of the survey was Caltrans construction and maintenance personnel. Given some of the differences in the characteristics of the selected WZIA systems, separate survey questionnaires were developed with a mix of standardized and open-ended questions designed to capture relevant and detailed responses from survey participants. Additionally, the survey responses served as an important source of data with respect to the goals and objectives of the evaluation framework as described in the previous section. Standardized questions such as those that involve participants' familiarity with WZIAs, perception of the systems' effectiveness, and impressions of alert mechanisms were designed to increase the reliability, objectivity, and validity of the recommendations provided as part of this research. The detailed survey forms are presented in Appendix C.

4 PILOT TESTING OF WZIA SYSTEMS

4.1 PILOT TESTING LOCATION AND SCHEDULE

To perform a preliminary evaluation of the three selected WZIA systems, a series of pilot tests was conducted in view of the evaluation framework and protocols developed as described in Chapter 3. The pilot testing of the WAS, SonoBlaster, and Intellicone systems was conducted in a closed-to-traffic location at the Caltrans Maintenance Equipment Training Academy (META) Facility in Sacramento in November 2018. For testing purposes, a mock lane closure on a two-lane road was set up with traffic control according to the T-13 Caltrans Standard Traffic Plan. Data was collected on:

- Device Information
- General Work Zone Information and Conditions
- Functional Characteristics – Deployment
- Sound Test Trials
- Functional Characteristics – Operation
- Miscellaneous Observations and Worker Survey/Feedback

Table 4.1 summarizes the pilot testing work zone conditions for the selected work zone intrusion alarm systems. One device was tested per day to adequately collect comprehensive data on each device. Detailed schedule, activities, and data collection plans are presented in Appendix D.

Table 4.1 WZIA Systems Pilot Testing – Schedule and Field Conditions

Work Zone Information	WAS	SonoBlaster	Intellicone
Date/Time:	11/13/2018	11/14/2018	11/15/2018
No. of Lanes:	2	2	2
No. of Lanes Closed:	1	1	1
Work Zone Speed Limit (mph):	25-55	25	NA
Weather description (Temperature, Wind):	56 F, 5 mph average wind speed	56 F, 7 mph average wind speed	60 F, 3 mph average wind speed
Type of Work Zone:	T-13*	T-13*	T-13*
Taper Length:	100 feet	100 feet	100 feet
Taper Cone Spacing:	25 feet	25 feet	25 feet
Work Area Length:	50 feet	50 feet	50 feet
Tangent Spacing:	25 feet	25 feet	25 feet

* Standard lane closure with reversible control, Caltrans Standard

4.2 PILOT TESTING RESULTS: THE WORKER ALERT SYSTEM

Two sets of WAS were tested; an older set procured by Caltrans, known as the "CAL" device, and a set procured by the research team a few months prior to the pilot testing, known as the "RT" device. The CAL set included a 12-foot long trip hose whereas the RT set came with a 33-foot trip hose. Two additional 33-foot trip hoses were also used to provide better coverage in the closure. The deployment layout of the WAS during pilot testing is shown in Figure 4.1 and Figure 4.2; both devices were tested under the same conditions.

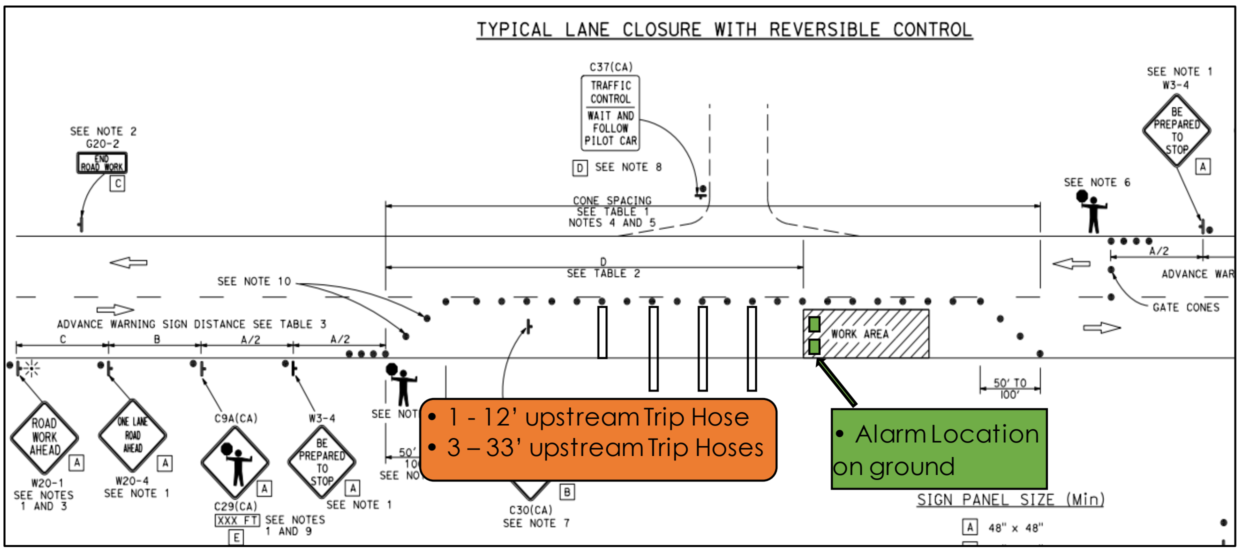


Figure 4.1 WAS Deployment Layout During Pilot Testing

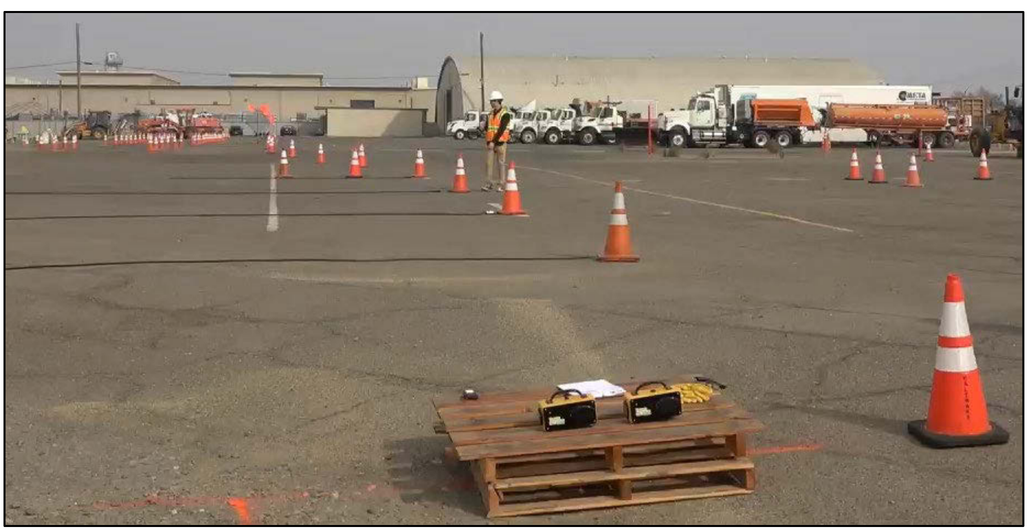


Figure 4.2 Photo of WAS Deployment During Pilot Testing

4.2.1 Functional Characteristics - Deployment

Table 4.2 and Table 4.3 describe the pre-deployment and actual work zone deployment process, setup time, and issues encountered with the WAS. No issues were encountered during the deployment process. However, there was a discrepancy in the manufacturer's instructions, indicating that the pressure sensor LED light, as shown in Figure 4.3, should flash for 10 seconds during setup and then turn off. Instead, the LED maintained a steady flashing green light after the setup. Consequently, the manufacturer was notified of this error, to be updated in future versions of its instruction manuals.

Figure 4.3 WAS Pressure Sensor LED Light

Table 4.2 Worker Alert System – Pre-Deployment Functional Characteristics

	Initial Setup (Maintenance Yard)
Initial Setup Process:	• Charge alarm device for at least 12 hours prior to use. • Replace batteries (2 AA) in the handheld remote, pressure sensor, and PSD. • Turn on the PSD and the pressure sensor, which will flash a green light for 10 seconds if the battery is working properly (see initial setup issues below). • While triggering (stepping on) the trip hose, the pressure sensor light should turn red indicating the trip hose is working properly. • Ensure the handheld remote, pressure sensor, and PSD are turned off or the switches are not pressed when transporting. • Trip hoses should be properly packed before transport to ensure they do not get kinked or tangled with each other.
Initial Setup Time:	• Approximately 15 to 20 minutes for four trip hoses, two PSDs, and one handheld remote (setup time will depend on the number of units).
Initial Setup Issues:	• One of the handheld remote buttons was pressed in the box during shipping and the alarm kept activating as soon as it was turned on, giving the false impression that the device was faulty. Care should be taken when transporting the devices. • One of the alarm unit's fuses blew during charging. • The instruction manual states that the pressure sensor light should turn off after 10 seconds of flashing. Instead, the pressure sensor light flashed rapidly for 10 seconds at start-up and continued to flash steadily green afterwards (manufacturer was notified).

Table 4.3 Worker Alert System – Work Zone Deployment Functional Characteristics

Deployment Characteristics/Issues	Description
Work Zone Deployment Process:	• Lay out the trip hose at an appropriate location upstream of the work area with the pressure sensor close to the shoulder. • Turn on the pressure sensor. When pressing the button, the LED indicator will flash rapidly "for 10 seconds (setup process) before flashing steadily" indicating the device is set up. • Deploy the alarm unit in the work area on the ground or attach to a vehicle using the magnet at the bottom of the alarm unit. • Turn on the alarm switch. A green LED light indicates the alarm unit is on. • Distribute the PSD and handheld remote devices.
Work Zone Deployment Time:	• Approximately 5 minutes (depends on the number of units and distance between the trip hoses and distance from the work area).
Deployment Location (Cones, Barriers, Vehicles, Equipment, Pavement, etc.)	• Alarm unit was placed on a pallet 1 foot above the ground. The alarm units can also be deployed on a vehicle using the unit's built-in magnet. • Trip hoses were deployed on the pavement at 25-, 50-, 75-, and 100-foot distances.
Ease of Set Up (comment):	• Generally, easy setup process from initial to work zone deployment stages except for the issues identified previously.
Stacking Capability (Y/N):	N
Identify Physical Requirements to Deploy Systems (comment):	• Trip hoses are light to carry. A single 33-foot trip hose weighs approximately 8 pounds. A single worker can easily carry two 33-foot hoses in one hand.
"False Positive During Deployment (comment):	• No false positive during deployment.
Battery Life Issues (comment):	• Batteries lasted the entire day of testing.
Retrieval Time (min):	• Approximately 5 minutes.
Any Issues During Retrieval (comment):	None

4.2.2 Relationship Between Sound Level and Distance

Tests were conducted to evaluate sound level and intensity of the alarm at distances ranging from 25 to 300 feet, in 25-foot increments up to 200 feet and in 50-foot increments thereafter, with the alarm speaker oriented downstream relative to the flow of the traffic. Table 4.4 describes the details of the sound test trials including setup and issues encountered for both the WAS sets. During the sound tests, the RT alarm unit had three false positives, the CAL alarm unit had two false positives, and there was one false positive and one false negative for the PSD; details are presented in Table 4.4.

Table 4.4 Worker Alert System – Sound Test Details Relative to Alarm Orientation and Distance

Sound Level Reading at a Distance of ____feet (25, 50, 75, 100, 125, 150, 175, 200, 250, 300):	• Results presented in Figure 4.4 and Figure 4.5
Location of Alarm in The Work Area (On Ground, Vehicle, Cone, etc.):	• 1 foot above the ground
Alarm Speaker Orientation Relative to Work Zone (Downstream, Towards Roadside):	• Downstream
Sound Meter - Location from the Ground:	• 4 feet
Alarm Noise - Sound Meter 1 (Downstream) Reading (dBA):	• Figure 4.4
Alarm Noise - Sound Meter 2 (Upstream) Reading (dBA):	• Figure 4.5
"False Results" During Sound Test Trials? (comment):	• At the start of the sound test trials, one of the PSD devices activated several minutes after being turned on without any trigger ("false positive"). • During Trial # 2 of the sound test, the downstream PSD did not activate ("false negative"). The reason could not be verified. • CAL device had two "false positive" alarms, one during Trial # 3 and one during Trial # 10. • RT device had three "false positive" alarms during Trial # 5.

Sound level measurements were recorded both upstream and downstream of the alarm unit location, as presented in Figure 4.4 (detailed results in Appendix D). The sound level meter was placed four feet above the ground and the alarm was one foot from the ground. Figure 4.4 shows that the sound level of both WAS devices decreased with increasing distance. However, the CAL device produced a significantly higher sound level than the RT device by almost 20 dBA in the first 100 feet. The difference in sound level was less than 10 dBA at a distance beyond 100 feet. Figure 4.4 also shows an unexpected spike in the sound level reading for the RT device at a 125-foot distance, which may be attributed to uncontrolled ambient noises from a nearby railroad track and a nearby airport. Although precautions were taken to ensure any readings affected by such ambient noises were discarded, maintaining the exact same ambient noise levels during each trial was difficult.

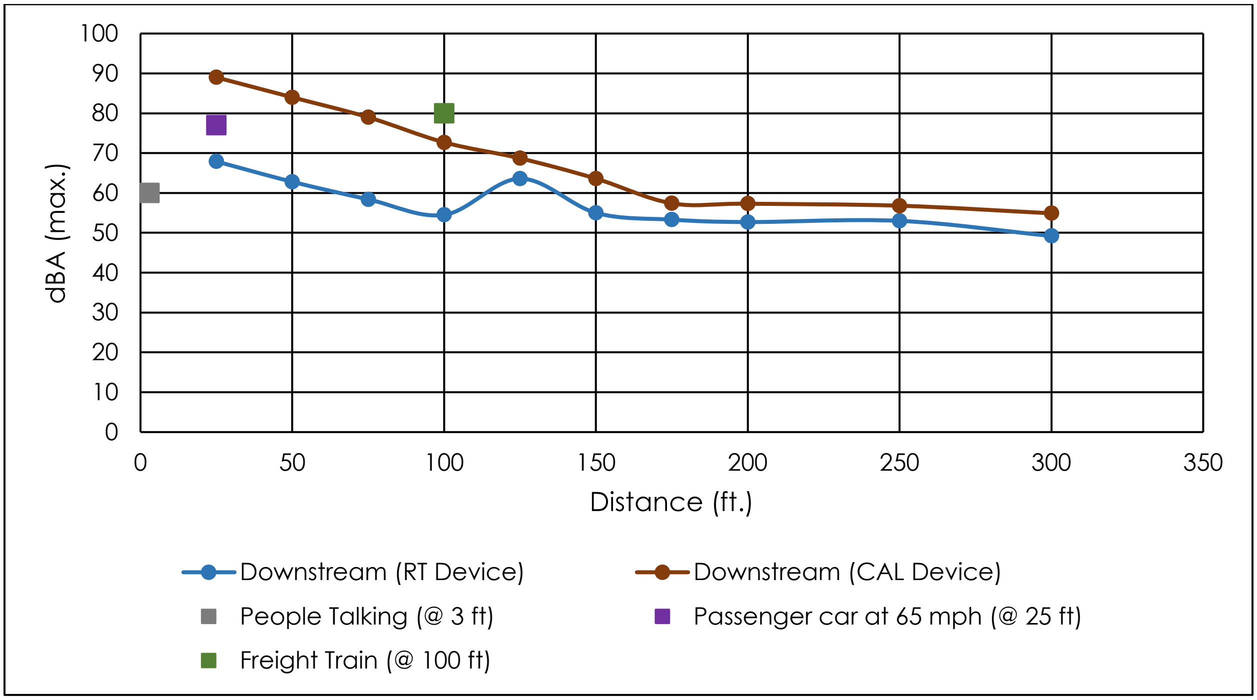


Figure 4.4 WAS Sound Level Measurements Downstream of Work Area

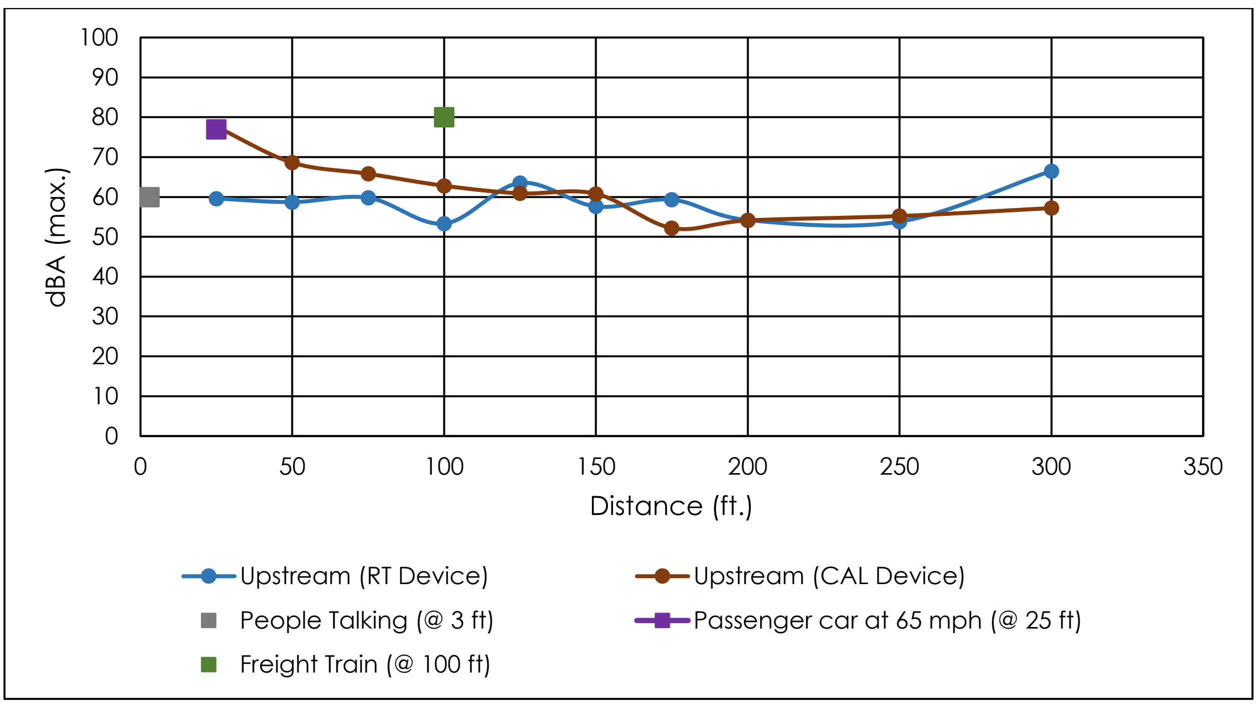


Figure 4.5 WAS Sound Level Measurements Upstream of Work Area

Figure 4.5 shows the sound levels of both WAS alarm units recorded by a sound level meter upstream of the alarm unit location. The CAL device had a higher sound level than the RT device up to 100 feet distance. However, mixed results were observed as the distance increased. A possible explanation for this could be uncontrolled ambient noises and the effect of wind direction on the sound levels recorded, especially considering the speaker on the alarm unit was pointing directly away from the position of the sound level meter.

4.2.3 Functional Characteristics - Operation

Evaluation trials were conducted during pilot testing to assess the operational characteristics of the WAS. The duration of alarm on the CAL and RT alarm units was found to be 2 and 5 seconds, respectively. The visual alarm activated as expected. However, because the light source is located on only one side, it can only be effective when it is within a worker's range of sight. Although the manufacturer specifications quoted a range distance of 1,000 feet between the trip hose and the alarm unit, the maximum range during pilot testing was found to be 400 feet with clear line of sight and 300 feet with a vehicle obstructing the line of sight. The range distance between the trip hose and PSD was measured to be approximately 125 feet. The reason for the difference between the range distance, as specified by the manufacturer, and as observed during pilot testing, could not be immediately ascertained in the field. Details of the operational trials setup and issues encountered are presented in Table 4.5.

Table 4.5 Worker Alert System – Operation Functional Characteristics

Vehicle intrusion characteristics:	• Test vehicle driving over trip hoses at 90-degree angles.
"False Positive" Alarm (no intrusion but alarm activated):	• None
"False Negative" Alarm (intrusion and no alarm activation)	• Yes
Visual alert effective (Y/N/NA, comment):	• Visual alarm is located only on one side.
Alarm duration (seconds):	• 2 seconds for CAL alarm • 5 seconds for RT alarm
Transmission Range field test results: (Manufacturer specification is 1,000 feet)	• 400 feet maximum range distance between the trip hoses and alarm **with** clear line of sight. • 300 feet maximum range distance between the trip hose and alarm **without** clear line of sight (test vehicle positioned in line of sight). • 125 feet maximum range distance between the trip hose and PSD (unreliable activation at up to 175 feet).

The range and alarm duration tests were followed by a series of operational trials at vehicle speeds ranging from 25 miles per hour (mph) to 55 mph using both CAL and RT alarm units to evaluate the performance and reliability of the WAS. Figure 4.6 shows a photo of the setup during the WAS operational trials. A total of 32 trials were conducted. Eighteen of the 32 trials were successful; some issues were observed in 14 tests, including four instances of false negatives and several instances of a delay in the activation of alarm units, PSDs, or both. Details are presented in Table 4.6. No false positives were observed during these trials. The reason for false negatives could not be ascertained immedietely in the field, but the problems were discussed later with the manufacturer to explore probable causes. These findings are discussed later in this report in Chapter 5.

Figure 4.6 Photo of WAS Operational Trials

Table 4.6 Worker Alert System – Results of Operational Trials During Pilot Testing

Trial #	Speed (mph)	"False Positive" Alarm	"False Negative" Alarm	PSD Activation Issues?	Comments
1	25	None	None	None	Test successful
2	25	None	None	None	Test successful
3	35	None	RT only	None	False Negative - RT device
4	35	None	RT and CAL	see comment	False Negative - All devices and PSD
5	30	None	None	None	Test successful
6	30	None	RT only	None	False Negative - RT device
7	35	None	RT only	None	False Negative - RT device
8	30	None	None	None	Test successful
9	25	None	None	see comment	2 PSDs activated, 1 delayed activation (approximately 1 - 2 seconds)
10	35	None	None	see comment	2 PSDs activated, 1 delayed activation (approximately 1 - 2 seconds)
11	35	None	None	None	Test successful
12	25	None	see comment	None	RT device delay (approx. 1 - 1.5 seconds) to activate alarm
13	25	None	see comment	None	RT device delay (approximately 1 - 1.5 seconds) to activate alarm
14-15	30	None	None	None	Test successful
16-20	25	None	None	None	Test successful
21-24	30	None	None	None	Test successful
25	30	None	None	see comment	2 PSDs activated, 1 delayed activation (approx. 1 - 2 seconds)
26	35	None	None	None	Test successful
27	35	None	None	see comment	2 PSDs activated, 1 delayed activation (approx. 1 - 2 seconds)
28	35	None	None	see comment	2 PSDs activated, 1 delayed activation (approx. 1 - 2 seconds)
29	35	None	None	None	Test successful
30	35	None	None	see comment	2 PSDs activated, 1 delayed activation (approx. 1 - 2 seconds)
31	45	None	None	see comment	2 PSDs activated, 1 delayed activation (approx. 1 - 2 seconds)
32	55	None	None	None	Test successful - Trip Hoses moved slightly at this speed

4.2.4 Observations and Feedback

Table 4.7 summarizes general observations and feedback from the research team and maintenance personnel present during the pilot testing of the WAS. Retrieving the WAS was simple, and no issues were observed. A few Caltrans field maintenance workers were invited to observe the deployment and operation of the WAS, and they provided feedback and recommendations. The workers observed that using multiple trip hoses would increase coverage in a work zone, and the system would be best suited for work zones on two-lane curved roadways and stationary operations. The WAS was not considered to be effective during freeway construction operations, given high traffic speeds and hazard exposure involved in deployment. Some concern was expressed regarding the alarm unit's sound level in the presence of live traffic and equipment noise in a work zone, which could possibly be addressed by using multiple alarm units in the work area. The PSD vibration feature was deemed effective in alerting workers; however, there was concern regarding its effectiveness when workers move around and may not feel the vibration during movement, or when workers unknowingly step out of the device's range.

Table 4.7 Worker Alert System – Miscellaneous Observations and Feedback

Miscellaneous Observations	
Retrieval/Removal time:	• Approx. 5 minutes for the tested number of devices.
Issues during activation/setup/removal:	• No issues during removal • Activation/setup issues as discussed previously in Sections 4.2.1 and 4.2.3
Describe any challenges in alarm mounting and device operation:	• The RT device had a slight (approx. 1 second) delay in activating the alarm during some trials. • One of the PSD devices had a delay in 7 out of 35 trials.
Describe any identified or perceived operational drawbacks:	• Inconsistent design and results from two separate devices and reliability issues.
Durability; does any part of the system get destroyed:	• One 33-foot trip hose became defective.
Comments/Feedback from Maintenance Workers (Advantages)	**Comments/Feedback from Maintenance Workers (Disadvantages)**
• Good for two-lane curved roadways • Good for work zone downstream alarm • Good for stationary operations (e.g. pumphouse)	• Not viable on freeways
Additional Comments / Concerns / Issues:	

Miscellaneous Observations	
• Need multiple trip hoses to extend the coverage area. • Reality – accidents typically occur within 100 feet of a work zone. • Overall, workers were neutral to positive towards WAS. • One Caltrans staff shared that 250 feet is an optimal distance between the alarm unit (work area) and a trip hose.	• One Caltrans staff suggested an idea of placing extended trip hoses in parallel to a barrier of cones to alert workers of a work zone intrusion between cone spacing. • The alarm sound is inadequate (not loud enough) given external roadway noises. • Two Caltrans staff found the PSD's vibrational feature effective in alerting a worker. • One Caltrans staff questioned the effectiveness of the PSD's vibration feature of alerting a worker physically moving and working inside a work zone.

4.3 PILOT TESTING RESULTS: SONOBLASTER

To conduct pilot testing of the SonoBlaster, several devices were installed on standard traffic cones. The SonoBlaster activates when a cone is tilted by more than 70 degrees or hit by an intruding vehicle. Therefore, no special layout plan was developed for the SonoBlaster. Instead, one device was tested at a time through manual activation during the pilot testing.

4.3.1 Functional Characteristics - Deployment

The SonoBlaster requires careful pre-deployment steps. The first installation of a SonoBlaster unit on a traffic cone took approximately 22 minutes. Subsequently, the installation time dropped to 12 minutes as multiple units were installed. The thick base of a standard traffic cone posed a challenge in securely installing the device because the unit could not be installed at the bottom of the cone base as specified by the manufacturer. The device was installed on the top of the cone base instead. Although cones with SonoBlaster units installed can be stacked as shown in Figure 4.7, such cones do not fit in a standard Caltrans cone body truck (Figure 4.8) because of insufficient space for two rows of cones. Furthermore, the cone body truck transports cones lying down on their sides as shown in Figure 4.9. During the process of retrieving a cone from the cone body truck, turning the knob to activate the system, and dropping it on to the road, the cone could potentially tilt by more than 70 degrees possibly activating the alarm. Table 4.8 and Table 4.9 describe in detail the pre-deployment and deployment functional characteristics of the SonoBlaster, respectively.

Figure 4.7 Stacked Traffic Cones with Installed SonoBlaster

Figure 4.8 Insufficient Space in Cone Body Truck for Two Rows of SonoBlaster Cones

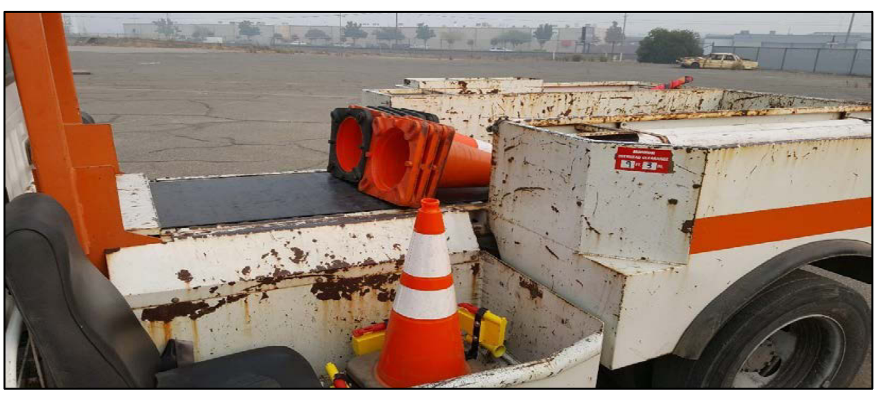


Figure 4.9 Deploying a SonoBlaster Mounted Cone from a Standard Caltrans Cone Body Truck

Table 4.8 SonoBlaster – Pre-Deployment Functional Characteristics

Initial Setup Types	Initial Setup (Maintenance Yard)
Initial Setup Process:	• Install SonoBlaster mounting bracket to the base of a cone or other traffic control device. • Attach SonoBlaster device to the mounting bracket. • Turn SonoBlaster knob to the "unlocked" position. Cock the device using the provided cocking tool. Turn the knob to the "locked" position. • Place a CO_2 cartridge in the casing and screw on to the SonoBlaster at the designated location. • Stack the cones with installed SonoBlaster units for transport.
nitial Setup Time:	• Bracket install (first couple of times): Approx. 22 minutes • Bracket install (after first few installs): Approx. 12 minutes • CO_2 cartridge install: Approximately 2 to 4 minutes.
Initial Setup Issues:	• Thick base of the cones both procured by the research team and at the Caltrans META facility made secure installation of the mounting bracket difficult. • Brackets were installed on top of the base of the cones instead of at the bottom as specified by the manufacturer. • The CO_2 cartridge casing screws onto the SonoBlaster, starting from a specific position. This may require a few trials to identify. • Manufacturer instructions show cones, which are stacked with SonoBlasters on four sides. However, Caltrans cone body truck transports cones lying on their sides, which means cones can be stacked with SonoBlasters on a maximum of three sides of a cone. • Caltrans cone body truck cannot carry two stacks of cones with SonoBlasters side-by-side with the brackets installed.

Table 4.9 SonoBlaster – Work Zone Deployment Functional Characteristics

Deployment Characteristics/Issues	Description
Work Zone Deployment Process:	• Pick up the cone from the transport vehicle and turn the SonoBlaster knob from "locked" to "unlocked" position before placing the cone at the appropriate location.
Work Zone Deployment Time:	• Minimal (5 to 10 seconds to pick up a cone and turn the knob).
Work Zone Deployment Issues:	• SonoBlaster devices stacked vertically deployed from a regular truck or contractor's vehicle that stores the cones vertically is easy to deploy. • While deploying from a Caltrans cone body truck, after the worker (in a seated position) picks up a cone and unlocks the SonoBlaster, the cone **may** tilt by more than a 70-degree angle while being placed on the pavement resulting in an alarm activation. • Deployment of cones from a cone body truck will be delayed as the worker turns the knob on the SonoBlaster during deployment.

Deployment Characteristics/Issues	Description
Deployment Location: (cones, barriers, vehicles, equipment, pavement etc.)	On traffic cones using supplied mounting brackets
Ease of set up (comment):	• Generally, cumbersome to set up including installation of the mounting bracket, non-compatibility of the brackets with the cones resulting in flimsy installations, and difficulty of screwing-in the CO_2 cartridges. • Other deployment issues as discussed previously.
Stacking capability (Y/N):	Yes, though problems were encountered as noted.
Deployed on: (cones, barriers, vehicles, equipment, pavement)	On traffic cones using supplied mounting brackets.
Identify physical requirements to deploy systems (comment):	• Weight of a 28-inch cone (7 pounds) with SonoBlaster installed is approximately 9 pounds. • Cone Body Truck capacity issues discussed above.
"False Positive" during deployment (comment):	None
Battery life issues (comment):	NA
Retrieval time (min):	Depends on the number of cones deployed and method of retrieval.
Any issues during retrieval (comment):	None

4.3.2 Relationship Between Sound Level and Distance

To evaluate the sound level and intensity of the alarm, sound level tests were conducted at distances ranging from 25 to 200 feet in 25-foot increments, and at 250 and 300 feet. With the air-horn of the alarm unit oriented downstream relative to the flow of traffic at the beginning of the work area, two sets of sound level readings were recorded both upstream and downstream of the device location as shown in Figure 4.10 (total of four sound level readings for each trial). First, the cone tilted to drop on the pavement with the air-horn pointing upwards at an angle of approximately 105 degrees from its original position. Second, the cone was tilted to drop on the pavement with the air-horn pointing downwards at an angle of approximately 95 degrees from its original position. Table 4.10 describes the details of the sound test trials, including the duration of the alarm that met the manufacturer's claim of minimum 15 seconds and varied between 15 and 90 seconds. Sound level measurements are presented in Figure 4.11 and Figure 4.12 (detailed in Appendix D). The sound level meter was approximately four feet above the ground and the alarm unit was six inches above the ground.

Figure 4.10 Photo of SonoBlaster Sound Test with Horn Pointing Downward

Table 4.10 SonoBlaster - Details of Sound Tests Relative to Alarm Orientation and Distance

Trial #:	• See Figure 4.11, Figure 4.12
Sound Level Reading at a Distance of ____feet (25, 50, 75, 100, 125, 150, 175, 200, 250, 300):	• See Figure 4.11, Figure 4.12
Location of Alarm in the Work Area (on ground, vehicle, cone, etc.):	• On a cone with device 6 inches from the ground.
Alarm Speaker Orientation Relative to Work Zone (downstream, towards roadside):	• SonoBlaster mounted cone was placed with the speaker pointing downstream. • Cone was tilted to drop on the pavement with the horn pointing upwards at approx. 105-degree angle from its original position. • Cone was tilted to drop on the pavement with the horn pointing downwards at approx. 100-degree angle from the original position.
Sound Meter - Location from the Ground:	4 feet
Duration of Alarm:	• Manufacturer claim of alarm duration is 15 seconds. • Alarm duration during testing varied from 15 to 90 seconds.
Visual Alarm (comment):	NA
"False Alarm" Activation during Sound Test Trials? (comment):	None

Figure 4.11 shows the downstream sound level measurements of a SonoBlaster with the alarm unit oriented both downwards and upwards. At 25 feet, the sound level is close to 100 dBA and slightly drops as the distance to the sound level meter increases. However, the sound level drop is not as pronounced as compared with the WAS. A similar trend can be observed for sound level measurements upstream of the alarm unit location as shown in Figure 4.12. The sound level measurements appear to be slightly higher with the air-horn pointing downwards but in general, the difference between the measurements is insignificant.

An increase in the sound level at a distance of 250 feet downstream was observed, which could be attributed to the inconsistent performance of the air horn. As mentioned in the literature review, multiple uses of a SonoBlaster device during the pilot testing produced freezing and moisture due to the discharge of the CO_2 cartridge. Therefore, six separate SonoBlaster devices were used, one at a time, allowing enough time for any accumulated ice and moisture to evaporate. This problem resulted in multiple devices being used, and differences were observed in the performance of each device with inconsistent sound level intensity and duration of the alarm. The inconsistency is presumed to be possibly due to either the performance of the CO_2 cartridges or the size and position of the hole punctured by the SonoBlaster trigger, which was inconsistent. Details of these issues and several other issues observed with the SonoBlaster device are described in detail in the next section.

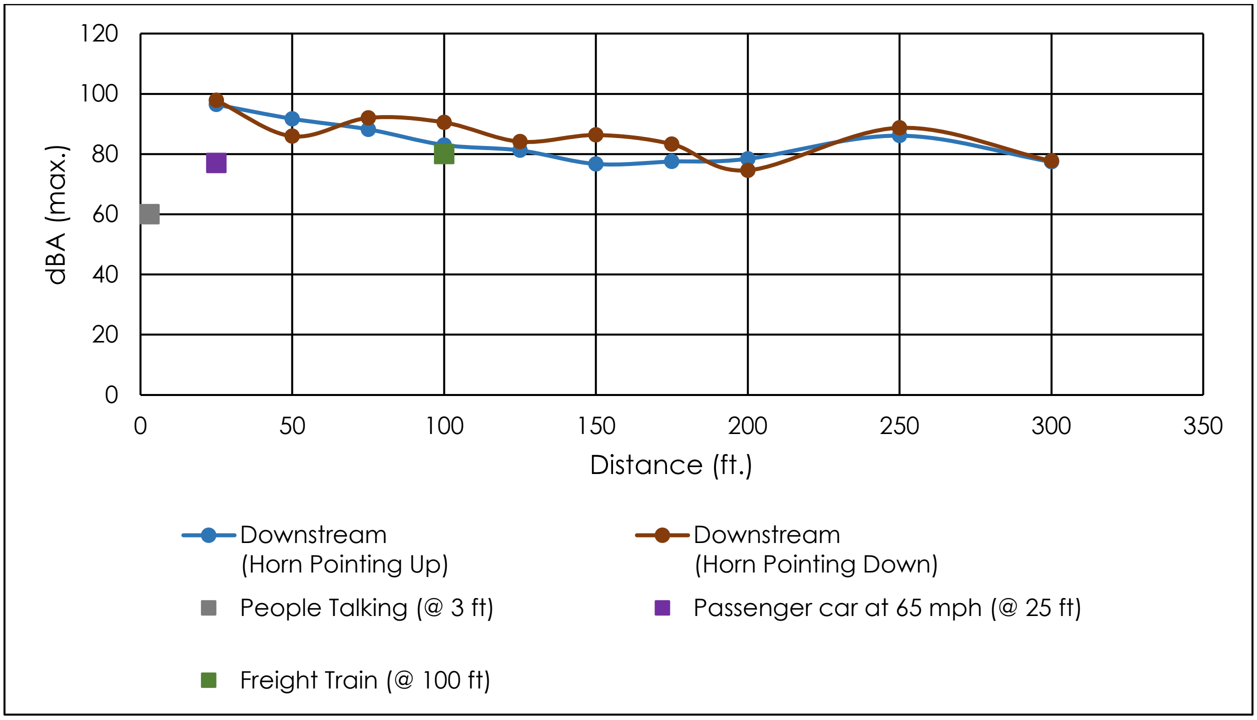


Figure 4.11 SonoBlaster Sound Level Measurements Downstream of Work Area

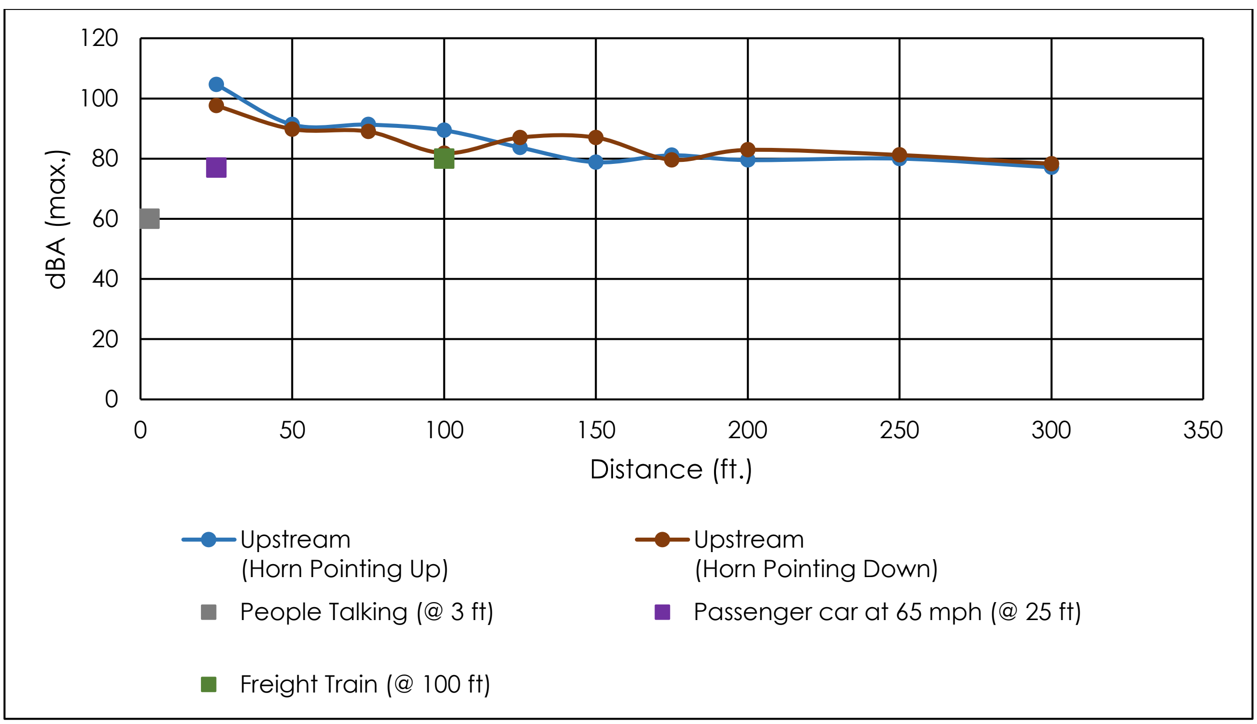


Figure 4.12 SonoBlaster Sound Level Measurements Upstream of Work Area

4.3.3 Functional Characteristics – Operation

SonoBlaster operational data were collected alongside the sound test trials. During a total of 20 trials (10 each with the air horn pointing upwards and downwards), 16 trials were successful, and four trials were unsuccessful with false negatives observed. Details of the outcomes of the operational trials and the various issues observed are presented in Table 4.11 and Table 4.12.

Table 4.11 SonoBlaster – Results of Operational Trials during Pilot Testing

Trial #	Alarm Duration (Horn Pointing Up) (sec)	Trial Successful / Unsuccessful?	Alarm Duration (Horn Pointing Down) (sec)	Trial Successful / Unsuccessful?	Comments
1	15	Successful	30	Successful	NA
2	15	Successful	42	Successful	NA
3	15	Successful	16	Successful	NA
4	16	Successful	15	Successful	NA
5	21	Successful	21	Successful	NA
6	31	Unsuccessful	15	Successful	"False Negative" - CO_2 cartridge not punctured. Successful trial after reinstalling another CO_2 cartridge.
7	80	Unsuccessful	17	Successful	"False Negative" - Device trigger mechanism functional but did not puncture the CO_2 cartridge. Device was determined to be faulty.
8	21	Successful	28	Successful	NA
9	42	Successful	27	Unsuccessful	"False Negative" - CO_2 Cartridge not punctured. Successful trial after reinstalling another CO_2 cartridge.
10	20	Unsuccessful	29	Successful	"False Negative" - Device trigger mechanism did not work and did not puncture CO_2 cartridge. Device was determined to be faulty.

Table 4.12 SonoBlaster – Operation Functional Characteristics

Trial #:	See details in Table 4.11
"False Negative" Alarm (intrusion but no alarm activation):	• Two cases of "false negatives" were observed in two separate SonoBlaster devices because of SonoBlaster's failure to puncture a hole in the CO_2 cartridge. It is presumed that the failure to puncture the hole is possibly due to unsuccessful installation of the CO_2 cartridge, which needs to be screwed in, starting at a specific point on to the device. A reinstall of CO_2 cartridges on these devices resulted in successful activation. • Two false negative cases were observed in two separate SonoBlaster devices that had been used three to four times. After changing a couple of CO_2 cartridges and giving enough time for the moisture in the devices to evaporate, the failure of the trigger mechanism is presumed to be the cause for the breakdown of the devices. • In one device, the trigger mechanism could be heard to activate; however, no hole was observed in the CO_2 cartridge. • In the other device, the trigger mechanism did not activate at all. No hole punctured in the CO_2 cartridge. • Rapid repeated use of a single SonoBlaster device led to moisture and freezing in the alarm unit, which caused the unit to malfunction. "False negative" cases when the single SonoBlaster device was being used in this repeated manner were discarded since they do not represent real-world operations. Remaining tests were conducted to avoid this problem.
Visual Alert Effective (Y/N/NA, comment):	NA
Alarm duration:	• Manufacturer claims the alarm duration is 15 seconds. • The alarm duration during tests varied from 15 to 90 seconds. • The variation in alarm duration is presumed to be due to variation in the quality of CO_2 cartridges or the puncture point (sometimes at the center, sometimes towards one side) on the tip of the CO_2 cartridge. • Any variations in the alarm duration due to repeated use of the alarm, which developed moisture in the device were disregarded.

4.3.4 Observations and Feedback

Given the issues encountered during the sound and operational trials, discarding the SonoBlaster device after activation in a live work zone deployment is recommended because the probability of malfunction increases with prior use. Furthermore, replacing a CO_2 cartridge immediately after the device activation was difficult, possibly due to freezing from the quick release of pressurized CO_2 gas. The most significant drawback was the issue of the CO_2 cartridge not being installed properly without knowing or being able to confirm this fact. Table 4.13 and Table 4.14 summarize various other observations and feedback from maintenance workers with respect to the SonoBlaster system.

Table 4.13 SonoBlaster – Miscellaneous Observations

Retrieval/Removal Time (min):	• Depends on the number of devices and method of retrieval.
Issues During Activation/Setup/Removal:	• No issues during removal. • (see Table 4.8 and Table 4.12 for other identified issues)
Give Impressions of How Well Workers Accept the Alarm:	(See comments/feedback below from maintenance workers)
Describe Any Challenges in Alarm Mounting and Device Operation:	• See below.
Describe Any Identified or Perceived Operational Drawbacks:	• Possible issues with worker exposure to traffic hazards while deploying the device. • Difficult to change a CO_2 cartridge right after a SonoBlaster is activated because of moisture/freezing in the device. Device may have to be replaced by another one in live traffic work zone conditions. • Given that two SonoBlaster devices broke down after three or four alarm activations, discarding the devices is recommended after a small number of activations, possibly as few as one. • Inconsistency in the location of the puncture hole in the CO_2 cartridges may have caused the variation in the alarm duration and sound level performance. However, all alarms that functioned properly met the manufacturer's 15 second minimum duration specification. • Further research is required on the effects of weather on the varied sound level performances of the SonoBlaster.
Durability; Does Any Part of The System Get Destroyed:	• Two out of six devices broke down during testing after three or four uses.

Table 4.14 SonoBlaster – Feedback from Maintenance Workers

Advantages	Disadvantages
• Good for secondary lane closures • May be good for closing a sidewalk	• Not feasible for lane closures • Not feasible in a cone body truck with the permanently affixed mounting bracket.
Additional Comments / Concerns / Issues:	
• Durability of brackets. • Easy for a worker to forget to replace a CO_2 cartridge.	• Complex and extensive effort to deploy units for a closure. • Workers like to deploy cones as fast as possible to reduce hazard exposure. Turning the knob to switch the SonoBlaster on slows down that process.

4.4 PILOT TESTING RESULTS: INTELLICONE

During pilot testing, two Intellicone Y-series PSA units and 10 lamps of various sensitivities, ranging from "very high," "high," "medium," "low," and "very low," were used as described in Section 3.1. The deployment layout of the Intellicone system during pilot testing is presented in Figure 4.13.

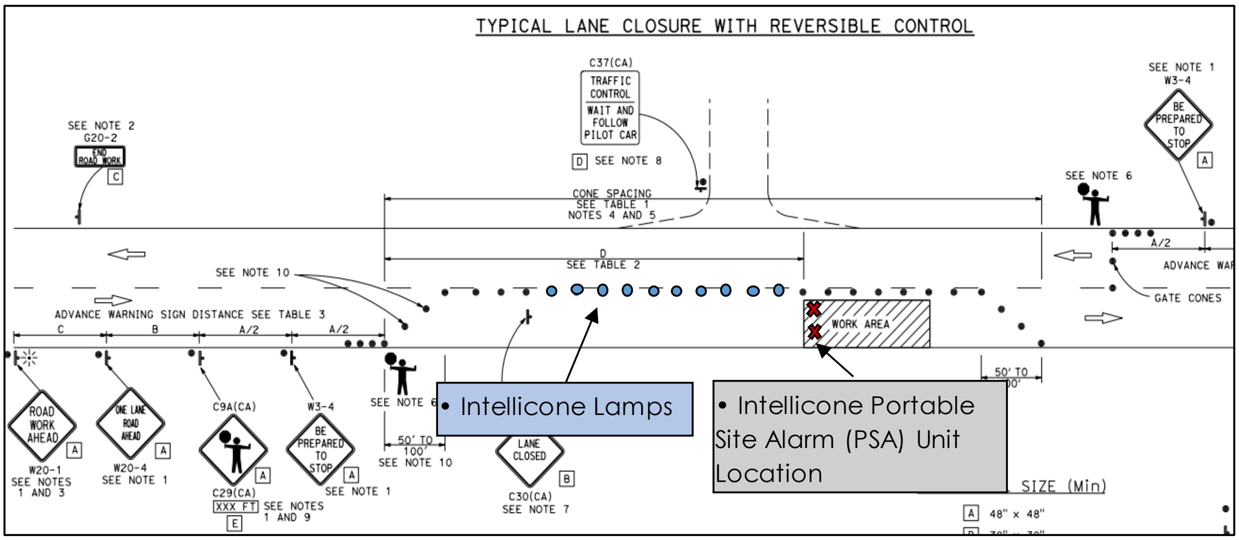


Figure 4.13 Deployment Layout of Intellicone System Deployment during Pilot Testing

4.4.1 Functional Characteristics - Deployment

Before deployment, the Intellicone PSA batteries must be charged for at least 24 hours. The batteries have an approximate lifespan of 50 hours (confirmed through testing in this research). Rechargeable or disposable batteries must be installed in each lamp. Additional pre-deployment steps must be completed either by Caltrans employees or the manufacturer. Details are presented in Table 4.15.

The Intellicone system is deployed by turning the device on using the power button and letting the system acquire a GPS and cellular network signal (where available). This takes three to five minutes. In this study, deployment was simple, and no issues were observed. However, deploying multiple lamps and PSAs may be challenging for one worker as each PSA unit weighs approximately three pounds. Typically, a worker can carry a maximum of three PSA units and eight lamps.

Table 4.16 presents details of the Intellicone system work zone deployment, including setup time and other characteristics.

Table 4.15 Intellicone – Pre-Deployment Functional Characteristics

	Initial Setup (Maintenance Yard)
Initial Setup Process:	• Charge PSA alarm unit for at least 24 hours prior to use. • Install/replace batteries in the lamps. • Use the Intellicone system map-based web interface (login access provided by Highway Resource Solutions Ltd., manufacturer of Intellicone) to draw a boundary around the work zone where Intellicone is to be deployed. This can also be set up and completed by the manufacturer. • Assign specific Intellicone PSA units (each unit has a unique ID) to a specific work zone boundary drawn on the map-based web interface. The assigned PSA units will only work within the boundary drawn on the map (using GPS). • Multiple PSA units assigned to the same boundary (work zone) will communicate only with each other within the boundary using radio (if within radio range) or cell phone network (if outside of radio range).
Initial Setup Time:	• Approx. one to two minutes for replacing battery in each lamp. • The time required to set up the work zone boundary using the web interface was provided by the manufacturer as approximately 15 minutes (will vary depending on the number of PSA units being deployed). Each PSA has a unique ID number printed on it which is required to complete the setup.
Initial Setup Issues:	None
	Pre-Deployment (Roadside/Vehicle)
Pre-Deployment Setup Process:	• Place the PSA outside in open-air. Turn it on and press the "Alarm" or "Alert" button to manually activate and test the device before deployment (sound can be muted).
Pre-Deployment Setup Time:	• Approximately three to five minutes (the time for connection to GPS and cellular phone network). • On test day: 2 minutes 34 seconds.

Table 4.16 Intellicone – Work Zone Deployment Functional Characteristics

Deployment Characteristics/Issues	Description
Work Zone Deployment Process:	• Place the lamps on top of the cones, while walking, or from a cone body truck. • The lamps automatically turn on after being placed on cones. • Deploy the PSA unit (switched on) in the work area, on the ground or over a cone. Cone mounting is recommended for better range in communicating with the lamps.
Work Zone Deployment Time:	• Depends on the number of lamps and method of deployment. • Six minutes to place 10 cones and two PSA units while walking.
Work Zone Deployment Issues:	None
Deployment Location (cones, barriers, vehicles, equipment, pavement etc.)	• One PSA alarm unit was placed on a pallet one foot above the ground. • The other PSA alarm unit was placed on a 28-inch cone and elevated by one foot.
Ease of Set Up (comment):	• Easy setup. No issues encountered except carrying the lamps to each cone to place them takes time, and one worker can carry a limited number of lamps.
Stacking Capability (Y/N):	No
Identify Physical Requirements to Deploy Systems (comment):	• One PSA weighs approximately 3 pounds each; a worker can carry a maximum of three PSA units. • Lamps have a handle and up to eight can be easily carried by a worker. Each Lamp with a battery weighs approximately 1 pound.
"False Positive" during Deployment (comment):	None
Battery Life Issues (comment):	• PSA battery life approximately 50 hours depending on weather conditions. • Lamp alkaline battery life - approximately 2 weeks ($10). • Lamp air-alkaline battery life - approximately 2 to 4 months ($50).
Retrieval Time (min):	Depends on the number of lamps placed.
Additional Notes:	• Once a cone was hit, the PSA alarm activated, and the cone returned to its upright position, it sometimes required a 35 - 45 second delay before the system became operational again. This was initially presumed to be a reset time but was eventually determined to be an issue that was ultimately resolved as discussed in Chapter 5.

4.4.2 Relationship Between Sound Level and Distance

To evaluate the sound level and intensity of the alarm, sound level tests were conducted at distances ranging between 25 and 300 feet, in 25-foot increments up to 200 feet and in 50-foot increments thereafter. The Intellicone PSA has three speakers all around the sides, hence the orientation of the unit was not considered during the sound tests. The PSA units were placed at a height of one foot and 3.5 feet above the ground, and the sound level meters were four feet above ground. Table 4.17 shows the details of the sound level test trials.

Sound level measurements were recorded both upstream and downstream of the PSA units in the work area. Details are presented in Figure 4.14 and Appendix D. In general, the sound level measurements dropped progressively as the distance from the PSA increased both downstream and upstream of the PSA as shown in Figure 4.14. Overall, there was less than 10 percent difference in the sound level measurements between upstream and downstream readings; this could be attributed to the orientation of the speakers on the PSA or the direction of the wind. Unlike the WAS and SonoBlaster systems, the Intellicone system has a three-tone alarm that was quite sharp and noticeably effective in its intensity. The visual alarm on the PSA was visible with rotating lights.

Table 4.17 Intellicone - Details of Sound Tests Relative to Alarm Orientation and Distance

Sound Level Reading at a Distance of ____feet (25, 50, 75, 100, 125, 150, 175, 200, 250, 300):	• See Figure 4.14
Location of Alarm in the Work Area (on ground, vehicle, cone, etc.):	• First unit 1 foot above the ground. • Second unit 3.5 feet above the ground.
Alarm Speaker Orientation Relative to Work Zone (downstream, towards roadside):	• NA (alarm has three speakers all around)
Sound Meter - Location from the Ground:	• 4 feet
Alarm Noise - Sound Meter reading (dBA):	• See Figure 4.14
Duration of Alarm:	• 30 (+/- 2) seconds
Visual Alarm (comment):	• Red rotating light, not very visible during daylight; more effective during nighttime.

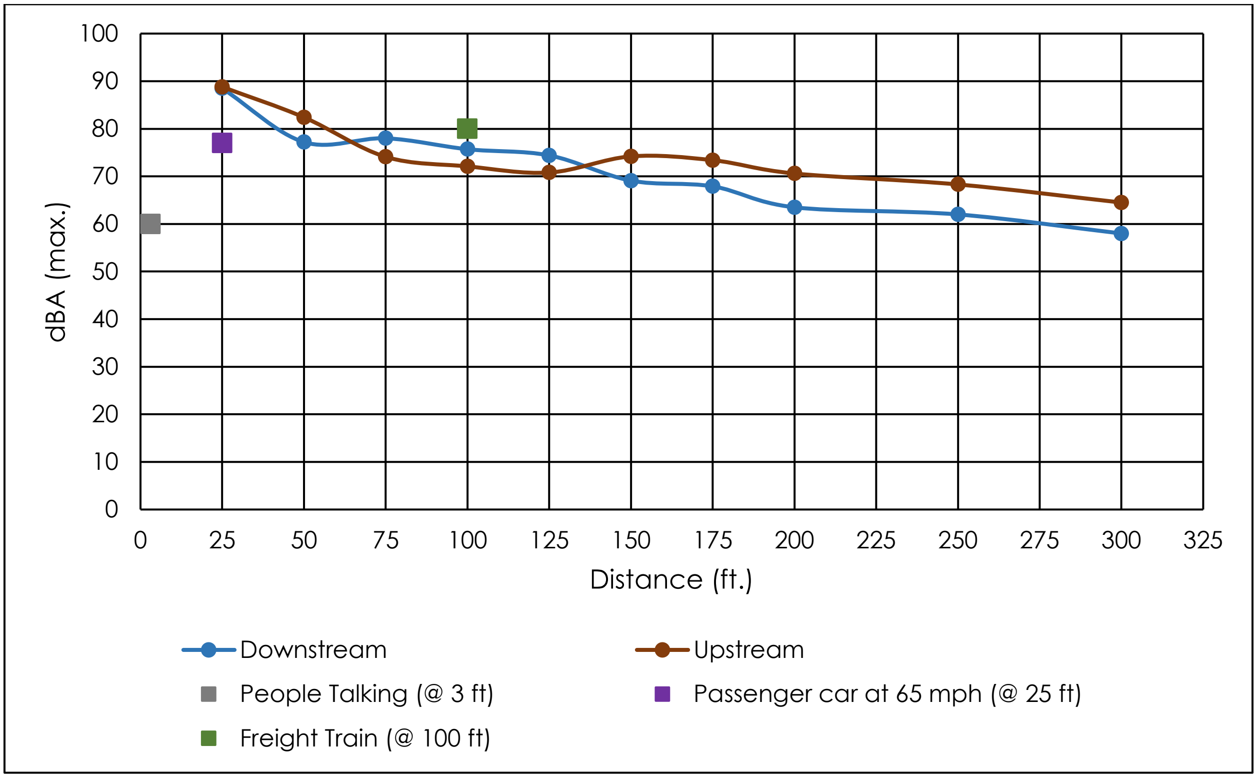


Figure 4.14 Sound Level Measurements Upstream and Downstream of Work Area for Intellicone

4.4.3 Functional Characteristics - Operation

Ten operational trials were conducted using one Intellicone PSA and five lamps of various sensitivities (two trials using each sensitivity lamp). The distance between the PSA and lamps was fixed at 100 feet as specified by the manufacturer. A few false negatives occurred during the initial trials, which were conducted in quick succession with less than a 10 second interval between trials. However, once the system was given 35 to 45 seconds to reset between test trials, no subsequent false negatives occurred. Therefore, the previous trials were discarded; ten new trials were conducted with sufficient reset time in between trials. These new trials were all successful as no further false negatives occurred. Table 4.18 presents all the details of the operational trials, including the duration of the alarm and the differences between the performances of the lamps of different sensitivities. Figure 4.15 shows the setup of operational trials for Intellicone, and Figure 4.16 shows the visual alert during a nighttime test that appears very bright with rotating lights.

Table 4.18 Intellicone – Operation Functional Characteristics

Trial #:	• Lamp sensitivity tested during 10 operation trials (see additional notes below). • All Lamps tested at a 100-foot distance. • All tests were successful.
"False Negative" Events (Intrusion but No Alarm Activation):	• No "false negative" events were observed when the system was properly deployed. • During initial operational trials, repeated activation of the alarm by tipping the cones, produced a few "false negative" events, perhaps due to not giving enough time for the PSA and lamps to reset after activation. • After several trials, the researchers determined that a gap of approx. 35 to 45 seconds between activations ensured the PSA and lamps were properly reset. • No "false negative" events were observed during the 10 subsequent operational trials. • All initial trials were discarded once the proper deployment process was identified.
Visual Alert Effective (Y/N/NA, Comment):	• The PSA unit has steady green light when ready for use. • A red rotating alarm light is not very visible during daylight, but is more effective at nighttime (see Figure 4.16).
Alarm Duration:	• 30 (+/- 2) seconds
Transmission Range Field Test Results: (Manufacturer claim 100 feet between all components)	• 100-foot maximum range distance between the lamp and PSA (manufacturer claims that lamps can be programmed to increase the range up to 3,000 feet). • 100-foot PSA to PSA maximum range distance (radio based). • Unlimited PSA to PSA range (depending on availability of cellular network coverage and work zone boundary designated using the map-based web interface).
Additional Notes	• "Very High" sensitivity lamps activate alarm when the cone is picked up or moved. • "High" sensitivity lamps will sometimes activate the alarm when the cone is picked up or moved. • "Medium," "Low," and "Very Low" sensitivity lamps activate the alarm only when the cone is dropped on the pavement.

Figure 4.15 Photo of Intellicone Operational and Lamp Sensitivity Test

Figure 4.16 Photo of Intellicone PSA Visual Alert Test at Night

4.4.4 Observations and Feedback

As mentioned in the previous section, a few false negatives were observed during the pilot testing of the Intellicone system, which were subsequently resolved once the system received a period of 35 to 45 seconds to reset between test trials. However, in consultation with the manufacturer, no concrete reason could be ascertained for this behavior during pilot testing. Further tests and consultation with the manufacturer would be required to find the precise cause for this issue. The Intellicone lamps automatically turn on and link to the PSA when placed onto the top of a traffic cone. However, placing multiple lamps on cones by a worker walking in a work zone may result in increased worker hazard exposure. Furthermore, placing the lamps on cones in the warehouse or maintenance yard may present issues as the lamps could be dislodged from the cones during transportation to the work zone. There is also an issue of security of the system, as the components are expensive and could easily be stolen and removed entirely from the work zone – costing the transportation agency while jeopardizing worker safety. Details of other observations during the pilot testing and the feedback results from maintenance workers observing the pilot testing are presented in Table 4.19 and Table 4.20.

Table 4.19 Intellicone – Miscellaneous Observations

Retrieval/Removal time:	• Approximately 5 minutes for one PSA and 10 lamps.
Issues during activation/setup/removal:	• PSA and lamps require 35 to 45 seconds to reset after activation, which was not mentioned in the manufacturer's manual. Trigger events that occur during the reset period will not activate the alarm.
Give impressions of how well workers accept the alarm:	• (See Comments/Feedback in Table 4.20 below from meeting with maintenance workers).
Describe any challenges in alarm mounting and device operation:	None
Describe any identified or perceived operational drawbacks:	• The manufacturer programs the lamp sensitivities based on the requirements of the user (work zone vibration levels and speed of traffic affecting cone movement). Manufacturer has tested the lamp sensitivities for U.K. traffic conditions. Similar tests in live traffic conditions will have to be conducted before a specific lamp sensitivity can be recommended for specific conditions in the United States. • Worker exposure may increase depending on the number of lamps if the lamps are placed by a worker while walking. The other option is to deploy from a cone body truck, but this may require two passes - first to deploy the cones and second to place the lamps, or the use of two cone body trucks. • Storing and transporting the lamps and PSA devices for deployment in a work zone could be an issue since a cone body truck is currently not designed to carry these devices or additional items, such as the lamps or PSAs. • There is a possibility of theft of the lamps since they are mounted on top of the cones and can be easily removed.

Table 4.20 Intellicone – Feedback from Maintenance Workers

Advantages	Disadvantages
• Good for ramp closures • Good for flagging operations • Good for onramps	• Not viable for long lane closures
Additional Comments / Concerns / Issues:	
• Durability of the lamps if thrown into and out of trucks. • Mixed reaction to the cost of the equipment.	• Loud, piercing alarm sound – good and effective in intrusion alerts. • Activates an alarm if cone gets hit or tipped; does not activate an alarm for work zone intrusions between cones.

5 SUPPLEMENTAL TESTING OF WZIA SYSTEMS

5.1 SUPPLEMENTAL TESTING BACKGROUND AND DETAILS

The pilot tests conducted in this research were the first time the researchers had an opportunity to deploy and operate the three selected WZIA systems in conditions similar to a live work zone. Consequently, several unexpected issues were observed. There were instances where the devices did not perform according to researchers' expectations or the manufacturer's specifications, for reasons that could not be ascertained at the time. Therefore, in consultation with the Project Advisory Panel, a decision was made to conduct supplemental tests to determine the reasons behind the issues encountered and fully understand the capabilities and limitations of each system. Discussions were conducted with some manufacturers to identify the cause of the issues and problems encountered during pilot testing.

Prompted by the feedback from the Project Advisory Panel during the review of pilot testing results, several revised tests and data collection activities were included in the supplemental testing. Draft testing plans included impact tests, which were eventually removed from the plans for various unresolved issues. Additional new units of the WAS and SonoBlaster system were also procured for supplemental testing. A summary of the reasons behind the issues encountered during pilot testing and details of the final supplemental testing plan are presented as follows:

1. Worker Alert System (WAS)
    a. The manufacturer confirmed that the CAL device received from Caltrans was an older model with different specifications and limited functionality, which could have interfered with the functionality of the newer RT model. The manufacturer confirmed that the older system lacked some of the capabilities of the newer versions of the device. Therefore, three new sets of WAS (alarm units, PSD, 33-foot trip hoses) were procured for supplemental testing, in addition to the pilot-tested RT unit.
    b. A series of systematic range tests were conducted to accurately determine the maximum operational range between each component of the WAS. The range measured during pilot testing was much less than the manufacturer's specification of 1,000 feet.
    c. A series of systematic tests were conducted using a single trip hose, alarm unit, and a PSD to accurately determine the number of "false

positives" and "false negatives" in view of inconsistent results from the pilot testing, where up to four sets of trip hoses were used.

2. SonoBlaster
   a. Additional tests, similar to pilot testing, were performed with ten new SonoBlaster devices installed on traffic cones, to be used only once to eliminate the possibility of freezing or any other mechanical issues observed during pilot testing.

3. Intellicone
   a. Although the false negatives observed during pilot testing were resolved by allowing the Intellicone system 35 to 45 seconds to reset after alarm activations, a series of systematic tests were performed to replicate the "false negatives" and determine the root cause behind them.
   b. Additional tests were conducted to accurately determine the level of force required for lamps of different sensitivities to activate the alarm.
   c. Additional tests were conducted to accurately determine the maximum range distance between lamps while placed in a straight line only (tangent section) versus placement on cones deployed on a combination of tangent and curve sections.

4. All Systems
   a. During pilot testing, comments and feedback were obtained informally from various maintenance workers at the Caltrans META Facility. However, no formal survey forms were completed. In consultation with the Project Advisory Panel, a select number of maintenance supervisors were formally invited to the supplemental testing. The research team set aside one day in the supplemental test schedule dedicated for work zone supervisor participation and feedback.
   b. Four Caltrans maintenance supervisors received training and information on each system, after which they deployed and operated the systems and completed survey forms to provide detailed and formal feedback on each system.

For testing purposes, a mock lane closure of a two-lane road was set up with traffic control, according to the T-13 Caltrans Standard Traffic Plan. All supplemental tests were conducted, and data was collected using some components of the evaluation framework and protocols developed as described in Chapter 3.

- Device Information
- General Work Zone Information and Conditions
- Functional Characteristics – Operation
- Misc. Observations and Worker Survey/Feedback

No additional data was collected for the following components of the evaluation framework as results of the pilot tests were deemed sufficient:

- Functional Characteristics – Deployment
- Sound Test Trials

5.2 SUPPLEMENTAL TESTING LOCATION AND SCHEDULE

In April 2019, supplemental tests of selected WZIA systems were conducted at the Caltrans META Facility in Sacramento under closed-traffic conditions. Three sessions of supplemental tests were conducted to add to the prior pilot testing results. Table 5.1 shows details of supplemental testing schedule and general work zone conditions. Details of the supplemental testing schedule, plan, and field data collection forms developed are presented in Appendix E.

Table 5.1 WZIA Systems Supplemental Testing – Schedule and Field Conditions

Work Zone Information	Worker Alert System & Intellicone	Worker Alert System & SonoBlaster	Maintenance Workers Training and Feedback & Intellicone
Date:	4/2/2019	4/3/2019	4/4/2019
No. of Lanes:	2	2	2
No. of Lanes Closed:	1	1	1
Weather description (Temperature, Wind):	58 F, 10 mph avg. wind speed	55 F, 8 mph avg. wind speed	60 F, 3 mph avg. wind speed
Work Zone Speed Limit (mph):	25 - 45	25 - 45	25 - 45
Type of Work Zone:	T-13*	T-13*	T-13*
Taper Length:	100 feet	100 feet	100 feet
Taper Cone Spacing:	25 feet	25 feet	25 feet
Work Area Length:	50 feet	50 feet	50 feet
Work Cone Spacing:	25 feet	25 feet	25 feet

* Standard lane closure with reversible control, Caltrans Standard

5.3 WORKER ALERT SYSTEM SUPPLEMENTAL TESTING RESULTS

For supplemental testing, four sets of the new WAS systems were available, including alarm units, PSDs, and 33-foot trip hoses, parts of which were used as described in the following sections. The older version CAL device received from Caltrans was not used.

5.3.1 Functional Characteristics – Operation and Range Test Trials

Although the manufacturer specifications for the WAS state a range of up to 1,000 feet between the trip hose and the alarm unit, pilot testing revealed inconsistent results at a range of 400 feet with clear line of sight and 300 feet without a clear line of sight. During supplemental testing, the researchers observed through trial and error that the consistency of the WAS alarm unit activation improved, and the range increased significantly when the alarm unit was held above the ground. Additionally, both the performance and range improved significantly when the pressure sensor was raised up by holding it in hand above the pavement. Since the pressure sensor cannot realistically be held by a worker in an active work zone, the WAS alarm unit was attached to a test vehicle using the magnet on its base approximately four feet above the ground and deployed in the work zone (Figure 5.1). The pressure sensor was positioned on the pavement towards the shoulder.

Figure 5.1 WAS Alarm Unit Attached to a Vehicle in the Work Zone (4 Feet Above the Ground)

With the abovementioned setup, systematic trials were conducted between various components of the WAS to accurately determine the maximum range at which the system would perform without problems. Details are presented in Table 5.2. The layout of the range tests and final outcomes are illustrated in Figure 5.2, which shows the maximum distances between the various components of the WAS.

Table 5.2 Worker Alert System – Range Tests

Range Test Description	**Maximum Range Distance (feet)**	**Comments**
Range Test between Trip Hose and Single Alarm Unit (Function: transmission of a trip hose trigger event to the alarm unit)	225 (See Comments)	• Range distance variable (unreliable) with alarm unit on or near the ground. • Range distance stable when alarm units placed four feet above the ground on the side of a test vehicle with clear line of sight and pressure sensor on the ground towards the shoulder in the closure. • 50 trials conducted.
Range Test between Single Alarm Unit and PSD *(Function: transmission of an alarm signal to the PSD)*	75	• PSD carried in worker's pocket, downstream of an alarm unit. • 10 trials were conducted.
Range Test between Two Alarm Units (Function: transmission of an alarm signal from one alarm unit to another alarm unit to increase coverage areas)	175	• Alarm units placed four feet above the ground on the side of a test vehicle with clear line of sight and pressure sensor on the ground towards the shoulder in the closure. • 30 trials were conducted.
Range Test between Two PSDs (Function: transmission of an alarm signal from one PSD to another PSD)	NA (see Comments)	• PSD units do not tether to each other. They only receive transmission from an alarm unit or pressure sensor.

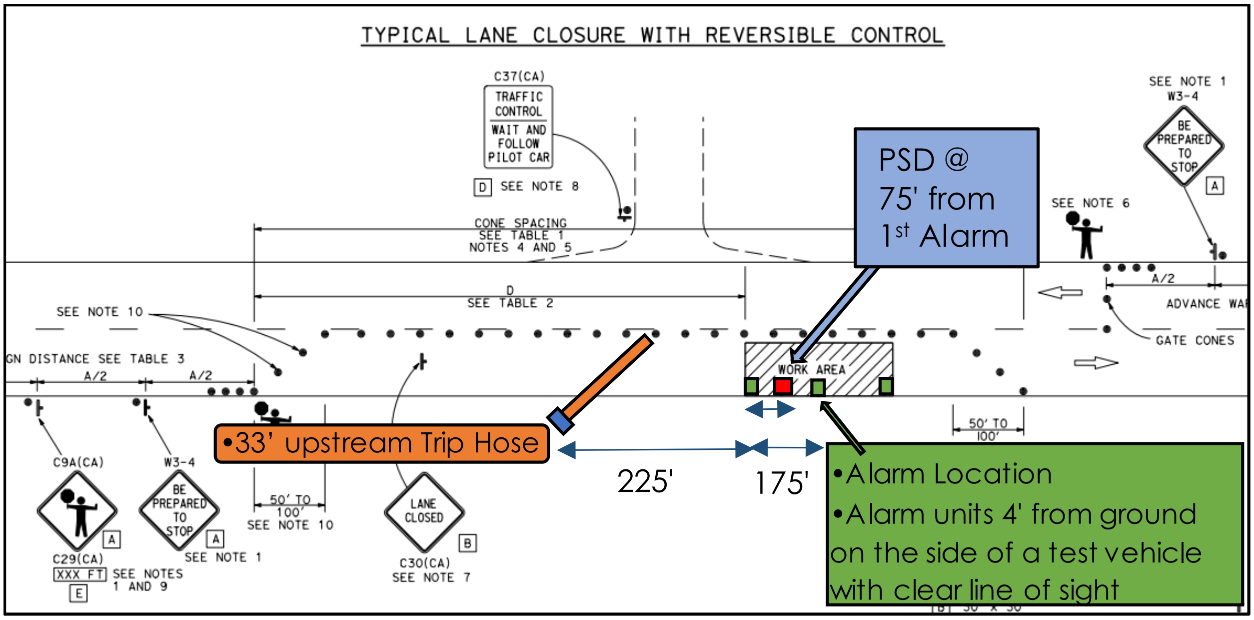


Figure 5.2 Deployment Layout of WAS Range Tests during Supplemental Testing

Figure 5.2 also shows the general layout that was subsequently used (after accurately determining the range of WAS components) to conduct operational tests of the WAS at 25 mph, 35 mph, and 45 mph using a live vehicle to activate the system. Results, in Table 5.3, show that all 30 trials were successful with the alarm unit and PSD working without any issues or true negatives.

Table 5.3 Worker Alert System – Results of Operational Trials during Supplemental Testing

Trial #	Speed (mph)	False Positive Alarm (no intrusion but alarm activated)	False Negative Alarm (intrusion but no alarm activation)	PSD Activation Issues?	Comments
1-10	25	None	None	None	Test successful
11-20	35	None	None	None	Test successful
21-30	45	None	None	None	Test successful

5.4 SONOBLASTER SUPPLEMENTAL TESTING RESULTS

Prior to supplemental testing, several informal tests using the SonoBlaster system were performed at California State University, Sacramento testing grounds, in view of the issues observed during pilot testing. However, the results of the trials remained inconsistent with issues similar to the observed pilot testing results, e.g. improper installation and puncturing of the CO_2 cartridges, freezing and moisture, etc. During supplemental testing, the SonoBlaster device did not activate when it was used by the maintenance supervisors who had been invited to provide feedback. Additional supplemental testing with the SonoBlaster system was not conducted because of other issues related to installation of the devices onto the traffic cones, transportation and deployment, hazard exposure to workers while deploying SonoBlaster cones in a work zone, etc. (as summarized during the pilot testing).

5.5 INTELLICONE SUPPLEMENTAL TESTING RESULTS

During pilot testing, a few false negatives were observed when the Intellicone system alarm was activated in quick succession. After providing a reset time of 35 to 45 seconds, no additional false negatives were observed. However, the exact cause of the false negatives could not be confirmed during pilot testing. Extensive trial and error during supplemental testing showed that the issue of the false negatives was replicated when multiple lamps with vastly different sensitivities were deployed at the same time, e.g. “very high” and “very low” sensitivity lamps, simultaneously. The signals from the different sensitivity lamps seem to have interfered with the correct operation of the Intellicone system. The manufacturer had not previously encountered the issue because all active work zone deployments would include lamps with the same sensitivity for given work zone conditions.

In view of these observations, all previous trials of the Intellicone system were discarded and a series of 30 operational trials were conducted using lamps with the same or similar sensitivity. All trials were successful without false negatives.

Following the successful operational trials, several tests were conducted to determine the differences in activation using lamps of differing sensitivities, as shown in Figure 5.3. Similar tests were conducted during pilot testing using visual observations. The supplemental testing showed the following:

- "Very High" sensitivity lamps activate the alarm when a cone is picked up or moved.
- "High" sensitivity lamps will sometimes activate the alarm when a cone is picked up or moved.
- "Medium", "Low", and "Very Low" sensitivity lamps activate the alarm only when a cone is dropped on the pavement.

In supplemental testing, a high-speed camera that captured images at a rate of 120 frames per second (fps) was used to record detailed images to reveal differences between the performance of lamps with different sensitivities. However, an analysis of the video footage shows results similar to those observed during the pilot testing, as presented above.

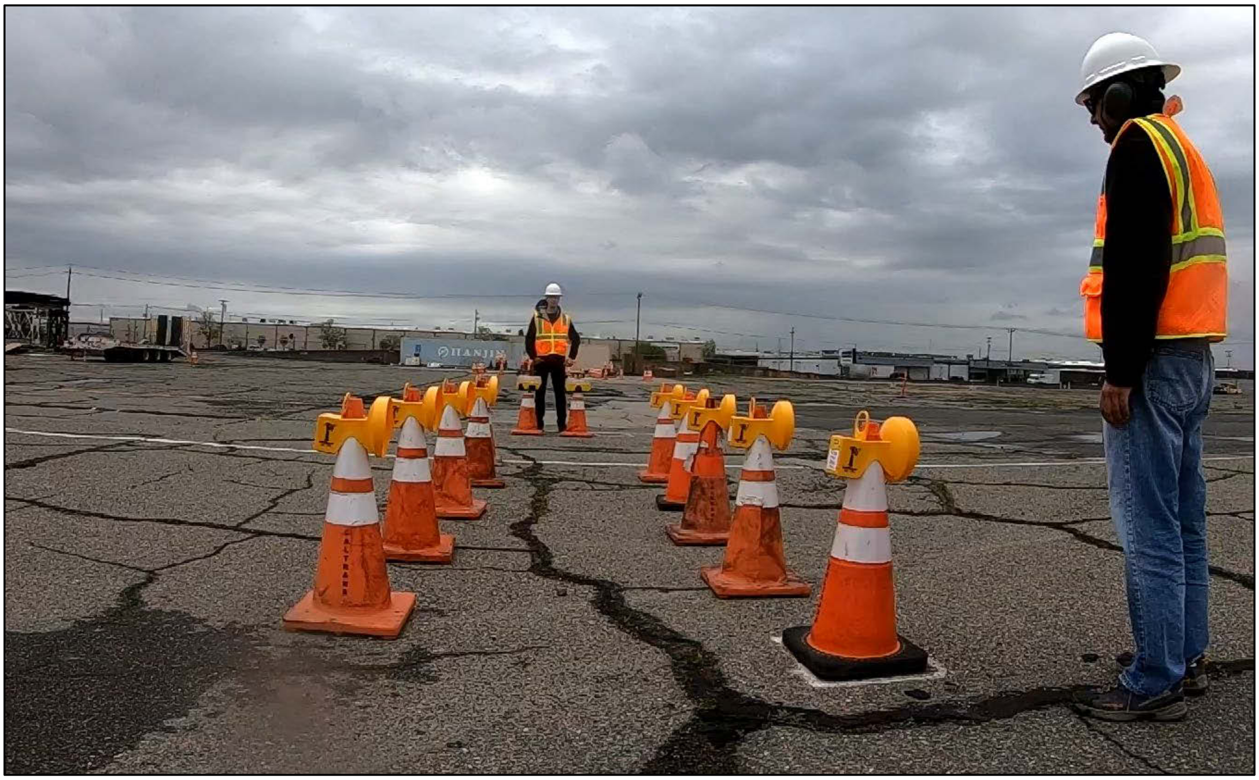


Figure 5.3 Photo of Intellicone Lamp Sensitivity Tests Using High Speed Video

During pilot testing, Intellicone lamps were placed on cones in a straight line only. To determine if changing the line of sight and angle between the lamps would impact the range and performance of the Intellicone system, additional tests were conducted by placing lamps on cones deployed on a combination of tangent and curve sections (Figure 5.4). No differences were observed in the performance of the Intellicone system when deployed on the tangent-curve combination.

Figure 5.4 Photo of Intellicone Operation Tests with Lamps Deployed on a Tangent-Curve Combination

5.6 WORK ZONE MAINTENANCE WORKERS TRAINING, DEPLOYMENT, OPERATION, AND FEEDBACK SESSION

Caltrans DRISI and the Maintenance division invited several maintenance supervisors and staff for a training and feedback session. Four workers attended a half-day session that included an introduction, test deployment and operational training, and live deployment and operation of the three selected WZIA systems. All activities were conducted at the Caltrans META Facility in Sacramento (Figure 5.5). Following the WZIA test deployment and interaction, the maintenance staff shared feedback and completed the survey forms that were developed as described in Chapter 3 and presented in Appendix D. Detailed setup and deployment instructions for the WZIA are provided in Appendix F. The survey results of the data collected are summarized in the following sections.

Figure 5.5 Caltrans Maintenance Supervisors Training and Feedback Session

5.6.1 Effectiveness of Mitigating Collisions and Improving Work Zone Safety

With regards to the overall effectiveness in mitigating collisions, Figure 5.6 shows that respondents ranked the WAS the highest followed closely by the Intellicone system. However, the SonoBlaster was "slightly effective" or "not at all effective." Figure 5.7 shows that the Intellicone and WAS have a higher likelihood of improving work zone safety whereas the SonoBlaster may even reduce safety in the work zone, due to increased worker exposure while deploying the system in practice.

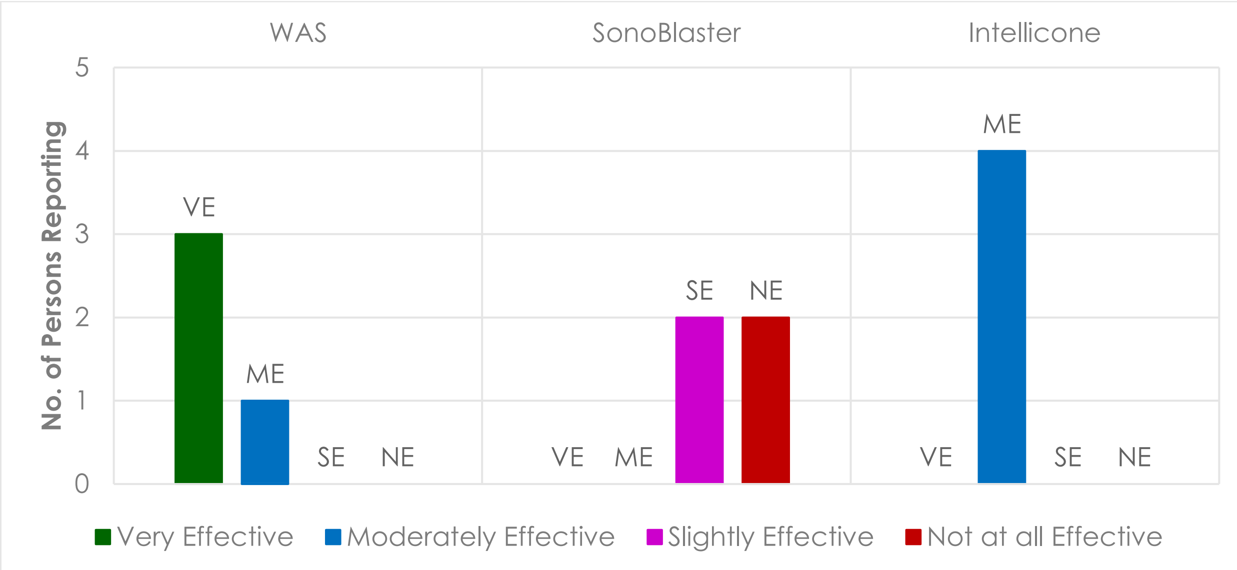


Figure 5.6 Effectiveness of WZIA Devices in Mitigating Work Zone Collisions

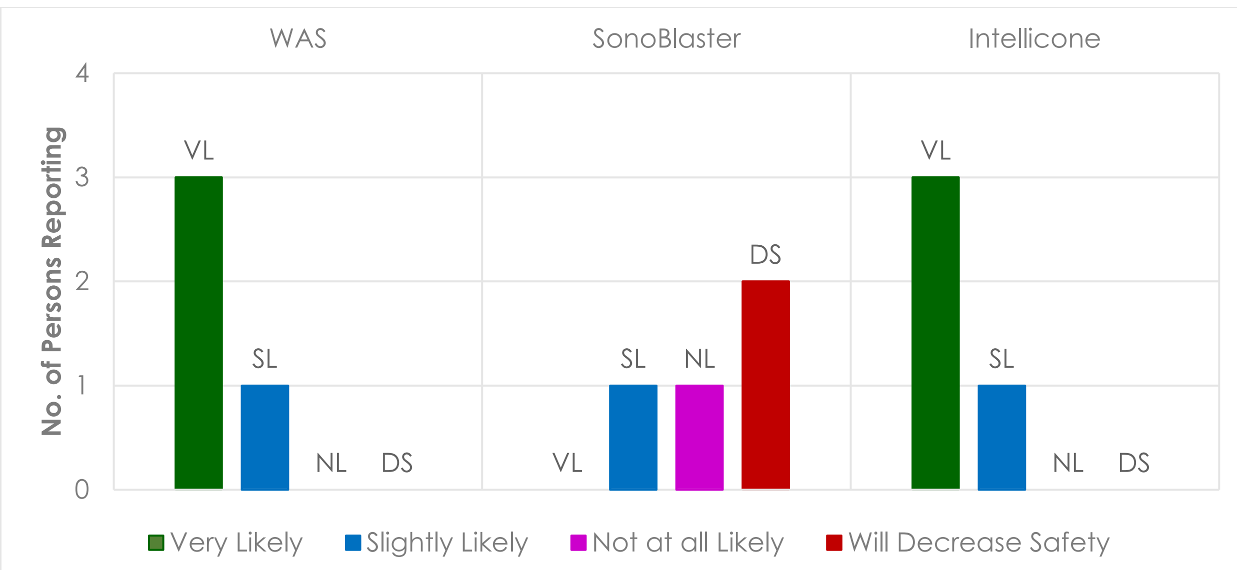


Figure 5.7 Effectiveness of WZIA Devices in Improving Work Zone Safety

5.6.2 Device Effectiveness

In response to a series of questions about the various aspects of the devices' effectiveness such as sound level, reaction time, safety, coverage, visual coverage, and PSD (if available), the Intellicone system scored slightly higher overall in terms of effectiveness than all other systems. The WAS also received mostly effective responses. The results for SonoBlaster were mixed with varying opinions amongst the respondents. Figure 5.8, Figure 5.9, and Figure 5.10 present details of the responses with regards to the WAS, SonoBlaster, and Intellicone systems, respectively.

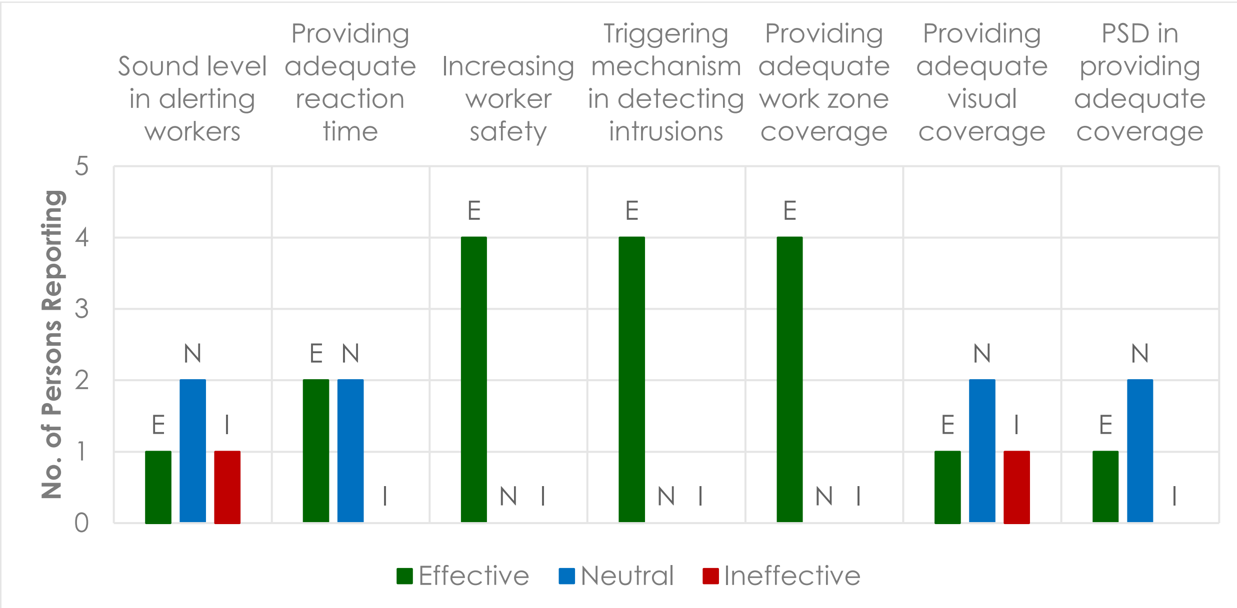


Figure 5.8 General Effectiveness of the Worker Alert System

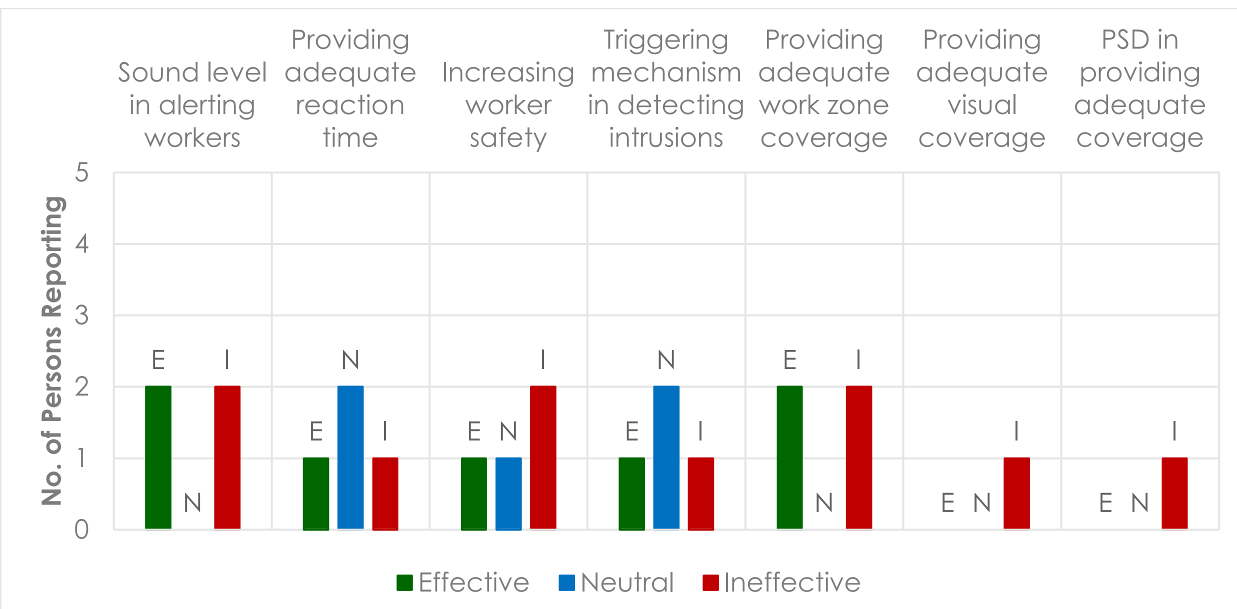


Figure 5.9 General Effectiveness of the SonoBlaster

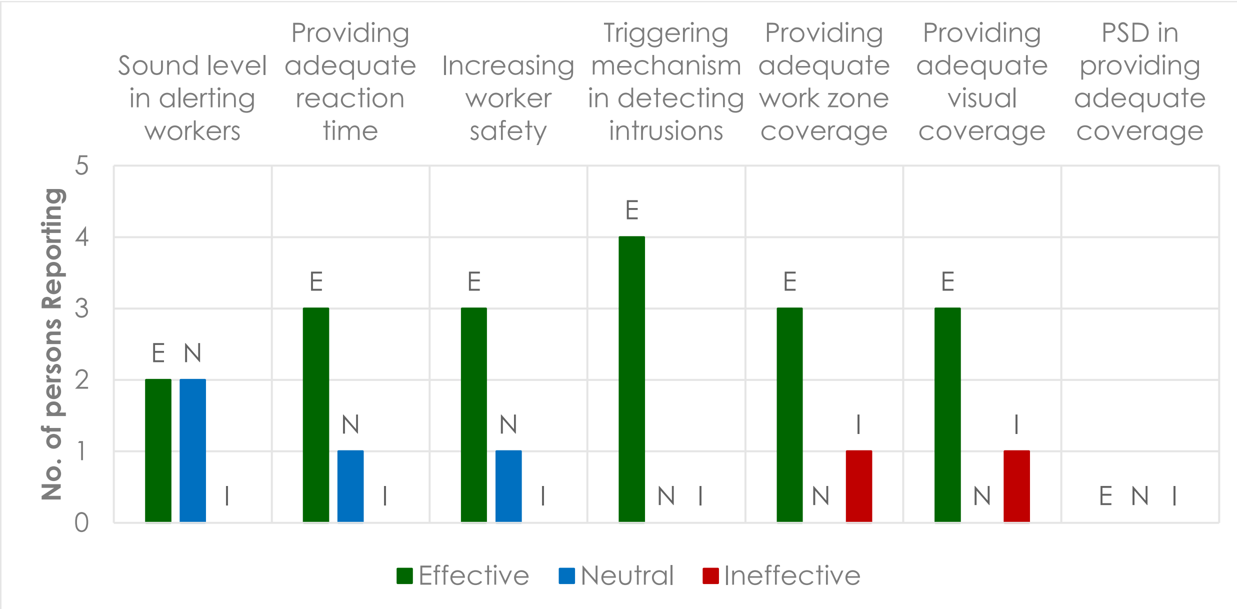


Figure 5.10 General Effectiveness of the Intellicone System

5.6.3 Deployment and Operation

The survey responses on the deployment and operation of the WAS, SonoBlaster, and Intellicone systems are presented in Figure 5.11, Figure 5.12, and Figure 5.13, respectively. The results show that the WAS scored much higher in terms of ease of deployment and operation, followed by the Intellicone system. The SoundBlaster was considered mostly difficult in all aspects of deployment and operation.

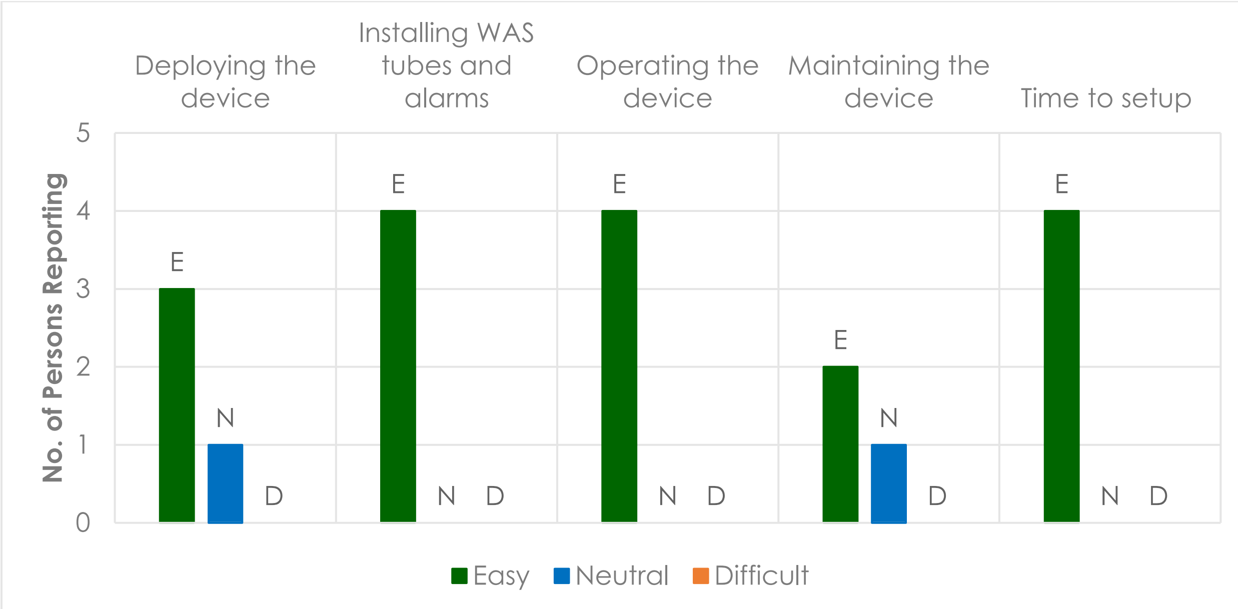


Figure 5.11 Difficulty/Ease of Deploying and Operating the Worker Alert System

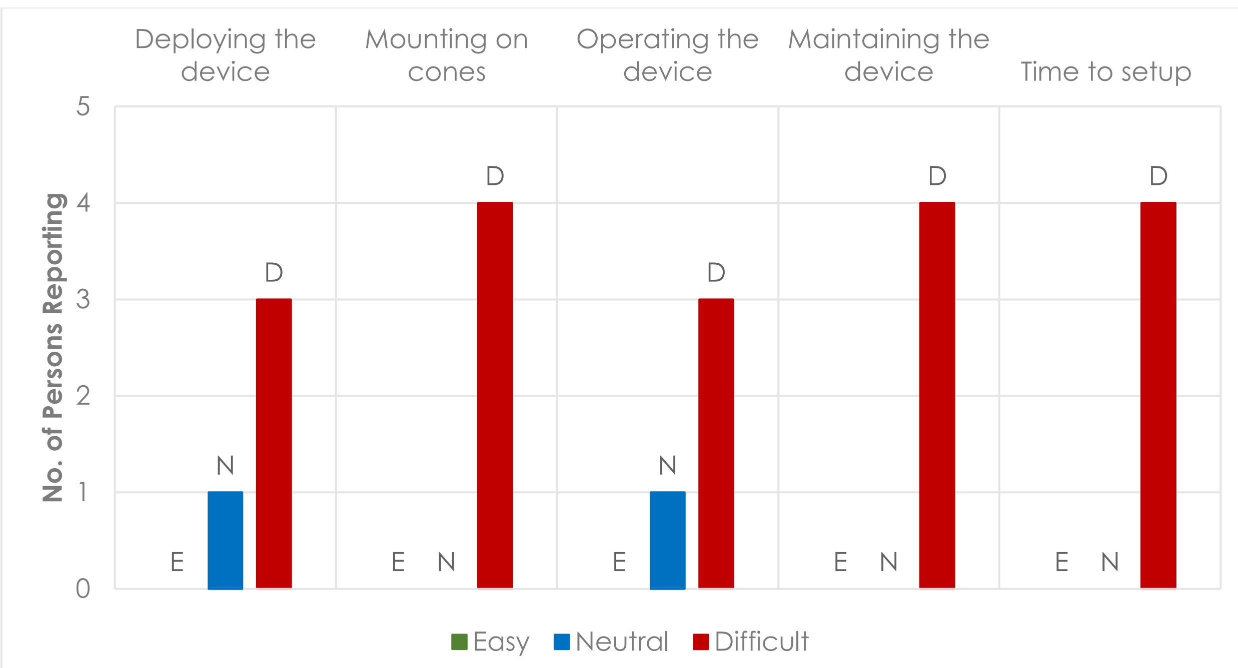


Figure 5.12 Difficulty/Ease of Deploying and Operating the SonoBlaster

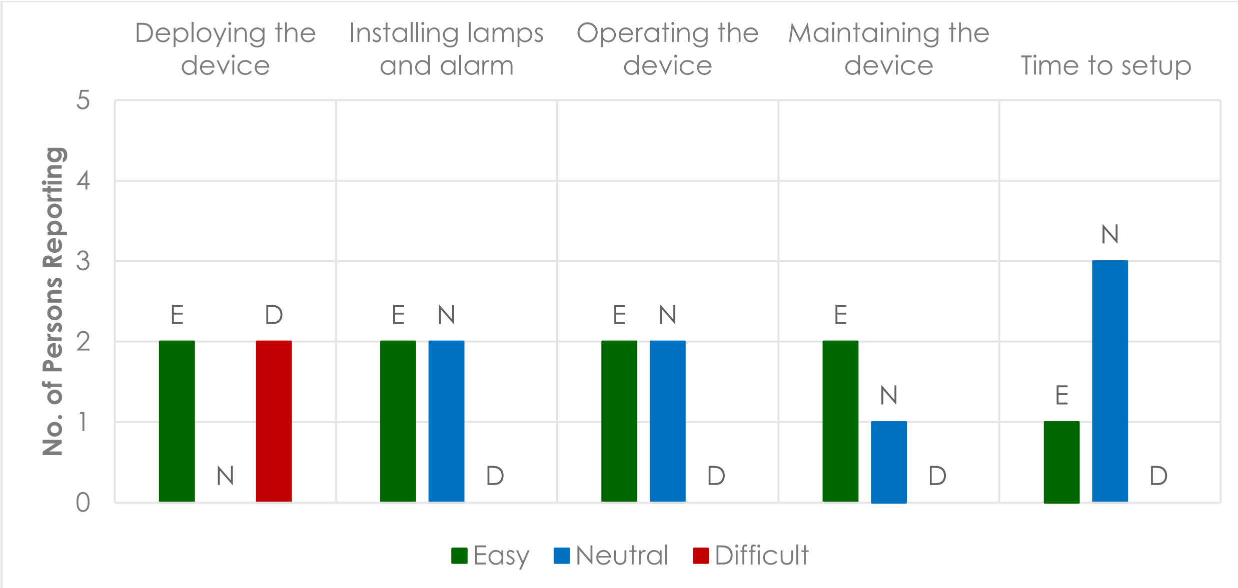


Figure 5.13 Difficulty/Ease of Deploying and Operating the Intellicone

5.6.4 Durability of Devices

The question on the durability of the systems, as perceived by the maintenance staff, was a difficult one to answer, given they had no long-term experience with using the systems in the field. However, the aim was to utilize their field experience of work zone conditions in assessing how durable the systems would be and if there were components too fragile for an active work zone. Figure 5.14, Figure 5.15, and Figure 5.16 show the results on durability of the WAS, SonoBlaster, and Intellicone systems, as perceived by the maintenance staff. Although there were some non-responses to these questions, there was a clear consensus that the SonoBlaster was considered too fragile in terms of durability.

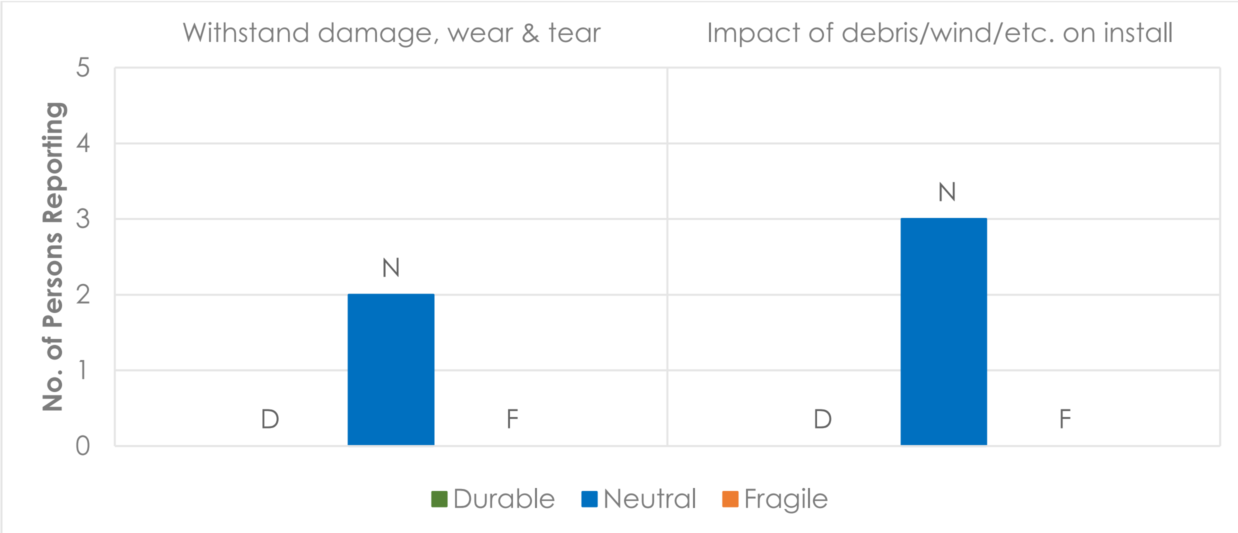


Figure 5.14 Durability of the Worker Alert System

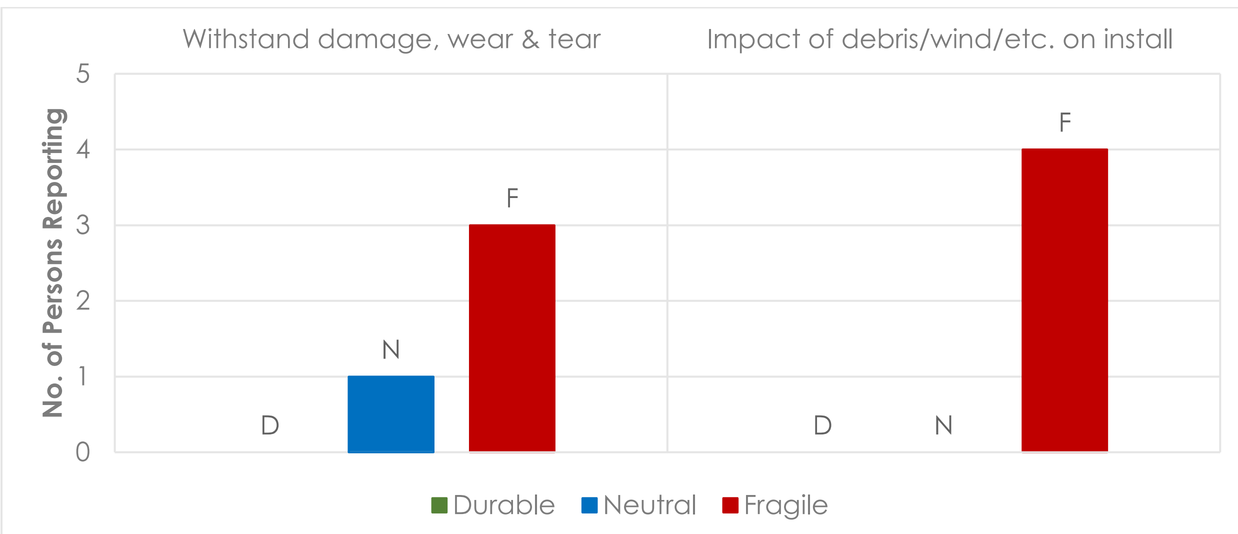


Figure 5.15 Durability of the SonoBlaster

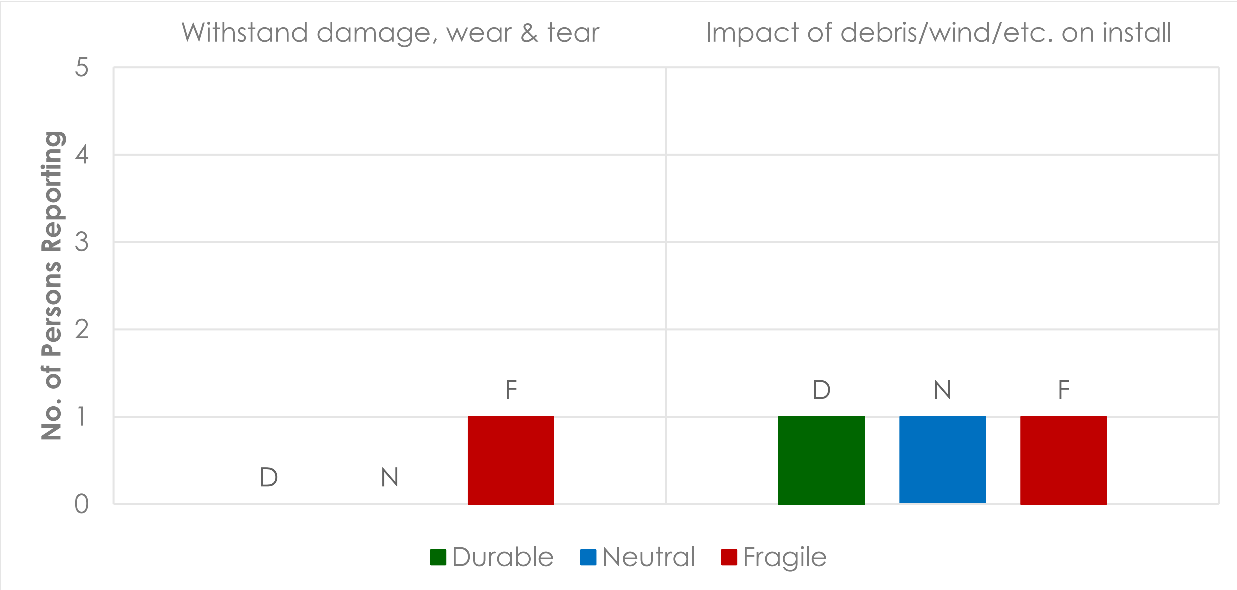


Figure 5.16 Durability of the Intellicone System

5.6.5 Distinctiveness of Sound

The survey results on the distinctiveness of the alarm sound to alert work zone workers, considering general work zone noise levels and determining the direction of intrusion, are presented in Figure 5.17, Figure 5.18, and Figure 5.19 for the WAS, SonoBlaster, and Intellicone systems, respectively.

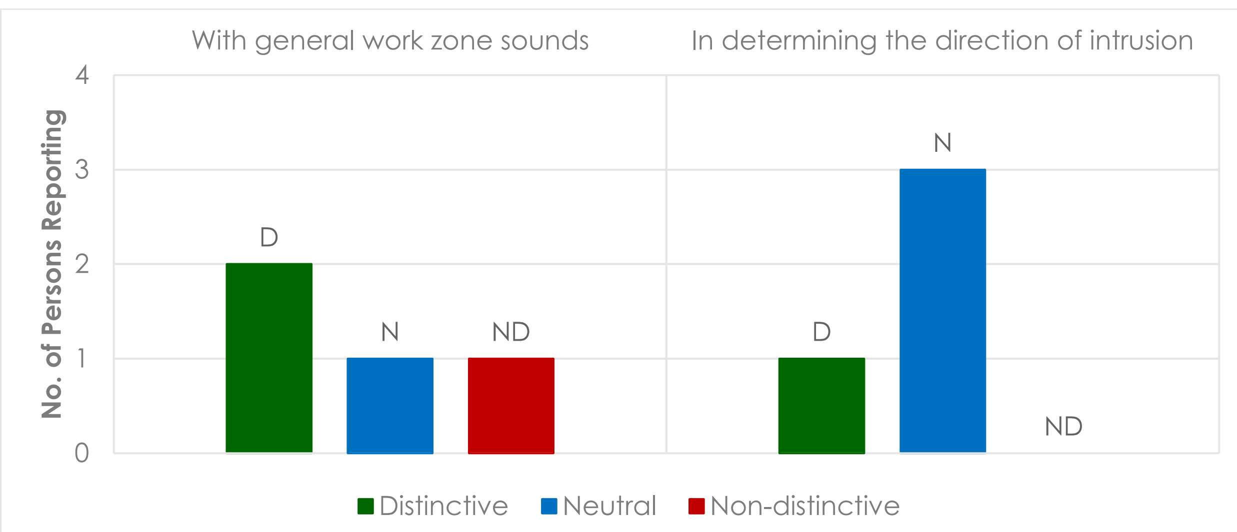


Figure 5.17 Sound Distinctiveness of the Worker Alert System

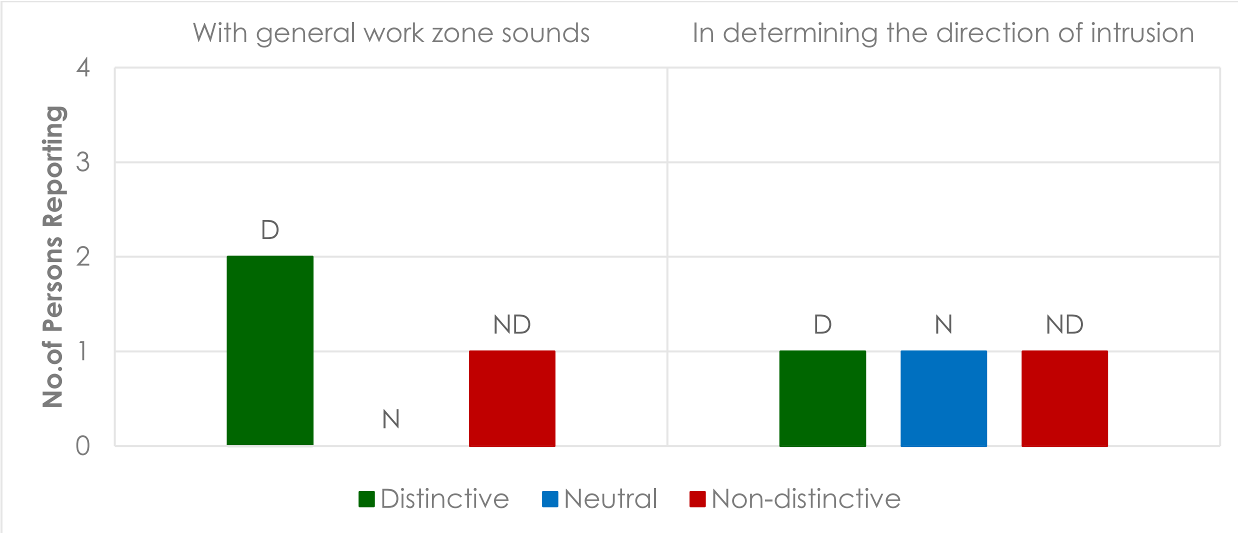


Figure 5.18 Sound Distinctiveness of the SonoBlaster

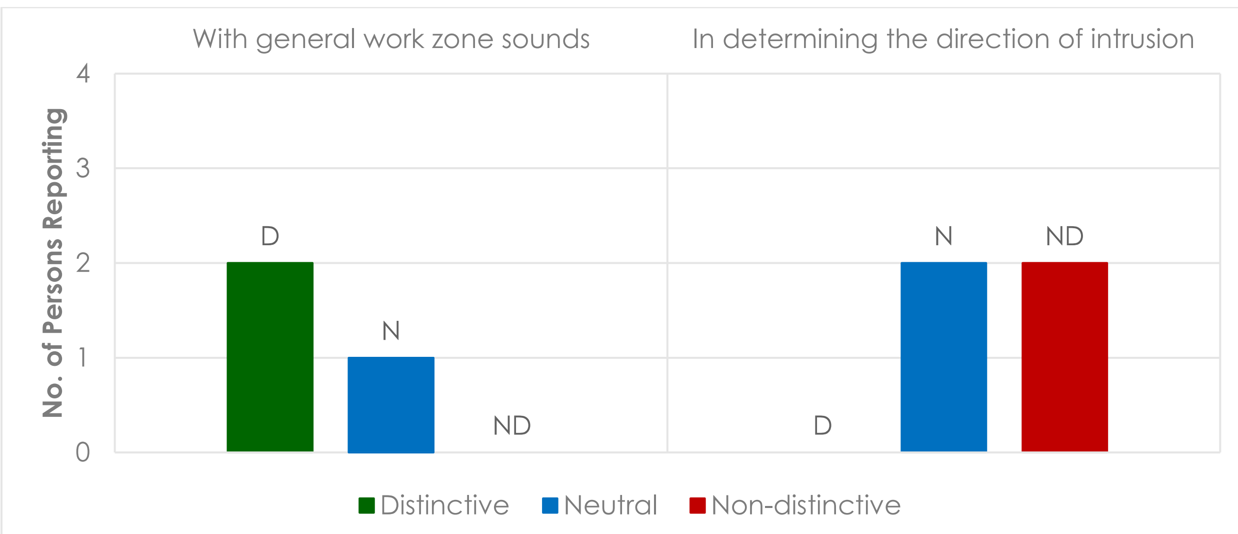


Figure 5.19 Sound Distinctiveness of the Intellicone System

5.6.6 Summary of Survey Comments, Feedback, and Recommendations

As part of the survey, maintenance staff were requested to provide open-ended written responses to most of the questions, including comments and feedback on all aspects of the devices and possible recommendations that could improve the performance of the systems. A summary of the written comments for each system including benefits, issues, and recommendations is presented in Table 5.4.

Table 5.4 Summary of Written Comments by Maintenance Staff on WZIA Systems

WZIA System	Benefits	Issues	Recommendations
WAS	• Device is easy to deploy, use, and retrieve (multiple comments). • Surface coverage was superior to the other two systems in this study.	• Alarm needs to be louder. • The PSD can get dislodged during normal maintenance activities.	• The alarm signal relays should be modified to drop onto cones. • Can be used for on/off ramps, shoulder and lane closures. • Implement a battery charge indicator in the alarm unit. • Deployment recommended by backing up a truck from the work area into the closure for minimum exposure. • Incorporate a belt clip on PSD.
SonoBlaster	• Sound level was loud on alarm activation.	• First test of device failed (possibly due to improper installation of CO_2 cartridge). • Too fragile and high maintenance. • High worker exposure during setup. • Not very durable during routine maintenance yard operations. • Optimal alarm audio is dependent on the direction it is pointed. • Uncertainty about use during low temperature conditions impacting system performance. • Uncertainty about if the device is set up or functioning properly prior to use.	• A "sleeve bracket" should be developed that can attach to the device to drop on to a traffic cone for quick installation.
Intellicone	• Simplest to use, less exposure time (multiple comments). • Sound level was loud on deployment.	• Alarm could be louder. • Excessive sensors needed in long work zones. • Lighted sensors may conflict with Chapter 8 Safety Codes.	• The lamps should have flashing lights and audio alerts.

6 WZIA SYSTEMS EVALUATION DISCUSSION AND GUIDANCE ON PRACTICAL IMPLEMENTATION

In light of the results of the pilot and supplemental testing, this chapter presents a detailed discussion on the overall evaluation, performance, and implementation of each of the three selected WZIA devices. Furthermore, guidance on practical deployment of the systems in a work zone is also provided to supplement current Caltrans work zone traffic control plans.

6.1 OVERALL EVALUATION OF WZIA SYSTEMS – DISCUSSION AND OUTCOMES

6.1.1 Overall Evaluation of the Worker Alert System

During pilot testing, some issues were observed in the performance of the WAS. Subsequently, the research team determined that a possible reason was the use of an older version of the alarm unit, with limited capabilities, that had been received by Caltrans. Once the older version of the alarm unit was excluded from the supplemental testing, the WAS performance improved.

The overall WAS pilot and supplemental testing results showed that the system required some pre-deployment steps, such as charging the rechargeable alarm battery and ensuring the disposable batteries in the pressure sensor and PSD work properly. Transportation and deployment of the system are relatively easy with minimum exposure to the maintenance workers, given that the trip hoses can be deployed quickly without getting too close to the travel way for long periods of time. One issue noticed during transportation and testing was the accidental activation of the alarm due to the nature of the manual activation buttons on the hand-held remote and PSD. The manual activation buttons on these devices are slightly recessed into the body of the devices but not enough to avoid accidental activation. Upon deployment during tests, the alarm was activated because one of the hand-held remote buttons was pressed against the box in which it was being transported. Until the manufacturer improves the design, to avoid this issue, removing the batteries from the devices prior to transporting to the work zone is recommended. This may not be an issue in practice as employees would recognize the problem after becoming familiar with the system.

One of the main advantages of the WAS is the flexibility of the trip hose to be deployed in any configuration in the work zone. Multiple trip hoses can be connected together to transmit signals over a large area to the alarm unit to provide adequate coverage. Additionally, the trip hoses can be configured to provide openings for maintenance and delivery vehicles. Therefore, positioning the pressure sensor towards the shoulder in the work zone is recommended to avoid accidental damage from traffic travelling in the open lane.

The sound level tests and survey feedback from maintenance staff showed that the sound level was lower and less effective than other systems given the general noise levels in a work zone. However, this issue can be easily remedied by using multiple alarm units in the work area, as was shown during supplemental testing, where three alarm units were deployed. The system would be more effective if multiple alarm units were used. However, the exact number of alarm units to be used to produce effective sound levels would depend on the size of the work area. The WAS alarm was limited by a single speaker on one side; therefore, care should be taken in orienting the alarm speaker towards the workers or the work area when deployed. It is possible the manufacturer could add multiple speakers and/or higher sound levels on future versions of the WAS.

A critical advantage of the WAS is the availability of a PSD, which provides haptic and audio alerts (through included ear buds). None of the other systems tested had, or can provide, personalized alerts to the workers. Adding an audio alert that did not require ear buds and a built-in belt clip would increase the functionality of the PSD. Furthermore, the WAS system includes a hand-held remote that can manually activate the alarm unit and can be used for flagging operations in a work zone.

The WAS specifications state a maximum transmission range of 1,000 feet between the trip hose and alarm unit; however, the transmission range observed during the evaluation tests was much shorter. Deploying the alarm unit (with a base magnet) at some height above the ground was observed to produce consistent alarm activations. Consequently, deploying the WAS alarm at least four feet (a typical height if the unit is attached to the side of a vehicle) above the ground is recommended. At this height, the maximum transmission range in which no issues were observed during numerous trials measured at: 225 feet between a trip hose and an alarm unit, 175 feet between two alarm units in a work area, and 75 feet between an alarm unit and PSD. If the manufacturer could increase the reliable transmission range of the system through the addition of a high-power repeater unit, the functionality/value would be significantly increased. Based on test results, if the trip hose pressure sensor could be elevated, its reliable transmission range would be increased. Something as simple as a hook on the sensor would allow it hang from the top of a cone placed on the shoulder, or possibly a collar that drops over the top of a cone.

A review of the video data from the evaluation tests showed that the WAS alarm unit activated almost immediately with no discernable delay when a vehicle crossed the trip hose. Assuming a minimal setup of a single trip hose, a single alarm unit at the start of the work area, no delay in the activation of the alarm, and given the maximum transmission range as measured and observed in this research, the minimum reaction times for work zone workers can be calculated as shown in Table 6.1. This highlights the effectiveness of the WAS in alerting workers. Figure 6.1 illustrates the layout of the WAS for calculation of reaction times. The table shows that as the vehicle speed at trip hose impact increases, the reaction time for workers decreases as expected. The reaction times range from a maximum of 6.1 seconds to a minimum of 2.4 seconds for speeds of 25 and 65 mph, respectively. Workers located further downstream in the work zone will have additional reaction time.

Table 6.1 Worker Alert System Reaction Time for Workers with Minimal Setup

Vehicle Speed at Trip Hose Impact - miles per hour (feet per second)	Minimum Reaction Time (seconds) for Workers to React (Using a Minimal Setup*)
25 (37)	6.1
30 (44)	5.1
35 (51)	4.4
40 (59)	3.8
45 (66)	3.4
50 (74)	3.1
55 (81)	2.8
60 (88)	2.6
65 (96)	2.4

*A minimal setup includes only a single trip hose and alarm unit.

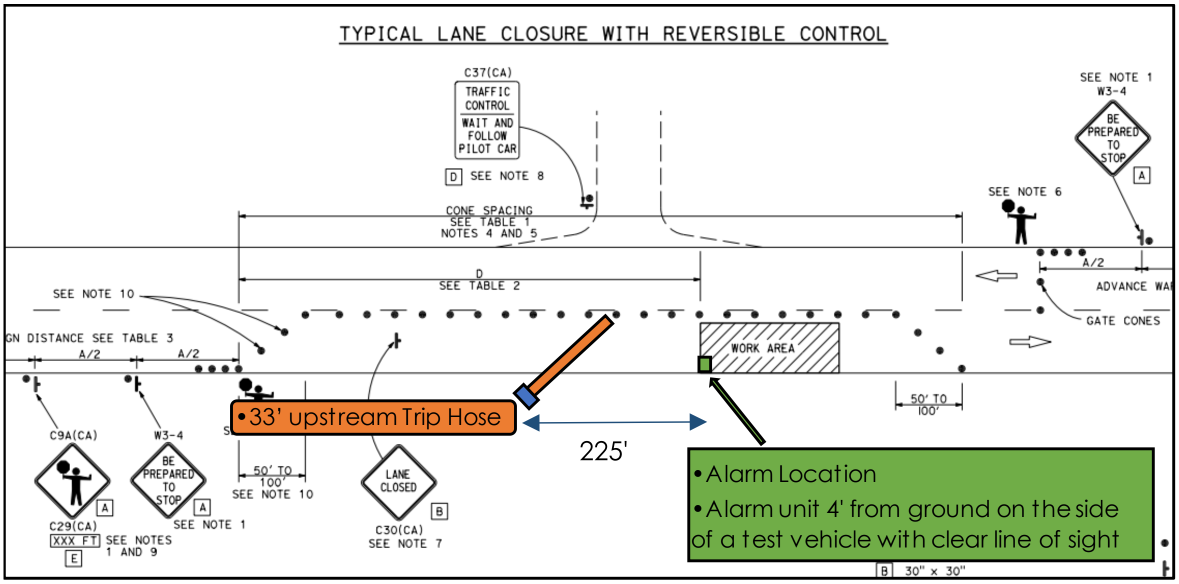


Figure 6.1 Worker Alert System Layout for Reaction Time Calculations

The reaction times, shown in Table 6.1, are based on a minimal setup of a single trip hose and alarm unit given the signal transmission range measured and observed during the evaluation tests in this research. Any additional trip hoses upstream of the trip hose as shown in Figure 6.1 would result in increased reaction time for workers assuming the vehicle is travelling within the closure. The eventual reaction times available and effectiveness of the WAS would depend upon the exact entry point of the intruding vehicle in to the closure and whether it crosses over a trip hose or not. Using additional trip hoses would provide more effective coverage in the work zone.

Having general information on minimum reaction times needed by workers would have been ideal to specify how far out the systems could be deployed in order to be useful. However, a thorough literature review on the subject matter did not reveal any studies or information on this subject matter and is recommended for future research.

Although the transmission range observed in this research was less than the manufacturer's specifications, the results of the reaction time calculations show that the use of WAS in a work zone is still practical, especially given the tethering capabilities of multiple trip hoses to transmit a signal to the alarm unit over a long range. Additionally, the availability of the PSD presents a distinct advantage with the WAS in alerting workers in the work zone.

The overall feedback from the maintenance staff training and survey regarding the WAS was positive given the system's deployment flexibility, minimum worker exposure during deployment and operation, ease of use, and overall effectiveness.

6.1.2 Overall Evaluation of the SonoBlaster

The SonoBlaster system is a mechanically operated device (does not require batteries) and had the loudest alarm of all the systems evaluated in this research. However, several issues were observed with the system during the evaluation tests with inconsistent results, and some of the issues remained unresolved.

SonoBlaster attaches to a traffic cone using a mounting bracket that needs to be preinstalled in the warehouse or maintenance yard. Each bracket can be installed in approximately 10 to 15 minutes by an experienced person, which can be a significant amount of time depending on the number of cones to be deployed. Furthermore, the instructions recommend installing the bracket at the base of a traffic cone. However, the manufacturer's recommended install was not possible given the thickness of the base of the cone, thus making the installation flimsy and stacking the cones more difficult. The creation of a slip-on collar to install the SonoBlaster would be a valuable alternative.

Transporting and deploying the SonoBlaster devices installed on a standard traffic cone was difficult given the space limitations in a standard Caltrans cone body truck. The cone body truck, which typically carries two rows of cones, could not accommodate both rows with SonoBlaster-installed cones. Furthermore, the cones are transported laying on their side, and given the tilt angle of the cone when a worker picked up the cone and unlocked the device arming the alarm, there was a possibility of unintentionally activating the alarm. One suggestion to avoid these issues would be to transport and deploy the SonoBlaster with traffic cones stacked vertically. Deploying the SonoBlaster also presented a higher level of worker exposure than the other systems, especially while manually turning the knobs to unlock the devices before deployment. This issue was mentioned several times by multiple maintenance workers during feedback sessions and surveys.

During operational trials, the SonoBlaster sound level was the loudest and effective in alerting the workers. The alarm duration was measured and observed to be between 15 and 90 seconds, which met the manufacturer's specifications of a minimum of 15 seconds. Not all trials were successful, and the results were inconsistent for several reasons. One reason for inconsistent results was the freezing and moisture accumulation from the CO_2 cartridge discharge, which developed after repeated use of a device. Although this issue is not a concern given that a single device is not expected to be used repeatedly within a short time frame, the observation does allude to concerns identified in the literature with regards to the performance of the SonoBlaster in cold weather conditions.

Another reason for inconsistent results was the potential improper installation of the CO_2 cartridge. Despite following the manufacturer's instructions, 100 percent success in the correct installation of the CO_2 cartridges was difficult to achieve, resulting in false negatives. This issue was highlighted during the work zone maintenance staff training and deployment session when the first SonoBlaster trial was unsuccessful due to an improper CO_2 cartridge installation. Furthermore, a couple of the devices broke down after repeated use with a faulty trigger mechanism, leading to suggest that in practical applications, any impacted or activated SonoBlaster device should not be reused. The issue with proper cartridge installation needs to be resolved to provide confidence that a deployed unit is going to function properly.

The overall feedback and comments received from the maintenance staff regarding the SonoBlaster were generally unfavorable given the issues summarized in this section. In view of the issues experienced in this research and feedback from the maintenance staff, the Project Advisory Panel and researchers were cautious against recommending widespread use of the SonoBlaster system. Therefore, specific deployment recommendations or worker reaction times were not calculated for the SonoBlaster system. However, if usage is desired, the key to the effectiveness of the SonoBlaster system is to use as many of the devices as possible to achieve maximum coverage and mitigate the possibility of any devices that may fail to activate (assuming an intruding vehicle impacts multiple devices). Details of the spacing between the cones in a taper and on a tangent section in a work zone according to the Caltrans standards is shown in Appendix G.

6.1.3 Overall Evaluation of the Intellicone System

During pilot and supplemental testing, the Intellicone system performed the most consistent of all the WZIA systems barring the issue related to the mixing of the lamps with different sensitivities. Although the issue was resolved by allowing 35 to 45 seconds of reset time after alarm activation, the exact reason for the issues was the use of multiple lamps with different sensitivity levels. The manufacturer recommends using the same sensitivity lamps in a work zone to avoid this issue, but this recommendation was not noted in the product documentation.

The pre-deployment steps for the Intellicone system include charging the PSA for at least 24 hours and checking/replacing the battery (rechargeable or disposable) in the lamps. Given the weight and build of the system, a single worker can typically carry two to three PSA units or up to eight lamps. Deployment is simple with a single power button turning on the system, which requires up to five minutes for the PSA to acquire a GPS and cellular network signal. The lamps turn on automatically when placed on top of a cone. The simple deployment procedure was pointed out by the maintenance workers as a benefit of the Intellicone system. However, the need for a worker to walk to each traffic cone to place the lamps was pointed out as a potential issue increasing worker exposure in the work zone.

During operational trials, the Intellicone system performed consistently barring the resolved issue related to the mixing of the lamps with different sensitivities. The maximum transmission range that resulted in consistent performance between a single lamp and the PSA and between two PSA units was 100 feet, as specified by the manufacturer. The lamps have tethering capability to connect with each other and can transmit a signal eventually to the PSA, theoretically giving the system an unlimited coverage range. If a lamp is placed on every cone in a work zone, the 100 feet transmission range as observed in this research is more than sufficient given the cone spacing as specified in the Caltrans standard traffic control plans in a work zone for various speeds. However, for effective coverage, additional cones with lamps can be placed inside the work zone transverse to the flow of traffic as illustrated in Figure 6.2. Details of the spacing between the cones in a taper and on a tangent section in a work zone according to the Caltrans standards is shown in Appendix G.

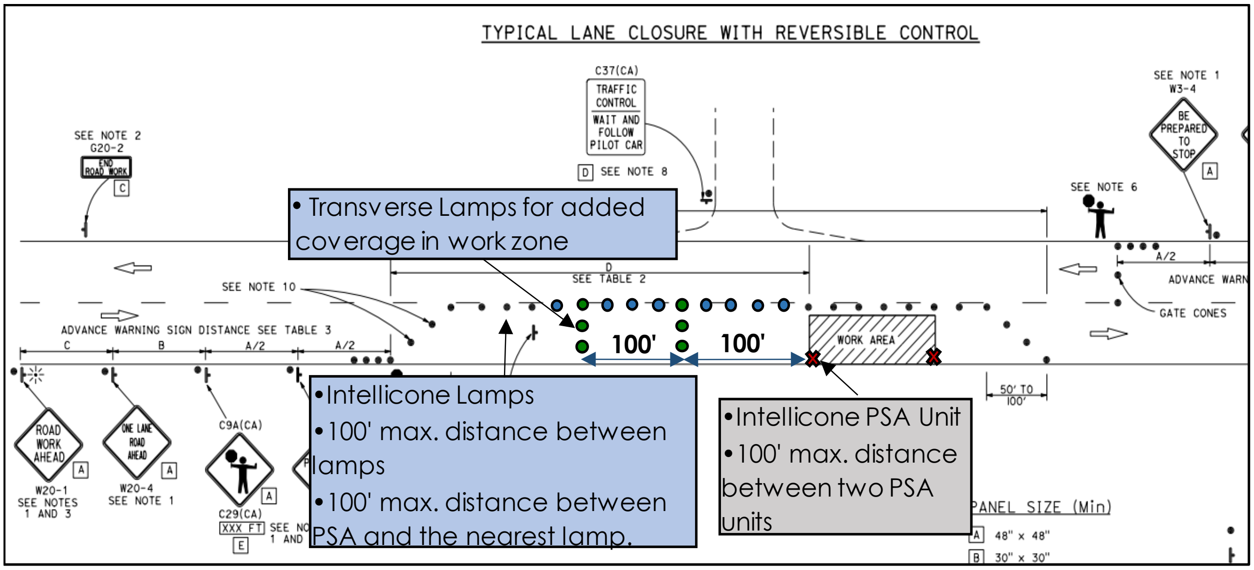


Figure 6.2 Intellicone System Layout for Reaction Time Calculations

A review of video data from the evaluation tests showed that the Intellicone alarm unit activated almost immediately with no discernable delay when a cone with a lamp was impacted. As illustrated in Figure 6.2 and considering deployment of transverse lamps at a distance of 100 and 200 feet away from the work area (in addition to lamps placed on the taper and the tangent cones), no lamps greater than 100 feet away from each other or the nearest PSA, and no delay in the activation of the alarm unit, the minimum reaction times for work zone workers can be calculated as shown in Table 6.2, highlighting the effectiveness of the Intellicone system in alerting the workers.

Table 6.2 Intellicone System Reaction Time for Workers with Minimal Setup

Vehicle Speed at Cone Impact - miles per hour (feet per second)	Minimum Reaction Time (seconds) for Workers (Cones Impacted 100 feet from Alarm)	Minimum Reaction Time (seconds) for Workers (Cones Impacted 200 feet from Alarm)
25 (37)	2.7	5.4
30 (44)	2.3	4.5
35 (51)	1.9	3.9
40 (59)	1.7	3.4
45 (66)	1.5	3.0
50 (74)	1.4	2.7
55 (81)	1.2	2.5
60 (88)	1.1	2.3
65 (96)	1.0	2.1

Table 6.2 shows that as the vehicle speed at the impacted (transverse) lamp increases, the reaction time for workers decreases as expected. The reaction times range from 1.0 to 2.7 seconds for transverse cones 100 feet away and 2.1 to 5.4 seconds for transverse cones 200 feet away from the work area. The reaction times as shown in Table 6.2 are based on an assumed setup to illustrate the usefulness of the Intellicone system in alerting workers. Any additional lamps placed transversely upstream of the work area would provide better coverage and added reaction time for workers, assuming the vehicle is travelling within the closure and the point of intrusion is further away from the work area. The actual reaction time available to workers and effectiveness of the Intellicone system would depend upon the exact entry point of the intruding vehicle into the closure and whether a lamp is impacted or not. Additionally, workers further downstream in the work zone will have additional reaction time.

6.2 GUIDANCE ON PRACTICAL DEPLOYMENT IN WORK ZONES

One of the goals of this research was to provide supplements to the Caltrans standard work zone traffic control plans on the practical deployment of WZIA systems. In view of the comprehensive evaluations conducted in this research, detailed guidance and recommendations on the practical deployment of WZIA systems in an active work zone are discussed in this section. Given the performance of each WZIA system and feedback from Project Advisory Panel, the primary focus of the deployment plans was on a typical lane closure on a two-lane road using a T-13 Caltrans standard traffic control plan. The reason for this was the prevalence of lower speeds in such work zones, making the WZIA systems more effective, as opposed to high-speed (e.g.

freeway, etc.) applications. Given the functionality of current WZIAs, high-speed applications may yield inadequate alert times for workers, present higher exposure levels to workers during deployment, or be obscured by higher noise levels in such areas rendering the alarms ineffective. Additionally, there is limited information on the reliability/functionality of the systems at higher impact speeds. More research is required to objectively assess the performance of the selected WZIA devices in such applications.

6.2.1 Worker Alert System – Recommended Deployment Plans

Based on the results of operational and range tests conducted in this research, Figure 6.3 illustrates a recommended deployment plan for the WAS on a T-13 standard lane closure on a two-lane roadway as a supplement to the standard Caltrans traffic control plan. Figure 6.3 shows recommended and maximum distance between components of the WAS at which the evaluation trials produced 100 percent successful results. Figure 6.3 shows a distance of 225 feet between the first alarm unit and the nearest trip hose. Additional trip hoses upstream of the first trip hose are recommended to increase the coverage area in the work zone. Although Figure 6.3 shows three trip hoses, a recommendation on the specific number of trip hoses is not provided since that would depend upon the length of the work zone and availability of the number of devices. Instead, a maximum distance of 75 feet between the trip hoses is recommended based on discussions and feedback from maintenance workers during supplemental testing, as it provided effective coverage with minimum gaps for intruding vehicles to miss a trip hose. Based on this recommendation, the total number of trip hoses can be calculated given the length of a work zone.

Laying out the trip hoses diagonally at an approximate angle between 45 to 70 degrees is also recommended to improve the coverage area. Multiple alarm units should be placed, ideally, at the start, middle, and end of the work area ensuring the maximum distance between the alarm units does not exceed 175 feet with a clear line of sight. Also, the units should be placed at least four feet above the ground. The speaker on the alarm unit should be oriented towards the workers during day time and the light source should be oriented towards the workers during nighttime operations.

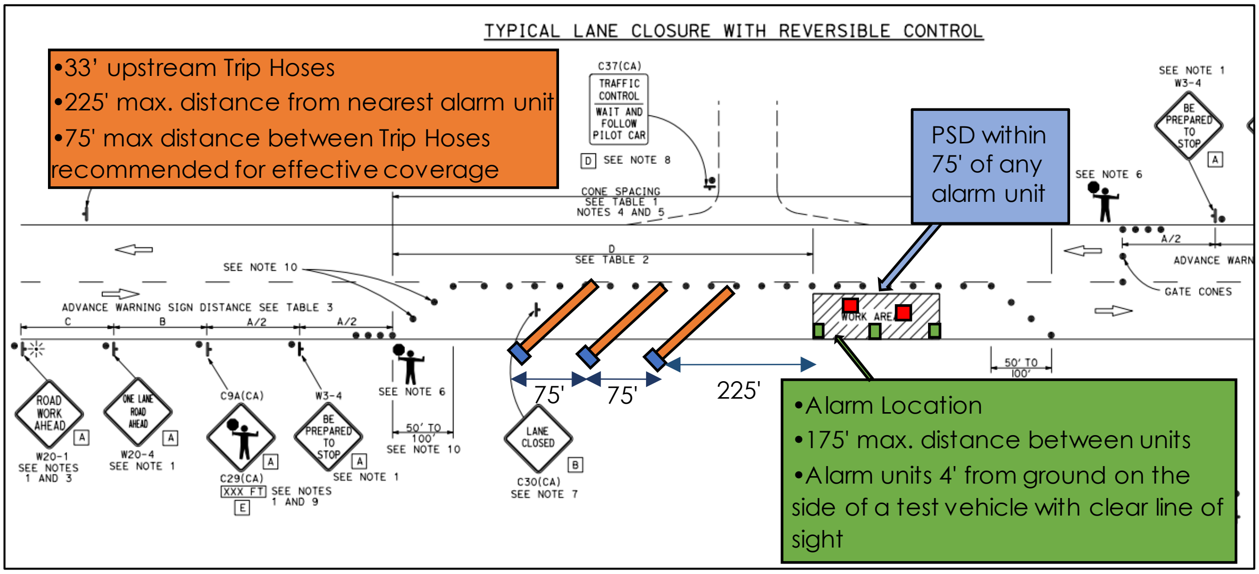


Figure 6.3 Recommended Deployment Plan for Worker Alert System on a Standard T-13 Closure

Given the deployment details as shown in Figure 6.3, Figure 6.4 illustrates a minimum deployment plan for the WAS on a typical exit ramp closure as a supplement to the standard Caltrans traffic control plan. Figure 6.4 shows a single trip hose placed behind the traffic barricades and the alarm unit downstream in the work area along with any PSD. Additional trip hoses and alarm units can be deployed for greater coverage given the range distance limitations shown in Figure 6.4 and as discussed previously. The exit ramp closure deployment plan can also be adopted for implementation on closure at an entrance ramp.

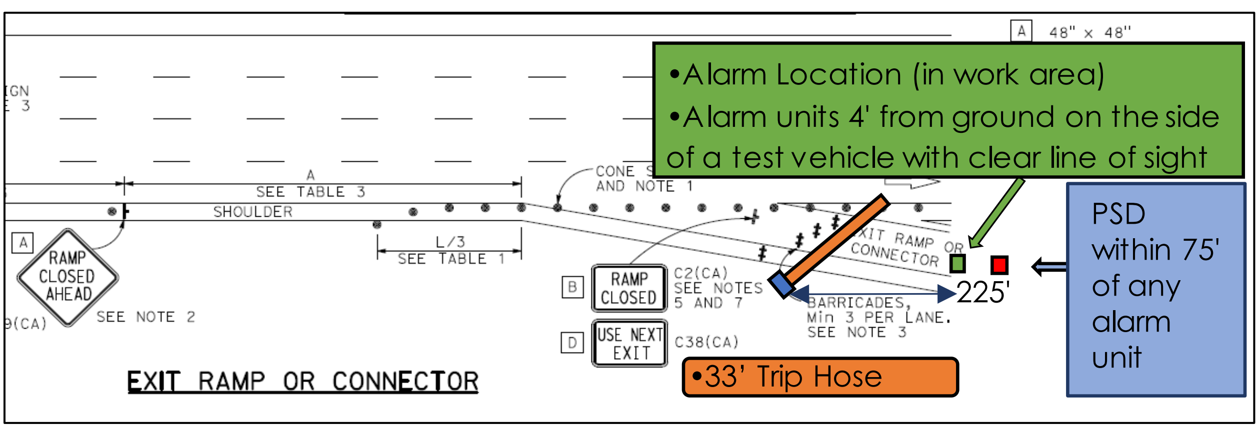


Figure 6.4 Recommended Deployment Plan for Worker Alert System on a Standard Ramp Closure

6.2.2 SonoBlaster – Recommended Deployment Plans

Based on the results of the evaluations in this research and the various issues encountered, no formal recommendations are provided on the deployment of the SonoBlaster system. Instead, the maintenance supervisors are recommended to use their judgement whether the SonoBlaster would be effective and practical to deploy in view of the results and observations presented in this research. The deployment location of the SonoBlaster cones would follow the same standards as shown in the Caltrans standard tables for the traffic control system in Appendix G.

6.2.3 Intellicone – Recommended Deployment Plans

During deployment of the Intellicone system, the need for a worker to walk to each traffic cone to place the lamps was pointed out as a potential issue increasing worker exposure in the work zone. A possible solution recommended is to utilize two cone body trucks (one with cones and the other with prepared Intellicone lamps) to reduce direct worker exposure time. The first truck would set out the cones, and the second truck would follow, placing the lamps on the deployed cones. Alternatively, one cone truck could make two separate passes, first placing the cones, then returning to place the lamps.

Based on the results of the operational and range tests conducted in this research, Figure 6.5 illustrates a recommended deployment plan for the Intellicone system on a T-13 standard lane closure on a two-lane roadway as a supplement to the standard Caltrans traffic control plan. Figure 6.5 shows Intellicone lamps on the taper and tangent cones with spacing as required by the Caltrans standard traffic control plan tables (see Appendix G). The maximum distance between the lamps, a PSA and the nearest lamp, and between two PSA units, must be less than 100 feet, at which the evaluation trials in this research produced 100 percent successful results. For effective coverage, additional cones with lamps are recommended to be deployed transverse to the traffic flow as shown in Figure 6.5. Two cones are recommended with a maximum spacing of five feet. This configuration should be repeated every 100 feet, starting from the work area and going upstream in the work zone. Deploying as many cones with lamps as possible/available is recommended to increase the coverage area of the system in a work zone. Based on the work zone speed and spacing between the cones, the number of cones required for a specific work zone can be calculated. Lamps of all sensitivities except the "very high" are recommended to be used in the presence of heavy vehicles and speeds exceeding 35 mph. For lower speeds and no heavy vehicles, the "very high" sensitivity lamp should be used.

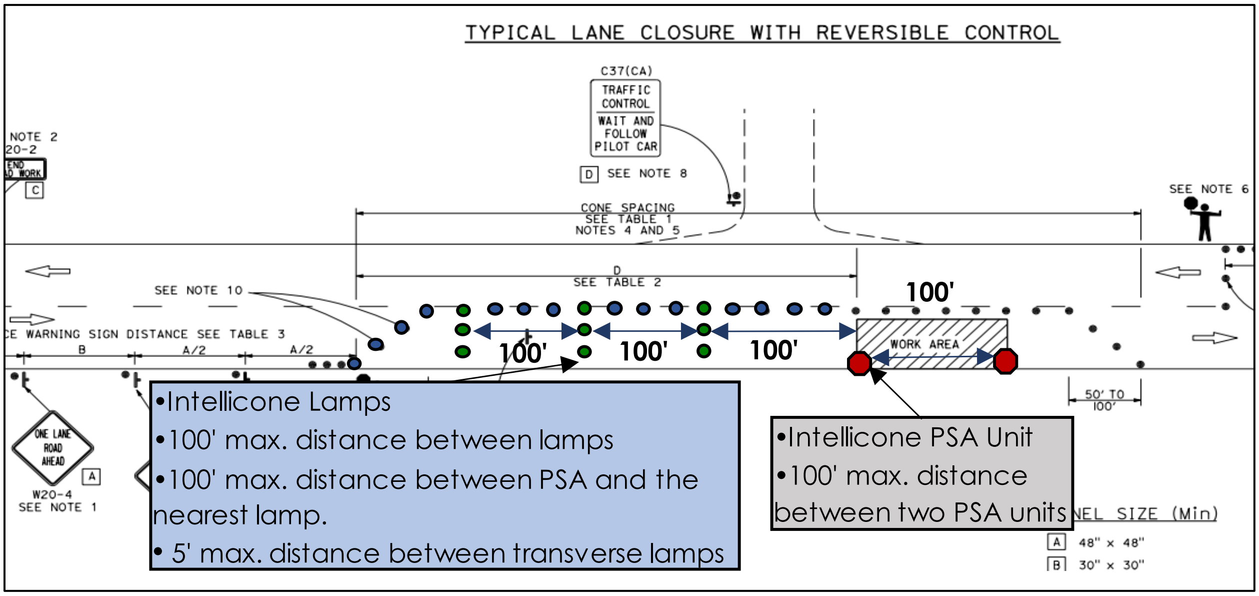


Figure 6.5 Recommended Deployment Plan for Intellicone on a Standard T-13 Closure

Given the deployment details as shown in Figure 6.5, Figure 6.6 illustrates a minimum deployment plan for the Intellicone system on a standard exit ramp closure as a supplement to the standard Caltrans traffic control plan. Figure 6.6 shows lamps placed on all cones and two PSA units in the work area (the minimum is one PSA), ensuring the maximum distance between the PSA and the nearest lamp unit does not exceed 100 feet. A set of transverse cones with lamps are also recommended behind the barricade closure for additional coverage. The exit ramp closure deployment plan can also be adopted for implementation on closure at an entrance ramp.

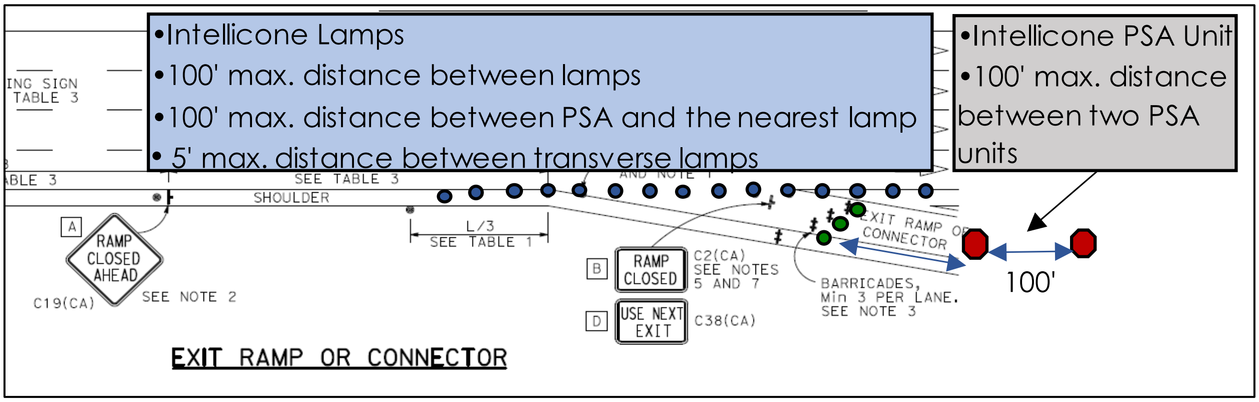


Figure 6.6 Recommended Deployment Plan for Intellicone on a Standard Ramp Closure

The Intellicone lamps with different sensitivities provide an additional option to deploy the system for different functions according to the needs of specific work zone conditions. For example, the "very high" sensitivity lamps can be deployed to create a closure, preventing anyone from moving the cones without activating the alarm. The "low" and "very low" sensitivity lamps can be deployed in high-speed areas to minimize false positive alarms where high-speed traffic or heavy vehicles may possibly move the cones, but not knock them over.

6.2.4 Additional Guidance on WZIA Systems Deployment

In addition to the deployment plans recommended in the previous sections, the WZIA systems evaluated in this research can be deployed in shoulder closures, bridge work closures, and other access control situations according to the specifications and distances as discussed in the previous sections.

6.3 COST BENEFIT ANALYSIS OF SELECTED WZIA SYSTEMS

One of the significant considerations in the successful adoption of WZIA systems is the cost factor and potential benefits. The general feedback from maintenance supervisors and staff surveyed in this regard was mixed. One view was that high cost would deter the use of such systems. Conversely, the other view was that cost is irrelevant if there is potential safety benefit to be gained from the use of WZIA systems in saving the lives of work zone workers. A quantitative assessment of the benefits and costs associated with the use of the selected WZIA systems would provide useful guidance to transportation agencies in adopting WZIA systems.

6.3.1 Cost Analysis

The cost of using the selected WZIA systems can be calculated by considering the cost associated with procuring, setup, deploying, retrieving, and maintaining each system. A general cost analysis for a hypothetical half-mile closure on a two-lane road with 12-foot wide lanes was used to demonstrate the potential cost impact for each selected system. A speed limit of 25 mph was assumed in the hypothetical closure resulting in a taper length of 250 feet at the start and end of the closure and a tangent length of 2,140 feet according to the Caltrans Standard Plan specifications (Appendix G). The cone (or any other channelizing device) spacing is given as 25 feet for the taper and 50 feet for the tangent sections resulting in a total of 63 cones required for the entire work zone. The length of the work area was assumed to be 500 feet. The cost estimates were calculated using the system procurement costs in this research but did not take into account the labor cost due to the variability of such analyses and the effort being outside the defined scope of this research.

6.3.1.1 Worker Alert System

The total cost estimated for using the WAS on a hypothetical half-mile closure as described in this section was $4,630 assuming the use of ten PSDs, three alarm units, six 33-foot trip hoses with chargers, and a single hand-held remote trigger. A recommendation on the specific number of system components was not provided in this research since that would depend on the level of coverage desired by the work zone supervisor specific to each work zone. The number of system components assumed in this section was based on the general observations of the researchers.

6.3.1.2 SonoBlaster and Intellicone

The exact cost of the Intellicone system was assumed based upon the insurance value of the system during shipping by the manufacturer since the system is not currently marketed in the United States. The cost of the SonoBlaster system included the cost of only one CO_2 cartridge per SonoBlaster unit.

The use of the SonoBlaster and Intellicone systems is partially dependent upon the number of cones (or any other channelizing devices) available in a work zone since components of these systems have to be placed on them. Assuming that no system components are placed on the end taper cones and additional components are required for placement within the closure (on transverse cones), the total number of SonoBlaster units required for a hypothetical half-mile closure was assumed to be 63. Using similar assumptions, the total number of Intellicone lamps required was 63 as well, in addition to two PSA units. Thus, the total cost estimated for the SonoBlaster and the Intellicone system for a hypothetical half-mile closure as described in this section was $5,670 and $11,100, respectively.

Although there is a relatively large difference in the cost of the selected WZIA systems, the cost difference should be considered in view of the different level of coverage and safety features offered by each system

6.3.2 Benefit Analysis

The benefit of using WZIA systems can be calculated by considering the potential of such systems in reducing injuries and fatalities related to work zone intrusion collisions. This requires an estimate of the number of work zone intrusion collisions (dependent on the traffic volume, type of roadway, daytime vs. nighttime conditions, etc.), which is difficult to calculate in the absence of specific and detailed work zone information. Furthermore, there was no information in the literature review on the long-term use of WZIA systems in active work zones to develop an estimate of their potential to reduce injuries and fatalities. However, given the high cost of a road fatality or injury and the relatively low cost of the selected WZIA systems, inferring that continued use of these systems could result in long-term benefits financially is reasonable.

7 CONCLUSIONS AND FUTURE RESEARCH

The main goal of this research was to evaluate the effectiveness of selected WZIA systems and assess whether such systems are ready to be deployed in California work zones. The objective was to provide recommendations to Caltrans on the effectiveness and practicality of implementing such systems and provide guidance on their implementation. Several tasks were completed during this research; outcomes are described in this chapter. In view of the preliminary findings during pilot testing, the active work zone testing task was replaced with supplemental testing to better assess the capabilities of the WZIA systems and strengthen the conclusions derived.

7.1 SUMMARY OF WZIA SYSTEMS, RELATED DEVICES, AND RELEVANT TECHNOLOGIES

A detailed review of the literature and the market was conducted to investigate multiple work zone safety-related devices, ranging from commercially available intrusion alarms systems and emerging technologies, to technologies that could be adapted/upgraded to mitigate work zone intrusions. Comprehensive details on three types of systems/devices were compiled to have a wide-ranging pool to select the most relevant devices for evaluation in this research. The types and list of systems/devices were as follows:

- Available Work Zone Intrusion Alarm Systems
  - Traffic Guard Worker Alert System (WAS)
  - SonoBlaster
  - Intellicone
- Emerging Work Zone Intrusion Alarm Systems
  - AWARE
  - Intellistrobe W1-AG
  - AutoFlagger 54 & 76X
- Systems and Devices Related to Work Zone Management and Safety
  - Wrong Way Detection Systems
  - Ver-Mac System
  - iCone
  - Temporary Speed Bumps and Rumble Strips

7.2 DEVELOPMENT OF TESTING PROTOCOLS FOR EVALUATING WZIA SYSTEMS

In consultation with the Project Advisory Panel, four WZIA systems were selected for detailed evaluation in this research.

1. Traffic Guard Worker Alert System (WAS)
2. SonoBlaster
3. Intellicone
4. TAPCO Portable Rumble Strips

The TAPCO Temporary Speed Bumps and Rumble Strips was subsequently dropped because of unavailability of the device due to temporary discontinuation of manufacturing.

A detailed evaluation framework was developed to examine various aspects of each WZIA system selected. The evaluation framework allowed for a systematic and objective evaluation process to effectively assess the detailed performance of each system and understand their capabilities, issues, and limitations. Details of the evaluation framework included goals, objectives, activities, and sources of data, to compile the following categories of information:

- Device Information
- General Work Zone Information and Conditions
- Functional Characteristics – Deployment
- Sound Test Trials
- Functional Characteristics – Operation
- Miscellaneous Observations and Worker Survey/Feedback

Detailed data collection forms were developed to be used in the field during formal testing.

7.3 PILOT TESTING OF SELECTED WZIA SYSTEMS

In view of the evaluation framework, detailed pilot testing was conducted to assess the performance of the selected WZIA systems. All tests were conducted in November 2018 at the Caltrans META testing facility. Most of the tests resulted in valuable data and information documented in this research; however, some known issues from the literature review, other new issues, and unexpected results were also revealed. For example, the older version of the WAS that Caltrans owns had limited capabilities as compared with the latest version available in the market. The SonoBlaster appeared to be the simplest of all systems yet displayed various issues and challenges during testing. The Intellicone system displayed intermittent and unexpected failures due to the simultaneous deployment of lamps with varying sensitivities (which were later resolved through appropriate deployment procedures). A summary of the outcomes of the pilot testing are presented as follows:

7.3.1 Worker Alert System

- WAS is the only system offering a Personal Safety Device (PSD) for workers.
- The system provides both visual and audio alerts through the alarm unit and PSD.
- The system requires pre-deployment steps (charging device battery, replacing batteries in the hand-held remote, PSD, and pressure sensor).
- A single system typically requires 15 to 20 minutes for pre-deployment set up, five minutes for deployment, and five minutes for retrieval time.
- The system experienced false negatives during pilot testing for both WAS devices, possibly due to interference and limitations of an older version of the alarm unit received from Caltrans.
- The average sound level for WAS was 60 dBA at a distance range of 25 to 300 feet.
- The alarm duration was two and five seconds for the older and newer version, respectively.
- The alarm sound level was higher for the older alarm unit than the newer unit.
- The visual alarm light was only on one side of the alarm unit, negating the effectiveness for workers not within the visual range.
- Multiple trip hoses have tethering capability to provide extended work zone coverage and range.

7.3.2 SonoBlaster

- The system is a mechanical device that requires no battery, but instead uses CO_2 cartridges.
- The system has audio only, and no visual alert.
- This is the loudest audio alarm of all systems tested.
- Several pre-deployment steps are required, including installation of a mounting bracket on a cone and a CO_2 cartridge. The installation of the mounting bracket and the CO_2 cartridge is a one-time operation unless the SonoBlaster is impacted by an intrusion.
- Installing the mounting bracket under the cone base, as per manufacturer instructions, is not possible due to the base thickness.
- Fitting two rows of SonoBlaster installed cones in a standard Caltrans cone body truck is not possible.

- There is the possibility of accidental activation of the alarm during cone deployment from a standard Caltrans cone body truck.
- The CO_2 cartridge was sometimes difficult to install (screw precisely in to place). There is no way to verify proper installation before triggering the system, creating a possibility that the alarm will not activate when it should.
- Freezing and moisture in the device formed immediately after activation resulting in inconsistent performance unless sufficient time was given for the unit to dry out.
- There were potential durability issues after a few activations, hence the device should be discarded after alarm activation.
- The alarm duration was 15 to 90 seconds with an average sound level of 78 dBA.
- False negatives were observed during pilot testing due to mechanical failure or improper CO_2 cartridge installation.

7.3.3 Intellicone System

- The three-tone audio alarm sound is specially designed to be highly effective in alerting workers.
- The visual alarm has two different colors.
    - Red alert for automatic detection of vehicle intrusion impacting a traffic cone with a special lamp installed
    - Blue alert for manual activation to warn for expected delivery and other authorized vehicles
- The visual alarm component is not very effective during daytime, but is highly effective during night time.
- The system requires pre-deployment steps such as charging/replacing batteries, and other back-end steps, which can be completed by a maintenance supervisor or the manufacturer.
- The alarm duration is 32 seconds, and the average sound level was 61 dBA.
- A few intermittent and unexplained false negatives were observed, which were remedied after allowing for a sufficient reset time of 35 to 45 seconds.

7.4 SUPPLEMENTAL TESTING OF SELECTED WZIA SYSTEMS

The outcomes of the pilot testing revealed useful information, which was documented, and some issues that had to be further investigated and understood. Therefore, in consultation with the Project Advisory Panel, the original task of active work zone testing was replaced with supplemental testing in closed-to-traffic conditions at the Caltrans META facility. Some of the issues documented during the pilot testing were clarified after discussions with the manufacturers while others were resolved through newly devised tests completed during the supplemental testing. While most issues were resolved eventually, others persisted, which are documented in detail in this research. A summary of the outcomes of the supplemental testing is presented as follows:

7.4.1 Worker Alert System

The final results showed that the WAS performed well with certain limitations and differences observed from the manufacturer's specifications. The major outcomes of the supplemental testing were as follows:

- The maximum range stated by the manufacturer of 1,000 feet could not be achieved during pilot or supplemental testing using a single trip hose and alarm unit.
- Systematic trials concluded that the maximum range to deliver consistently 100 percent success in alarm activation was:
  - 225 feet distance between a single trip hose and alarm unit,
  - 175 feet distance between two alarm units, and
  - 75 feet distance between a PSD and an alarm unit.
- Signal transmission range was highly sensitive to the height of the alarm unit above the pavement. A height of four feet is suggested for the alarm unit installation based on pilot and supplemental testing.
- Using the abovementioned distances and specifications, 100 percent success was observed during 30 operational trials.
- Speed tests at 25, 35, and 45 mph revealed consistent results without any operational issues at the higher speed.
- Caltrans maintenance workers liked the simplicity and flexibility of the system in deployment, operation, and overall improvement of work zone safety.

7.4.2 SonoBlaster

During the supplemental testing, the SonoBlaster system encountered several issues and limitations similar to those that were observed during the pilot testing. Most of these issues could not be resolved or corrected. The major outcomes of the supplemental testing were as follows:

- Even after careful review and practice on the CO_2 cartridge installation, issues persisted with improper installations, resulting in false negatives.

- The failure rate (false negatives) of the device after the first activation caused significant concern.
- Maintenance workers expressed a general lack of interest with the deployment and maintenance aspects of the device, especially the increased worker exposure during deployment.
- In the survey of Caltrans maintenance staff, the SonoBlaster was the only device that was perceived to decrease safety in a work zone when respondents were asked about how much the WZIA systems would improve work zone safety.

7.4.3 Intellicone

After extensive trial and error and consultation with the manufacturer, the intermittent issues with the Intellicone system observed during the pilot testing were resolved. The major outcomes of the supplemental testing were as follows:

- A 100 percent success rate in more than 50 formal and informal trials was observed when only lamps with the same sensitivity levels were used at the same time.
- Lamps of different sensitivities should not be simultaneously installed in the same work zone. The manufacturer stated that this is not the general practice.
- The maximum transmission range was 100 feet between two lamps and between a single PSA and the closet lamp.
- Tethering capability of the lamps to transmit signals to the PSA theoretically with an unlimited range.
- Cellular network capability (currently available in the United States and informally tested) allows two PSA units to transmit alarms over an unlimited range without intermediate lamps.

7.5 GUIDANCE ON PRACTICAL IMPLEMENTATION OF SELECTED WZIA SYSTEMS

In light of the evaluation results of the WZIA systems conducted during the pilot and supplemental testing; considering the capabilities and limitations of the systems as observed during this research; and after resolving most of the issues observed with the Intellicone and WAS, specific guidance was developed on the practical deployment of the selected WZIA systems in California work zones. This guidance was developed in the form of supplemental plans to the Caltrans standard work zone traffic control plans detailing the deployment location, range distances, and setup of the Intellicone and WAS. No specific guidance was provided on the implementation of the SonoBlaster given the issues and challenges observed during this research.

Based on the overall outcomes of this research, the Intellicone and WAS performed the best with consistent results of all evaluation tests once the pilot testing issues were resolved. Implementation of the Intellicone and WAS in California work zones could provide additional safety benefits, supplementing existing safety practices for the benefit of work zone workers and reducing work zone fatalities. The development of a detailed evaluation framework and testing protocols in this research provides governing and regulatory agencies the ability to conduct systematic and objective tests in the future to make informed decisions in selecting and implementing applicable WZIAs. Although potential false alarms and deployment time are drawbacks to the implementation of WZIAs, the systems tested in this research generally appear effective in alerting workers of work zone intrusions.

7.6 FUTURE RESEARCH

The results of this research were based upon pilot and supplemental testing conducted in closed-to-traffic conditions over a period of a few days. To assess the long-term performance, durability, and reliability of the selected WZIA systems, a comprehensive evaluation is recommended to be conducted over a longer period of time with repeated use, preferably in active work zone conditions.

Although active work zone testing was initially part of this research, it was eventually replaced with supplemental testing to better understand the capabilities of the selected WZIA systems and assess their performance. Nevertheless, the true success and effectiveness of WZIA systems would be best evaluated in an active work zone implementation. Therefore, active work zone testing is recommended to be conducted for the WZIA systems. Furthermore, all tests in this research were conducted during the daytime. It would be valuable to conduct detailed evaluations during night time conditions when safety of workers is in greater jeopardy.

Most of the recommendations and guidance provided to Caltrans regarding the deployment and implementation of the selected WZIA systems focused on work zones and lane closures on two-lane roads. Such conditions typically present lower speed traffic conditions as compared with freeway and multi-lane highway closures. The Project Advisory Panel believed the selected WZIA would be best suited for lower speed work zones, given the levels of exposure involved in high-speed work zone implementation and the performance capabilities of the systems. However, detailed evaluations under higher speed conditions are recommended to be conducted in the future to assess if the systems perform well or not under such conditions. Additionally, advances in the system designs warrant a periodic review by Caltrans to determine if updated or new systems are suitable for use in high-speed work zones.

In the literature review, there was a lack of knowledge and information on two critical aspects with regards to recommending detailed and specific deployment plans for the selected WZIA systems. The first was research on typical worker reaction times needed to safely recognize and react to a threat, and the second was a lack of information on the point of impact for a typical work zone collision. Although guidance was developed without these considerations on deployment plans for the selected WZIA systems in this research, detailed research on these two topics is recommended for the future to greatly enhance effective deployment of all WZIA systems. Such research could also be valuable to other studies intending to improve work zone safety. Additionally, a comprehensive cost-benefit analysis of WZIA systems to evaluate their economic feasibility is also recommended and would greatly benefit from the abovementioned research.

During this research, one of the suggestions from the Project Advisory Panel was to conduct impact tests of the selected WZIA systems to determine their effectiveness in close-to-real conditions in alerting work zone workers of vehicle intrusions. Although plans were developed to conduct some impacts tests, they were eventually removed from this research and focus was placed upon completing supplemental testing to resolve questions and concerns that arose during the pilot testing. Therefore, comprehensive and detailed impact tests are recommended to be conducted in the future to truly assess the performance and durability of the selected WZIA systems, especially if there is an interest in utilizing WZIA systems in high-speed settings as their operating ranges increase.

The detailed review of the literature and the market identified several systems, devices, and technologies that could be modified or adapted to be implemented as WZIA systems. In view of knowledge gained from this research and a good understanding of the capabilities of the current systems, it is recommended that Caltrans initiate discussions with the manufacturers of other systems to develop and adopt additional technologies towards implementation in work zones. Such concerted efforts would result in the development of robust and effective WZIA systems for the future, benefiting Caltrans and work zone safety overall.

Some general recommendations specific to the each of the selected WZIA systems were also documented in this research. These recommendations are developed based upon the feedback and input from the Project Advisory Panel, maintenance workers and staff, and the research team, and are summarized as follows:

- The WAS visual alert should be improved to provide a visual alert in all directions.
- The WAS should include multiple speakers to improve sound levels in all directions.
- The WAS should include a volume control, possibly in the form of a high/low setting that defaults to the high level upon power on.
- The WAS's PSD should be updated to include a built-in belt clip and an audio alert that does not require the use of ear buds (the ear bud functionality should be retained).
- The reliable transmission range of the WAS could be increased through the addition of a high-power repeater unit, thereby improving the system's functionality and value.
- The WAS pressure sensor should incorporate a hook or collar to allow its elevation off the ground (on a cone) to improve reliable signal transmission distance.
- The manual activation buttons on the WAS hand-held remote and the PSD should be further recessed to prevent accidental alarm activation.
- Battery level indicators should be incorporated on the WAS alarm unit, PSD, and pressure sensor.
- The reliability of the SonoBlaster device should be improved in terms of installation ease of the CO_2 cartridge.
- An alternative SonoBlaster mounting sleeve that can be dropped quickly onto a traffic cone should be developed.
- The Intellicone system would benefit from a sensor that can provide complete coverage over a wide area, such as the pneumatic sensor employed by the WAS system.

8 REFERENCES

Awolusi I. and Marks E.D., 2019. Active *Work Zone Safety: Preventing Accidents Using Intrusion Sensing Technologies*. *Frontiers in Built Environment*. https://www.frontiersin.org/articles/10.3389/fbuil.2019.00021/full. Accessed Mar. 06, 2019.

Be Work Zone Alert (BWZA), 2018. http://beworkzonealert.com/. Accessed May 4, 2018.

Brown H., Sun C., Zhang S. and Z.Q. Zhang, 2017. *Evaluation of Automated Flagger Assistance Devices.* University of Missouri-Columbia. Missouri Department of Transportation. https://library.modot.mo.gov/RDT/reports/TR201717/cmr17-010.pdf. Accessed Jan. 8, 2018.

California Department of Transportation (Caltrans), 2013. *Evaluating iCone Traffic Sensors for Work Zone Operations*. Caltrans Division of Research, Innovation and System Information. California Department of Transportation. http://www.dot.ca.gov/research/researchreports/two-page_summaries/tsm/icone_results_ver5.pdf. Accessed Feb. 22, 2018.

Caltrans, 2018. http://www.dot.ca.gov/paffairs/workersmemorial/worker-fatality-statistics.html. Worker Fatality Statistics. Accessed Mar. 3, 2018.

Caltrans District 3, 2017. Caltrans Introduces New Technology for Traffic Control. https://www.youtube.com/watch?v=hLi_OUVbNmM. Accessed Jan. 4, 2018.

Carlson, P., Fontaine, M. and Hawkins H., 2000. *Evaluation of traffic control devices for rural high-speed maintenance work zones*. Texas Transportation Institute, The Texas A&M University System. https://rosap.ntl.bts.gov/view/dot/14369/dot_14369_DS1.pdf. Accessed Feb. 16, 2018.

Federal Highway Administration (FHWA), 2013. *Guidance for the Use of Temporary Rumble Strips in Work Zones.* https://www.workzonesafety.org/files/documents/training/fhwa_wz_grant/atssa_temporary_rumble_strips.pdf. Accessed Dec. 14, 2017.

FHWA, 2017. *What's A Work Zone?* https://www.fhwa.dot.gov/publications/publicroads/99mayjun/workzone.cfm. Accessed January 11.

FHWA, 2018. *FHWA Work Zone Facts and Statistics.*

https://www.fhwa.dot.gov/publications/publicroads/99mayjun/workzone.cfm. Accessed May 15.

FHWA, 2009. *FHWA Manual on Uniform Traffic Control Devices for Streets and Highways (2009 edition)*, U.S. Department of Transportation Federal Highway Administration.

Fyhrie, P., 2016. *Work zone intrusion alarms for highway workers: Preliminary investigation*. Caltrans Division of Research, Innovation and System Information. California Department of Transportation (Caltrans). http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/work_zone_warning_preliminary_investigation.pdf. Accessed Jan. 09, 2018.

Gambatese, J.A., Lee, H.W., and Nnaji, C.A., 2017. *Work Zone Intrusion Alert Technologies: Assessment and Practical Guidance*. School of Civil and Construction Engineering, Oregon State University. Oregon Department of Transportation. http://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR790_IntrusionAlertTech.pdf. Accessed Dec. 1, 2018.

Hallmark, S., Turner, J., and Albrecht C., 2013. *Synthesis of Work-Zone Performance Measures.* Center for Transportation Research and Education (CTRE), Iowa State University.

Harris, L., 2014. *Temporary Rumble Strips Help Workers Feel Safer.* The University of Kansas Transportation Center for Road & Bridge Agencies. http://www2.ku.edu/~kutc/pdffiles/LTAPFS14-TempRumbleStrip.pdf. Accessed Feb. 21, 2018.

iCone Products®, 2018. Specs. http://iconeproducts.com/specs/. Accessed Feb. 5, 2018.

IntelliStrobe, 2017. W1-AG automated flagger assistance device. http://www.intellistrobe.com/. Accessed Nov. 18, 2017.

Kochevar, K., 2002. *Intrusion Devices, 2002: New and Emerging Technology in Worker Safety*. http://ops.fhwa.dot.gov/wz/workshops/originals/Ken_Kochevar_ID.ppt. Accessed Jan. 14, 2018.

Marks, E., Vereen, S., and Awolusi I., 2017. *Active Work Zone Safety Using Emerging Technologies*. University Transportation Center for Alabama, The University of Alabama. Alabama Department of Transportation.

http://utca.eng.ua.edu/files/2017/09/15412-Final-Report.pdf. Accessed Feb. 28, 2018.

Mid-America Transportation Center, Iowa Department of Transportation. 2013. http://www.intrans.iastate.edu/research/documents/research-reports/workzone_perf_msrs_w_cvr2.pdf. Accessed Jan. 18, 2018.

Novosel, C., 2014. *Evaluation of Advanced Safety Perimeter Systems for Kansas Temporary Work Zones*. MS Thesis, Civil, Environmental, and Architectural Engineering, University of Kansas. https://kuscholarworks.ku.edu/bitstream/handle/1808/18377/Novosel_ku_0099M_13762_DATA_1.pdf. Accessed Feb. 3, 2018.

Occupational Safety and Health Administration, 2017. Occupational Noise Exposure. https://www.osha.gov/SLTC/noisehearingconservation/. Accessed Aug. 06, 2017.

Old Castle Video Team, 2015. AWARE-Advanced Warning and Risk Evasion-External Version. https://vimeo.com/135969644. Accessed Dec. 5, 2017.

Safety Technologies, 2014. AutoFlagger® 76 AFAD. https://www.youtube.com/watch?v=5vWvYS5mNWY. Accessed Oct. 15, 2017.

Safety Technologies, 2014. AutoFlagger® 54 AFAD. https://www.youtube.com/watch?v=HnZeOB7DbIw&t=8s. Accessed Oct. 15, 2017.

Safety Technologies, 2015. AutoFlagger®. http://www.autoflagger.com/products/autoflagger-54/. Accessed Oct. 15, 2017.

Safety Technologies, 2015. AutoFlagger® 76X. http://www.autoflagger.com/products/autoflagger-76/ . Accessed Oct. 15, 2017.

Sun C. Edara P. and K. Ervin, 2016. *Elevated-Risk Work Zone Evaluation of Temporary Rumble Strips.* http://engineers.missouri.edu/csun/files/2016/08/Portable-Rumble-Strip-MU_revised_v1.pdf. Accessed Jan. 17, 2018.

Traffic & Parking Control Co., Inc. (TAPCO), 2013. Wrong Way Warning System. https://www.youtube.com/watch?time_continue=8&v=KDFwzxUeJRk. Accessed Nov. 11, 2017.

TAPCO, 2017. TAPCO Wrong-Way Solutions. https://www.tapconet.com/solar-led-division/wrong-way-warning-detection-and-alert-system. Accessed Oct. 17, 2018.

TAPCO, 2018. Astro Optics Traffic Guard Portable Speed Bump. https://www.youtube.com/watch?v=37kBmddYDn0. Accessed Oct. 22, 2018.

Terhaar, E.F., 2014. *Implementation of Automatic Flagger Assistance Devices (AFADs) for Minnesota Department of Transportation Flagger Operations*. Wenck Associates. Minnesota Department of Transportation. 2014. https://www.lrrb.org/pdf/201444.pdf. Accessed Jan. 16, 2018.

Theiss, L. Ulman, G.L. and T. Lindheimer, 2017. *Closed Course Performance Testing of The Aware Intrusion Alarm System.* The Texas A&M Transportation Institute. Oldcastle Materials, Inc. https://static.tti.tamu.edu/tti.tamu.edu/documents/TTI-2017-2.pdf. Accessed Feb. 16, 2018.

Trafficcalm Systems, 2018. Wrong Way Alert. http://trafficalm.com/wwa/. Accessed Jan. 9, 2018.

Trans Canada Traffic Inc. Intellicone. 2018. http://www.transcanadatraffic.ca/IntelliconeProductInformation.html#.WroA10xFzop. Accessed Jan. 5, 2018.

Transpo Industries Inc, 2009. SonoBlaster® Overview Video. https://www.youtube.com/watch?v=WRFjerUnNVo. Accessed Nov. 18, 2017.

Transpo Industries Inc, 2017. SonoBlaster Work Zone Intrusion Alarm. https://www.transpo.com/roads-highways/safety-products/wz-intrusion-alarm. Accessed Dec. 7, 2017.

Ver-Mac, 2016. Ver-Mac - SWZ video – 2016. https://vimeo.com/170024708. Accessed Feb. 28, 2018.

Ver-Mac, 2018a. JAMLOGIC - Smart Work Zone Solutions. https://www.ver-mac.com/en/jamlogic-software/smart-work-zones. Accessed Feb. 28. 2018.

Ver-Mac, 2018b. SP-3248V. https://www.ver-mac.com/en/products/series/serie/speed-signs/product/trailer-mounted-speed-display-sign/53. Accessed Feb. 28, 2018.

Virginia Department of Transportation, 2018. Work Zone Challenges. https://www.dmv.virginia.gov/safety/resources/pdf/rush.pdf. Accessed Mar. 6, 2019.

Wang, M., Schrock, S.D., Bai Y., and R.A. Rescot, 2011. Kansas Department of Transportation. Research and Innovative Technology Administration. http://idmweb.ksdot.org/PublicLib/publicDoc.asp?ID=003813661. Accessed Jan. 5, 2018.

APPENDIX A

LITERATURE REVIEW DETAILS

Description and Features of Intellicone Components

Name	Description	Features*	Range	Battery
Portable Site Alarm (PSA)	Portable Site Alarm connects to lamps and TMU	3-tone siren, green and red flashing LEDs; web portal reporting, text message alerts, GPS location tracking	RF: 164 feet	Internal recharge-able battery
Traffic Management Unit (TMU)	Traffic Management Unit	Enables remote site management and real time response to breaches; web portal status monitoring of multiple Intellicone systems, text message alerts, GPS location tracking	RF: 164 feet	Internal recharge-able battery
Unipart Dorman ConeLITE®	Cone lamp with sensor activates the PSA when pushed, impacted, or tilted	Communicates with other lamps/sensors and Intellicone PSA; Deploys in any order and works day and night	164 feet maximum between lamps	Two 6-volt type 4R25 batteries
Synchro-GUIDE	Lamp with intelligent wireless impact detection technology	Communicates with other lamps/sensors and Intellicone PSA; Deploys in any order and works day and night; Sequential flashing lamp	164 feet maximum between lamps	Two 6-volt type 4R25 batteries
Sentry	Ultrasonic single-ended sensor activates alarm when the emitted beam is breached	Communicates with other sensors and Intellicone PSA	98 feet maximum of Intellicone PSA or TMU	External 12-volt battery

**Some features are not currently available in the United States*

(Adapted from Trans Canada Traffic Inc., 2018)

Systems and Devices Related to Work Zone Management and Safety

Details of the systems and devices, with the potential to be retrofitted for use as WZIA systems, is presented below.

Wrong Way Detection Systems

The Wrong Way Detection Systems are designed to detect and deter wrong way drivers on roadways. The technology can potentially be adapted to detect work zone intruding vehicles or be used at ramp closure locations. However, adapting these systems would require a significant redesign for work zone applications. There are two types of wrong way detection systems currently available: the Wrong Way Alert System and the Wrong Way Warning

Blinker Sign System, as shown in Figure A.1 below. The systems use Doppler radar technology to detect wrong way drivers and produce a visual warning with a high intensity LED flasher bar. Furthermore, the systems can automatically send alerts to law enforcement or traffic safety personnel through short message service (SMS) or email informing them of a wrong way driving vehicle. The systems are primarily intended for permanent installation.

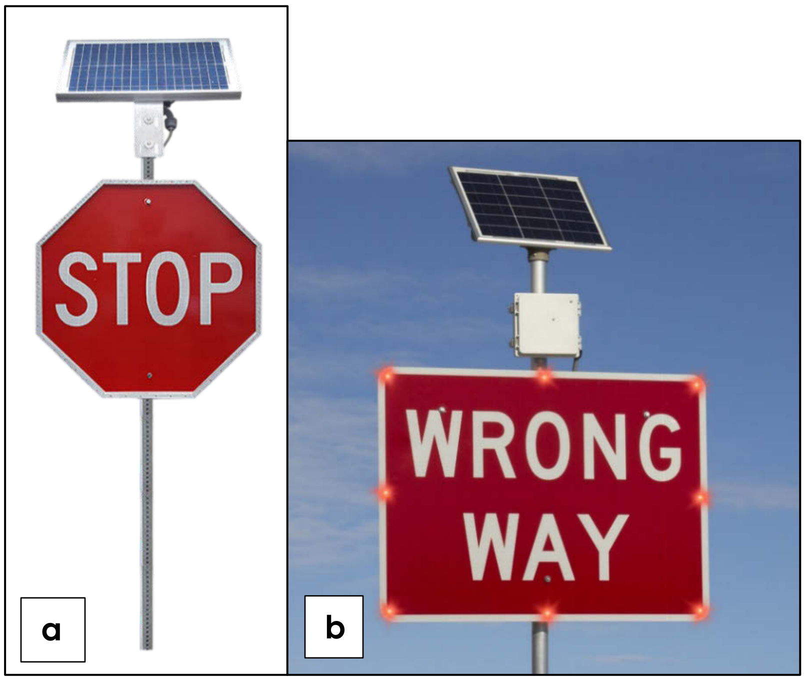


Figure A.1 Wrong Way Alert (a) and Wrong Way Warning Blinker Sign System (b)
(Source: trafficalm.com, 2017, tapconet.com, 2013)

Ver-Mac Smart Work Zone System and SP-3248V SpeedCam System

The Ver-Mac Smart Work Zone System, shown in Figure A.2, utilizes a combination of radar sensors and cameras to collect and analyze traffic speed and other relevant data in a work zone (Ver-Mac, 2016). The system uses proprietary software (JamLogic) to analyze traffic data collected through sensors placed around a work zone, and provides real-time information to the public about work zone traffic conditions (Ver-Mac, 2018a). The system automatically sends warnings to electronic message signs to alert drivers about detected blocked lanes and congestion. The system can provide automated queue warning and alternative route suggestions and display feedback messages when motorists exceed posted or work zone speed limits (Ver-Mac, 2016).

Figure A.2 Ver-Mac - SP-3248V System
(Source: ver-mac.com, 2018)

The Ver-Mac Smart Work Zone System consists of the following equipment:

- Portable changeable message signs
- Permanent dynamic message design
- Camera trailers
- Sensor trailers
- Sensor trolleys
- Speed portable sensors

Although detailed information regarding the software capabilities of the Ver-Mac Smart Work Zone System were limited, the system has the potential to be adapted for work zone intrusion alerts, given the sensors and their capabilities. Ver-Mac has also developed a separate system, known as the SP-3248V SpeedCam System, that is designed to automatically capture a photograph of a speeding vehicle along with speed and license plate information (Ver-Mac, 2018b). The SP-3248V SpeedCam System, combined with Ver-Mac's Speed Awareness Trailer and SpeedLog software, offers an alternative to other automated license plate recognition systems. Ver-Mac's on-board algorithms track vehicle license plates to accurately compute vehicle speeds and count traffic flow (Ver-Mac, 2016). Such sensors and technologies have the potential to be adapted for identification of work zone intrusions. Following are the main components of the Ver-Mac SP-3248V system:

- Trailer-mounted speed detection unit
- License plate and photo logging camera system
- SpeedCam with two camera sensors
- Infrared illuminator
- Dual-core processor

iCone System

The iCone system, shown in Figure A.3, consists of sensors embedded within drums that can monitor and collect traffic speed data using radar and other environmental data near a work zone. The system can collect and transmit real-time traffic conditions information to traffic personnel and the public via secure travel websites. The system can infer queue formation and length, if several iCones are strategically placed to link with one another. The system can also communicate with mapping technologies to visually display active work zone site information to users. The main components of the iCone system are as follows:

- Barrel(s)
- Computer chip
- Circuit board
- GPS antenna
- Radar sensor
- Backup satellite
- Communication capabilities & processor

Figure A.3 iCone System - Interior and Exterior
(Source: iconeproducts.com, 2018)

iCone system requires that a battery be recharged every 14 to 17 days, typically by connecting the iCone to an electrical outlet. Recharging takes between 12 and 20 hours. One of the disadvantages of this system is that it has the potential to be damaged by travelling vehicles (Hallmark et al., 2013). Caltrans found that iCones are effective in slowing traffic. iCone underestimates vehicle speeds in the innermost lanes, as vehicles in the closest lane block the radar transmitter's view of the other lanes (Caltrans, 2013). The iCone is accurate in monitoring speeds and queue lengths in temporary work zones and are most effective when measuring speeds on roadways with one or two lanes.

Temporary rumble strips, shown in Figure A.4, are portable devices that provide an audible and physical vibration to alert motorists as vehicle tires cross the strips. The portability of the rumble strips provides the flexibility to deploy the devices in any desired location offering the potential to be deployed in work zones to warn motorists of potential work zone intrusions. Furthermore, they present a relatively cost-effective and quick solution to some work zone safety issues.

Figure A.4 Temporary Speed Bump and Rumble Strips
(Source: tapconet.com, 2018)

Related Literature

The table below shows a summary of the important findings from the literature related to the temporary rumble strips and their effectiveness in alerting motorists, including reducing incidents and managing vehicular speeds in work zones.

Summary of Findings Related to Temporary Rumble Strips

FHWA, 2013	• Temporary rumble strips are effective in alerting motorists to a variety of conditions, such as, lane closures, detours, nighttime work zones, and changes in alignment.
Harris, 2014	• Kansas DOT tested rumble strips and found 1.5 inches of movement after 61 vehicles passes over the strips. • The presence of rumble strips can help reduce the incidence of back-of-the-queue collisions.
Sun et al., 2011	• The presence of rumble strips increases driver awareness as research shows that rumble strips result in increased driver braking and reduced vehicle speeds. • An evaluation of the Roadquake ™ portable temporary rumble strips (PTRS) found that strips deployed perpendicular to the flow of traffic had negligible movement, while angled strips slowly moved toward the shoulder.
Wang et al., 2011	• Study found that rumble strips reduced car speeds by 4.6 to 11.4 mph and truck speeds by 5.0 to 11.7 mph on average.

APPENDIX B

WZIA EVALUATION FRAMEWORK TESTING PROTOCOLS AND FIELD DATA COLLECTION FORMS

Appendix B: WZIA Evaluation Framework Testing Protocols and Field Data Collection Forms

Goal 1: General Work Zone and Device Information

Obj. ID	Objective 1: Work Zone Conditions	Data Source
1-a	Date	In-Field Data
1-b	Location	In-Field Data
1-c	Time of Day	In-Field Data
1-d	Weather	In-Field Data
1-e	No. of Lanes	In-Field Data
1-f	No. of Lanes Closed	In-Field Data
1-g	Work Zone Speed Limit	In-Field Data
1-h	Type of Closure (T-10, T-13 etc.)	In-Field Data
1-i	Total Length of Work Zone	In-Field Data
1-j	Taper Length	In-Field Data
1-k	Cone Spacing - Taper	In-Field Data
1-l	Cone Spacing - Tangent	In-Field Data
1-m	Length of Work Area	In-Field Data
1-n	Type of Activity	In-Field Data
1-o	Long Term Lane and Shoulder Closure?	In-Field Data
1-p	Lane Shifts?	In-Field Data
1-q	Detour?	In-Field Data
1-r	Narrowed Lanes?	In-Field Data
1-s	Location of Const. Vehicle Access Points	In-Field Data
1-t	No. of Workers Present in the Work Zone	In-Field Data
1-u	No. of Workers Outside of the Work Zone	In-Field Data
1-v	Traffic Volume and Heavy Vehicle Data	In-Field Data/Database
Obj. ID	**Objective 2: WZIA Device Information**	**Data Source**
2-a	WZIA Device Name	Prelim Research
2-b	Alarm Type/other Details	Prelim Research

Goal 2: WZIA System Functional Characteristics

Obj. ID	Objective 1: Evaluate Practicality of Deployment	Data Source/Evaluation Method
1-a	Evaluate Time to Fully Deploy	In-Field Data
1-b	Identify Physical Requirements to Deploy System	In-Field and Survey Data
1-c	Deployment Location	In-Field Data
1-d	Evaluate Worker Hazard Exposure	Survey Data
1-e2	Note and Evaluate Any Issues	In-Field and Survey Data
Obj. ID	**Objective 2: Evaluate Practicality of Equipment Use**	**Data Source/Evaluation Method**
2-a	Ease of Operating Equipment	Survey Data – Rating
2-b	Useful Features and Functions	Survey Data – Rating and Comments
2-c	Field Storage and Security Requirements	In-Field and Survey Data
2-d	Battery Life	In-Field Data
2-e	Worker Acceptance and Willingness to Use	Survey Data
2-f	Note and Evaluate Any Issues	In-Field and Survey Data
Obj. ID	**Objective 3: Evaluate Effectiveness and Reliability**	**Data Source/Evaluation Method**
3-a	Evaluate False-Positive Alarms (No Intrusion but Alarm Activated)	In-Field Data
3-b	Evaluate False-Negative Alarms (Intrusion but No Alarm Activation)	In-Field Data
3-c	Audible Alert (Alarm) Sound Level	In-Field Data
3-d	Visual Alert Effective	In-Field Data – Visual Test – Rating
3-e	Evaluate Duration of Alarm	In-Field Data
3-f	Worker Alert/Reaction Time (Lead Time)	In-Field Data – Video Recordings
3-g	Device Transmission Range	In-Field Data
3-h	Note and Evaluate Any Issues	In-Field and Survey Data
Obj. ID	**Objective 4: Evaluate Practicality of Equipment Removal**	**Data Source/Evaluation Method**
4-a	Evaluate Time to Remove/Retrieve	In-Field Data
4-b	Evaluate Worker Hazard Exposure	Survey Data – Rating
4-c	Note and Evaluate Any Issues	In-Field and Survey Data

Goal 3: WZIA System Benefits

Obj. ID	Objective 1: Evaluate Perceptions of Construction Personnel	Data Source / Evaluation Method
1a	Identify Features and Functions Noticed by Workers	Survey Data
1-b	Identify Features and Functions Thought to Be Confusing or Not Useful	Survey Data
1-c	Identify Practical Suggestions Provided by Workers	Survey Data

Device and General Work Zone Information

Device Information	
Device	
Alarm Type	
Other Details	
General Work Zone Information	
Date/Time:	
Location (road type, highway, Mile Post, etc.):	
Weather description (Temperature, Wind):	
# of lanes:	
No. of lanes closed:	
Work zone speed limit (mph):	
Transition Area	
Taper Length (ft):	
Spacing (ft):	
Activity Area	
Length (ft):	
Spacing (ft):	
Activity Type:	
Other Information	
Length of work zone (ft):	
Type of work zone, T-10, T-13:	
Closure type (full, shoulder, reverse):	
Lane shift (type and offset):	
Detour:	
Construction vehicle access points:	
Narrowed lane (Y/N):	
Heavy vehicle data:	
Traffic volume data (Annual Average Daily Traffic):	
# of crews within and outside WZ:	
Pavement condition:	
Stopping Sight Distance (ft):	

Functional Characteristics - Deployment

Set up time of the device (min):	
Ease of set up (comment):	
Deployment time (after setup, min):	
Deployed on: (cones, barriers, vehicles, equipment, pavement)	
Stacking capability (Y/N):	
Deployment Issues	
Deploying alarm device (comment):	
Deploying cones, barriers etc. (comment):	
Activating the device (comment):	
Identify physical requirements to deploy systems (comment):	
"False Positive" during deployment (comment):	
Battery life issues (comment):	
Retrieval time (min):	
Any issues during retrieval (comment):	

Sound Test Relative to Alarm Orientation and Distance (Manual Alarm Activation)

Trial #:	
Sound level reading at a distance of ____ft (25', 50', 75', 100', 125', 150', 175', 200', 250', 300', 400', 500'):	
Location of alarm in the work area (on ground, vehicle, cone, etc.):	
Alarm orientation relative to work zone (downstream, towards roadside):	
Sound Meter - Location from the ground (ft):	
Ambient noise - Sound Meter 1 (upstream) reading (dB):	
Ambient noise - Sound Meter 2 (downstream) reading (dB):	
Alarm noise - Sound Meter 1 (upstream) reading (dB):	
Alarm noise - Sound Meter 2 (downstream) reading (dB):	
Duration of alarm (sec):	
Visual alarm (comment):	
Distinctiveness of alarm (Post processing of in-field sound recording):	
"False Alarm" activation? (comment):	

Functional Characteristics - Operation

Trial #:	
Start Time:	
End Time:	
Vehicle intrusion characteristics (pilot testing - at taper; active work zone - other):	
"False Positive" Alarm (no intrusion but alarm activated):	
"True Negative" Alarm (intrusion but no alarm activation):	
Visual alert effective (Y/N/NA, comment):	
Alarm duration (sec):	
How many workers reacted?	
How many workers did not react?	
Worker alert/reaction Time (from video):	
Type of background noise?	
Any damage or injuries?	
Did the alarm prevent/reduce any injury?	
Did the alarm perform well & aid worker to safety?	
Transmission Range (ft) (see notes below)	
(for WAS, test max. distance at which alarm is activated and multiple alarm tethering)	
(for Intellicone, test max. distance between lamps and PSA device)	
(for SonoBlaster, NA)	

Miscellaneous Observations

Retrieval/Removal time (min):	
Issues during activation/setup/removal:	
Give impressions of how well workers accept the alarm:	
Describe any challenges in alarm mounting and device operation:	
Describe any identified or perceived operational drawbacks:	
Durability; does any part of the system get destroyed:	

APPENDIX C

MAINTENANCE WORKER EVALUATION SURVEY FORM

Appendix C: Maintenance Worker Evaluation Survey Form

Device: ____________

1. Please provide your contact information (Optional)

____

2. Please state your job title and agency: ____________________, ____________________

3. Years of industry experience: ____________________

4. What are the most common type(s) of work zone intrusion accidents you have observed?

____

____

5. How effective would this Work Zone Intrusion Alarm (WZIA) System be in mitigating those accidents?
   - ☐ Very effective
   - ☐ Moderately effective
   - ☐ Slightly effective
   - ☐ Not at all effective

6. Do you think the WZIA System tested today will improve work zone safety?
   - ☐ Very likely
   - ☐ Slightly likely
   - ☐ Not at all likely
   - ☐ Will decrease work zone safety

7. Were you familiar with this device before this testing?
   - ☐ Yes
   - ☐ No

8. Which location do you think is best to deploy this WZIA System?
   - ☐ Along the work zone
   - ☐ At the taper
   - ☐ At the taper and along the work zone
   - ☐ Other locations: ____

9. Rate on a scale of -1 to 1, how ineffective (-1) to effective (1) is the device.

Device Effectiveness

Items	-1	0	1	NA	Don't Know
Sound level in alerting workers.	☐	☐	☐	☐	☐
Providing adequate reaction time.	☐	☐	☐	☐	☐
Increasing worker safety.	☐	☐	☐	☐	☐
Triggering mechanism in detecting intrusions.	☐	☐	☐	☐	☐
Providing adequate work zone coverage.	☐	☐	☐	☐	☐
If applicable, providing adequate visual coverage.	☐	☐	☐	☐	☐
If applicable, Personal Safety Device (PSD) in providing adequate coverage.	☐	☐	☐	☐	☐

Comments/Additional Thoughts

10. Rate on a scale of -1 to 1, how unlikely (-1) to likely (1) are you to implement this device.

Likelihood of Implementation

Items	-1	0	1	NA	Don't Know
In a work zone.	☐	☐	☐	☐	☐
If each device costs $120 or less.	☐	☐	☐	☐	☐
Would you feel safe in implementing this system in an active work zone?	☐	☐	☐	☐	☐

Comments/Additional Thoughts

11. Rate on a scale of -1 to 1, how difficult (-1) to easy (1) are the actions to deploy this device.

Deployment

Actions	-1	0	1	NA	Don't Know
Deploying the device (stackability, mobility, etc.).	☐	☐	☐	☐	☐
Mounting the SonoBlaster on the cones.	☐	☐	☐	☐	☐
Operating the device (activation).	☐	☐	☐	☐	☐
Maintaining the device (maintenance upkeep).	☐	☐	☐	☐	☐
Time wise, setting up the device.	☐	☐	☐	☐	☐

Comments/Additional Thoughts

12. Rate on a scale of -1 to 1, the fragility (-1) to durability (1) of this device.

Durability

Items	-1	0	1	NA	Don't Know
Ability to withstand damage and wear & tear.	☐	☐	☐	☐	☐
Impact of debris/wind/other factors on cone installs.	☐	☐	☐	☐	☐

Comments/Additional Thoughts

13. Rate on a scale of -1 to 1, how non-distinctive (-1) to distinctive (1) is the alarm sound.

Sound Distinctiveness

Items	-1	0	1	NA	Don't Know
With general work zone sounds.	☐	☐	☐	☐	☐
In determining the direction of intrusion.	☐	☐	☐	☐	☐

14. Please use the comment section below to share your additional comments.

The bullets below are some examples of items you could comment on.

- Did you encounter any problems/issues with the alarm?
- How easy or difficult was it to deploy and use the SonoBlaster system?
- What do you like about the SonoBlaster alarm system?
- What did you dislike about the SonoBlaster alarm system?
- What types of work zones would be ideal for the SonoBlaster system?
- Any anticipated barriers to using the SonoBlaster system?
- Any other features/characteristics that would enhance this device?

Comments/Additional Thoughts

APPENDIX D

PILOT TESTING SCHEDULE, PLAN, AND RESULTS

Appendix D: Pilot Testing Schedule, Plan, and Results

The pilot testing schedule to be conducted from November 13, 2018 to November 16, 2018 is presented in the table below.

Day	Date	Time	Device
1	November 13, 2018	9 AM – 5 PM*	Worker Alert System
2	November 14, 2018	1 PM – 5 PM	SonoBlaster
3	November 15, 2018	Noon – 5 PM	SonoBlaster
4	November 16, 2018	9 AM – 5 PM*	Intellicone

*possible lunch break or other breaks depending on testing progress

Pilot Testing Plan (Tentative – the order of activities may be varied)

1. Safety Meeting
    a. Safety gear
    b. Conduct during live testing with vehicle
    c. Hydration
    d. Skin protection
2. Set up workstation/work area for equipment and data collection paperwork
3. Field Setup Plan
    a. Device setup and operation instructions and handout for participants
    b. Set up workstation/work area for equipment and data collection paperwork
    c. Set up data collection equipment (video and audio equipment)
4. Record General Information (see testing protocols)
5. Start the process of deploying WZIA system
    a. Record Functional Characteristics – Deployment of Devices data (see testing protocols)
6. Conduct sound tests (see testing protocols)
7. Conduct Transmission Range tests (where applicable) (see testing protocols)
8. Conduct tests with a vehicle
    a. Record Functional Characteristics – Operation data (see testing protocols)
9. WZIA system retrieval and wind-up (see testing protocols)
10. Distribute survey to participants
11. Wrap-up for the day.

Results of Sound Level Measurement Trials for WAS

Trial #	Distance (feet)	Downstream - RT Device (maximum dBA)	Downstream - CAL Device (maximum dBA)	Upstream - RT Device (maximum dBA)	Upstream - CAL Device (maximum dBA)	Average Sound Level (dBA)
1	25	68	89	60	78	**74**
2	50	63	84	59	69	**69**
3	75	58	79	60	66	**66**
4	100	55	73	53	63	**61**
5	125	64	69	64	61	**64**
6	150	55	64	58	61	**59**
7	175	53	57	59	52	**56**
8	200	53	57	54	54	**55**
9	250	53	57	54	55	**55**
10	300	49	55	67	57	**57**
Device Averages (dBA)	NA	**57**	**68**	**59**	**62**	NA

Results of Sound Level Measurement Trials for SonoBlaster

Trial #	Distance (feet)	Downstream - Horn Pointing Up (max dBA)	Downstream - Horn Pointing Down (max dBA)	Upstream - Horn Pointing Up (max dBA)	Upstream - Horn Pointing Down (max dBA)	Average Sound Level (dBA)
1	25	96	98	105	98	**99**
2	50	92	86	91	90	**90**
3	75	88	92	91	89	**90**
4	100	83	91	89	82	**86**
5	125	81	84	84	87	**84**
6	150	77	86	79	87	**82**
7	175	78	83	81	80	**80**
8	200	78	75	80	83	**79**
9	250	86	89	80	81	**84**
10	300	77	78	77	78	**78**
Device Averages (dBA)	NA	**84**	**86**	**86**	**85**	NA

Results of Sound Level Measurement Trials for Intellicone

Trial #	Distance (feet)	Downstream (maximum dBA)	Upstream (maximum dBA)	Average (dBA)
1	25	89	89	**89**
2	50	77	82	**80**
3	75	78	74	**76**
4	100	76	72	**74**
5	125	74	71	**73**
6	150	69	74	**72**
7	175	68	73	**71**
8	200	64	71	**67**
9	250	62	68	**65**
10	300	58	65	**61**
Device Average (dBA)	NA	**71**	**74**	NA

APPENDIX E

SUPPLEMENTAL TESTING SCHEDULE, PLAN, AND FIELD DATA COLLECTION FORMS

Appendix E: Supplemental Testing Schedule, Plan, and Field Data Collection Forms

Supplemental Testing Schedule

In view of the feedback from the Nov. 2018 Pilot Test results, three to four sessions of supplemental tests are planned to be conducted to add to the prior Pilot testing results of selected Work Zone Intrusion Alarm (WZIA) systems. These tests will include impact tests, tests at various speeds, and other miscellaneous deployment and operation tests. Some testing schedules are currently tentative, depending on the availability of a test vehicle for impact tests and work zone/maintenance workers as identified by Theresa Drum.

The table below shows the dates and tentative schedule for supplemental tests to be conducted at the META test site. Specific details of the plan are subject to change in view of the characteristics of the test vehicle and availability of work zone/maintenance workers.

Day	Date	Time	Device/Activity	Comments
1	April 2, 2019	9 AM – 5 PM*	Impact Tests (all devices)**	See next section for testing details.
2	April 3, 2019	1 PM – 5 PM	Intellicone/SonoBlaster	Start time may be moved to 9 AM if maintenance workers are available on this date.
3	April 4, 2019	9 AM – 5 PM*	Deployment, operation, and feedback session with work zone/maintenance workers**	Survey to be completed at the end of the session.
4	April 5, 2019	9 AM – 5 PM	Worker Alert System	None

*possible lunch break or other breaks depending on testing progress
**depending on availability date of testing vehicle or work zone/maintenance workers, this activity date may be rescheduled to one of the earlier/later dates in the table

Test Equipment and Setup Scenario

1. All tests will be conducted using a simulated T-13 lane closure setup at the Caltrans META site with changes made according to specific test requirements.
2. Caltrans META will be requested to setup a quarter mile (1,320 ft) mock T-13 lane closure at the META test site for a 25-mph speed zone with standard taper and tangent cone spacing.
3. A test vehicle will be used for impact tests (type and availability of vehicle TBD).

Supplemental Testing Plan – Impact Tests

Impact tests will be conducted between a test vehicle (type and details TBD) and the three WZIA systems selected in this research. The plan of activities on the testing day are presented below (the order of activities may vary).

4. Set up work station/work area for equipment and data collection paperwork
5. Safety Meeting
    a. Safety gear
    b. Conduct during live testing with vehicle
    c. Identify "safe zone" at least 100' away from the impact zone where all personnel should be present during impact tests (see #4 and #5 for details)
    d. Hydration
    e. Skin protection
6. Ensure that any air bags in the test vehicle have been deactivated.
7. Conduct "dry runs" of the test vehicle to identify safe maximum speed achievable before conducting the impact tests. Identify the best direction to run the vehicle given the pavement condition and driver perception.
8. Identify and mark three zones:
    a. Acceleration zone: vehicle accelerates up to the testing speed.
    b. Impact zone: WZIA device to be placed in this zone.
    c. Braking zone: Adequate distance for the vehicle to come to a safe stop.
9. If required, mark lines on the pavement parallel to the vehicle trajectory path to guide the driver in the impact zone to align the vehicle properly to hit the device. Mark the location of the device as well.
10. All personnel must be a minimum perpendicular distance of 100 ft away from the impact zone.
11. Setup and install cameras within the test vehicle and on a tripod with a diagonal field of view of the impact zone.
12. Deploy the WZIA device in the impact zone with any visual alerts oriented towards the camera.
    a. For the WAS, deploy the trip hose and orient the transmitter to be impacted by the test vehicle. Place the alarm unit outside of the impact zone.
    b. For the SonoBlaster, deploy a single device on a cone in the impact zone.
    c. For the Intellicone, deploy a single lamp over a cone in the impact zone. Place the alarm unit outside of the impact zone.
13. Turn on all cameras before beginning impact tests.
14. Record observations:
    a. Video data collection
    b. Field data collection

c. Any response by personnel present in the field in view of the tripod camera, e.g. response to WAS Personal Safety Device (PSD).
d. Measure and take pictures of the debris field.
e. Check the video recording devices to ensure video has been captured.
f. Manually test the device after impact to observe if it is functional or not.

15. Retrieve the WZIA device and clean-up any debris on the pavement.
16. Wrap-up for the day.

Note: Most of the test results will be compiled in-house after careful review of recoded videos in slow motion using 60 fps recordings.

Worker Alert System – Impact Test Data Collection Sheet

Test No.	Speed (mph)	Collision Type (comments)	Alarm Activated? (Y/N)	Alarm Delay	PSD Activated? (Y/N)	Device Usable? (Y/N)	General Comments

SonoBlaster – Impact Test Data Collection Sheet

Test No.	Speed (mph)	Collision Type (comments)	Alarm Activated? (Y/N)	Alarm Delay	Device Usable? (Y/N)	General Comments

Intellicone - Impact Test Data Collection Sheet

Test No.	Speed (mph)	Lamp Sensitivity	Collision Type (comments)	Alarm Activated? (Y/N)	Device Usable? (Y/N)	General Comments

Supplemental Testing Plan – Work Zone/Maintenance Workers Deployment, Operation, and Feedback Session

1. Safety Meeting
    a. Safety gear
    b. Conduct during live testing with vehicle
    c. Hydration
    d. Skin protection
2. Field Setup Plan
    a. Device setup and operation instructions and handout (presented later in this document) presented to participants
    b. Set up work station/work area for equipment and data collection paperwork
    c. Set up data collection equipment (video and audio equipment)
3. Maintenance workers will deploy and operate each WZIA system
4. Manual activation of WZIA systems conducted
5. Record general information and feedback during deployment and operation by maintenance workers
6. Distribute survey to participants
7. Wrap-up for the day.

Supplemental Testing Plan – Miscellaneous Tests of WZIA Systems

In view of the feedback from the Nov. 2018 Pilot Test results, several miscellaneous tests will be conducted for each WZIA system.

1. Worker Alert System
    a. Additional operation tests using all new devices. The older device received from Caltrans was found to have limited functionality given it was an older model. The manufacturer confirmed it lacked some of the capabilities of the newer versions of the device.
    b. Systematic tests of a single trip hose and Personal Safety Device (PSD) to accurately determine the number of "False Positives" and "True Negatives" in view of inconsistent results from Pilot Tests.
    c. Systematic tests of a single trip hose and PSD to accurately determine the range and tethering capabilities ("signal hopping") of the device.
2. Intellicone
    a. Systematic tests to determine the general level of force required to active the alarm unit given five different sensitivity levels of the lamp devices.
    b. Accurately determine the max. distance between lamps given placement in a straight line (tangent section) vs. placement on cones on a combination of a tangent and curve.

3. SonoBlaster
    a. Install and activate at least 10 different units of SonoBlaster devices to determine the operational performance reducing the chance of True Negatives given frosting issues observed during the pilot tests.

APPENDIX F

WZIA SYSTEMS – DETAILED SETUP AND DEPLOYMENT INSTRUCTIONS

Appendix F: WZIA Systems - Detailed Setup and Deployment Instructions

Worker Alert System – Set up and Deployment Instructions

Rechargeable Horn/Light Alarm Assembly

1. Charge the horn/light assembly for 6-8 hours to achieve a full charge.
2. Power the horn/light assembly ON by pressing the rubber sealed/toggle switch once.
3. The green indicator light will be illuminated on the horn/light assembly when powered on.
4. Any time the hose/sensor is stimulated by a change in pressure, the alarm should go off.
5. If it does not, refer to the third step under the next section for linking instructions.
6. When finished, press the On/Off button and place in a safe location until it is needed next.

Figure F.1 Turning on Horn/Light Alarm

Hose/Sensor Assembly

Figure F.2 Turning on the Pressure Sensor

1. Power Check
   a. Check AA batteries in the pressure sensor by powering the unit on and looking for the green or red indicator light to flash quickly while the sensor calibrates.
   b. The light will change to steady flashing green after the sensor is calibrated.
2. Test pressure sensor
   a. Power on pressure sensor and step on the hose
   b. The light on the sensor will turn red if it has successfully detected a change in pressure.
3. Link pressure sensor to the horn/light alarm
   a. Activate the hose/sensor by stepping on it **while simultaneously** powering on the horn/light alarm.
   b. Listen for horn to activate and watch for the flash. Once they do, the unit is linked and should not have to be linked again after multiple power cycles.
   c. Always test the complete system before using in the field.
   d. Note: The sensor and the horn/light assembly have approximately 1,000'+ range (line of sight).

Personal Safety Device (PSD) Assembly

1. Check battery power by powering
   a. If the indicator light is green, the unit has ample power
   b. If the indicator light is yellow, the unit has medium power
   c. If the indicator light is red, the unit is almost dead.
2. Link PSD to pressure sensor assembly
   a. To link, activate the hose/sensor **while simultaneously** powering the PSD ON.
   b. The unit should vibrate and send a sound to the earpiece if plugged in.

Figure F.3 Turning on Personal Safety Device

SonoBlaster – Set up and Deployment Instructions

Installing Mounting Bracket on a Standard Traffic Cone

1. **Bracket Alignment:** Align the SonoBlaster Bracket on base of cone with alignment tab positioned over edge of cone base. The tab should, assure proper alignment to provide cone clearance when stacking.
2. **Drill Mounting Holes:** The bracket is attached to cone base with two ¼ - 2” screws. One screw is used at each end of the bracket. Choose one hole at each end that avoids interference with the feet under the cone base. Mark hole locations remove bracket and drill 1/4 “or 9/32" holes.
3. **Choosing Mounting Screws:** Choose the longer 2” screws provided with SonoBlaster unit for thicker bases. Use the shorter 1¼" screws provided with bracket for thinner bases.
4. **Attach Bracket:** Attach the bracket to the cone base using washers on the bracket and under the base of the cone. Tighten screws securely.
5. **Mount SonoBlaster Unit:** Attach the SonoBlaster to the bracket using the remaining screws & washers. Do not over tighten screws.

Figure F.4 SonoBlaster Bracket Assembly

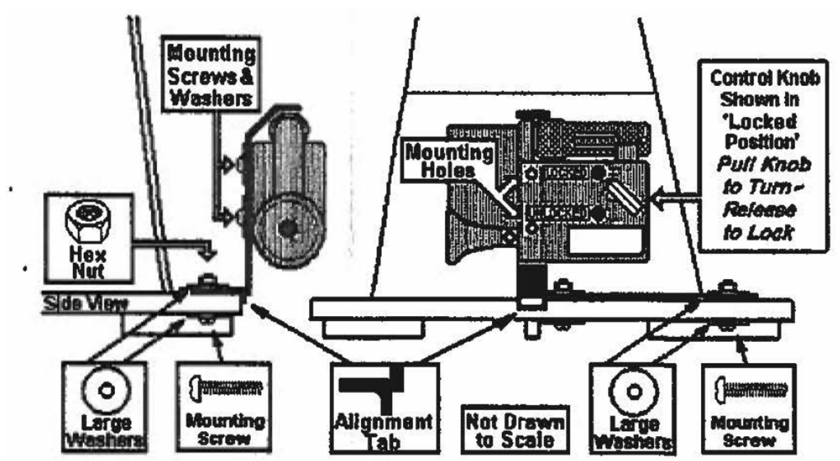


Figure F.5 SonoBlaster Bracket Assembly

Stacking SonoBlaster Units

1. Deactivate the SonoBlaster unit prior to stacking unit for storage by turning knob to locked.
2. Turn SonoBlaster equipped cone one-quarter turn (90 degrees) and place on top of prior SonoBlaster cone.
3. Continue stacking units by rotating the next unit one-quarter turn.
4. Keep SonoBlaster units locked while in storage.

Inserting/Replacing Cartridge

1. With empty (or spent cartridge) SonoBlaster in unlocked position, unscrew the cartridge cover and cock the arming mechanism using the provided cocking tool.
2. Switch the knob to locked position. Insert the cartridge and replace the cartridge cover.
3. Switch the knob to unlocked position to arm the SonoBlaster.
4. After firing, repeat steps 1 to 3.
5. SonoBlaster will fire in unlocked position even when the cone tilts.

Activating/Replacing Cartridge

1. After deploying cones with attached SonoBlaster unit, switch the knob to unlocked position.
2. The SonoBlaster is now armed and will fire if tilted or moved.

Intellicone – Set up and Deployment Instructions

Portable Site Alarm – Set up

1. Remove Portable Site Alarm from its case and place onto a traffic cone or other elevated platform (ideally at least 1m above ground level).
2. Press the power button to turn on. The Portable Site Alarm will automatically connect to all devices in the site's geo-fence (please refer to Chapter 2 for Geo-fence setup in detailed manual).
3. Wait for the Portable Site Alarm to connect Data and Location (SIM/GPS). When both have been acquired, the Portable Site Alarm indicators will flash and turn green on the right-hand side of the control panel. This can take up to 5 minutes to connect.
4. The Sound button on the Portable Site Alarm control panel can be used to mute/unmute the sounders.
5. The Blue Alert Button can be pressed to *manually* activate the *blue lights* and *single tone siren* to warn workers of emergency vehicles and other controlled hazards.
6. The Red Alarm Button can be pressed to *manually* activate the "Safe lane Incursion Warning System" (work zone intrusion) with *red flashing lights* and *3 tone sirens*.
7. The Reset Button can be pressed to reset the system.

8. Press the power button to turn off at the end of the shift to turn off the Portable Site Alarm and place in its storage case.
9. The Portable Site Alarm must be placed outside in a location that is fully visible to the sky. DO NOT place the device underneath a bridge or other object that would impede its ability to acquire a GPS location via satellites.

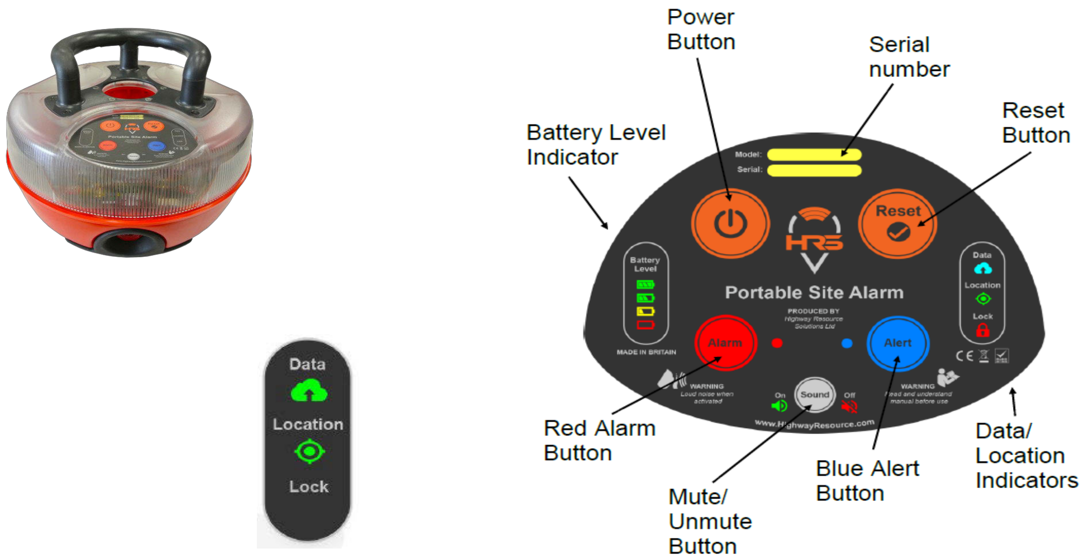


Figure F.6 Intellicone System PSA Detail

Intellicone Static Cone Lamp

1. Place the Intellicone lamp on top of a standard traffic cone.
2. The Lamp will automatically turn on and beep 3 times.
3. After 10 seconds the motion sensor will activate.
4. After 1 minute, the on-board backup power supply within the lamps will have fully charged providing optimal transmission range.
5. If the lamp and cone are moved, the lamp will beep and subsequently transmit an alarm signal to a Yellow Portable Site Alarm. (maximum range of single lamp is 100 feet)
6. Do not remove the lamp from the cone during operation. If the lamp is removed for more than 3 seconds, you will need to wait for a period of up to 10 minutes, so it resets itself before placing the lamp back on a cone.

APPENDIX G

CALTRANS TRAFFIC CONTROL SYSTEM TABLES FOR LANE AND RAMP CLOSURES AND T13 STANDARD TRAFFIC CONTROL PLAN

Appendix G: Caltrans Traffic Control System Tables for Lane and Ramp Closures and T13 Standard Traffic Control Plan

2015 REVISED STANDARD PLAN RSP T9

Dist	COUNTY	ROUTE	POST MILES TOTAL PROJECT	SHEET No.	TOTAL SHEETS

REGISTERED CIVIL ENGINEER Devinder Singh
January 20, 2017
PLANS APPROVAL DATE
THE STATE OF CALIFORNIA OR ITS OFFICERS OR AGENTS SHALL NOT BE RESPONSIBLE FOR THE ACCURACY OR COMPLETENESS OF SCANNED COPIES OF THIS PLAN SHEET.
PROFESSIONAL ENGINEER Devinder Singh No. C50470 Exp. 6-30-17 CIVIL STATE OF CALIFORNIA

TO ACCOMPANY PLANS DATED ______

TABLE 1

TAPER LENGTH CRITERIA AND CHANNELIZING DEVICE SPACING

SPEED (S)	MINIMUM TAPER LENGTH * FOR WIDTH OF OFFSET 12 FEET (W)				MAXIMUM CHANNELIZING DEVICE SPACING		
	TANGENT 2L	MERGING L	SHIFTING L/2	SHOULDER L/3	X TAPER	Y TANGENT	Z ** CONFLICT
mph	ft	ft	ft	ft	ft	ft	ft
20	160	80	40	27	20	40	10
25	250	125	63	42	25	50	12
30	360	180	90	60	30	60	15
35	490	245	123	82	35	70	17
40	640	320	160	107	40	80	20
45	1080	540	270	180	45	90	22
50	1200	600	300	200	50	100	25
55	1320	660	330	220	50	100	25
60	1440	720	360	240	50	100	25
65	1560	780	390	260	50	100	25
70	1680	840	420	280	50	100	25
75	1800	900	450	300	50	100	25

* - For other offsets, use the following merging taper length formula for L:
For speed of 40 mph or less, $L = WS^2/60$
For speed of 45 mph or more, $L = WS$

Where: L = Taper length in feet
W = Width of offset in feet
S = Posted speed limit, off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph

** - Use for taper and tangent sections where there are no pavement markings or where there is a conflict between existing pavement markings and channelizers (CA).

TABLE 2

LONGITUDINAL BUFFER SPACE AND FLAGGER STATION SPACING

SPEED *	Min D **	DOWNGRADE Min D ***		
		-3%	-6%	-9%
mph	ft	ft	ft	ft
20	115	116	120	126
25	155	158	165	173
30	200	205	215	227
35	250	257	271	287
40	305	315	333	354
45	360	378	400	427
50	425	446	474	507
55	495	520	553	593
60	570	598	638	686
65	645	682	728	785
70	730	771	825	891
75	820	866	927	1003

* - Speed is posted speed limit, off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph

** - Longitudinal buffer space or flagger station spacing

*** - Use on sustained downgrade steeper than -3 percent and longer than 1 mile.

TABLE 3

ADVANCE WARNING SIGN SPACING

ROAD TYPE	DISTANCE BETWEEN SIGNS *		
	A	B	C
	ft	ft	ft
URBAN - 25 mph OR LESS	100	100	100
URBAN - MORE THAN 25 mph TO 40 mph	250	250	250
URBAN - MORE THAN 40 mph	350	350	350
RURAL	500	500	500
EXPRESSWAY / FREEWAY	1000	1500	2640

* - The distances are approximate, are intended for guidance purposes only, and should be applied with engineering judgment. These distances should be adjusted by the Engineer for field conditions, if necessary, by increasing or decreasing the recommmended distances.

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

TRAFFIC CONTROL SYSTEM TABLES FOR LANE AND RAMP CLOSURES

NO SCALE

RSP T9 DATED JANUARY 20, 2017 SUPERSEDES STANDARD PLAN T9 DATED OCTOBER 30, 2015 - PAGE 249 OF THE STANDARD PLANS BOOK DATED 2015.

REVISED STANDARD PLAN RSP T9

2015 STANDARD PLAN T13

Dist	COUNTY	ROUTE	POST MILES TOTAL PROJECT	SHEET No.	TOTAL SHEETS

Devinder Singh
REGISTERED CIVIL ENGINEER
October 30, 2015
PLANS APPROVAL DATE
THE STATE OF CALIFORNIA OR ITS OFFICERS OR AGENTS SHALL NOT BE RESPONSIBLE FOR THE ACCURACY OR COMPLETENESS OF SCANNED COPIES OF THIS PLAN SHEET.

REGISTERED PROFESSIONAL ENGINEER
Devinder Singh
No. C50470
Exp. 6-30-17
CIVIL
STATE OF CALIFORNIA

NOTES:

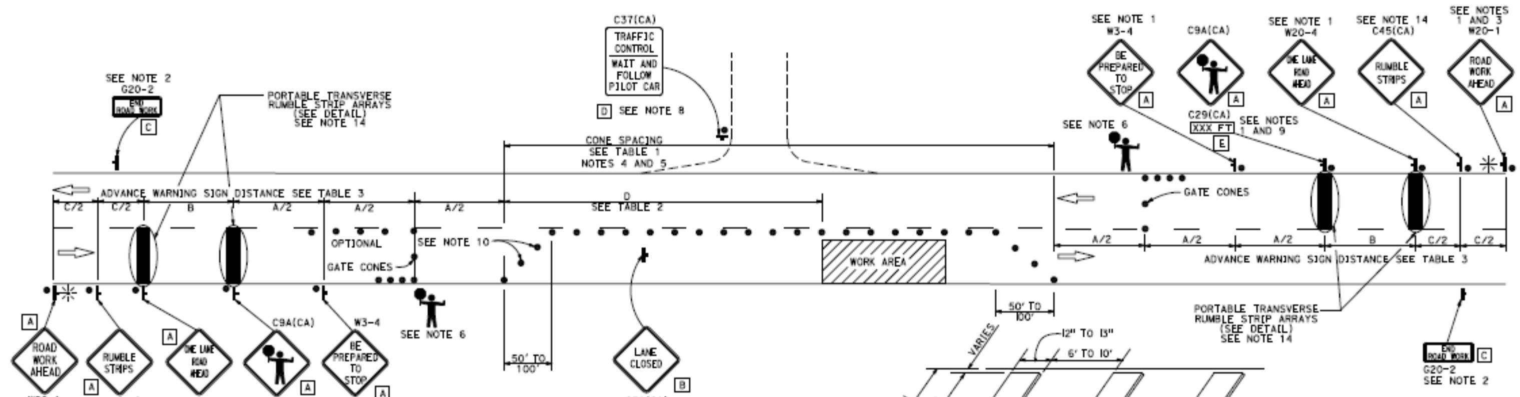
See Standard Plan T9 for tables.

Use cone spacing X for taper segment, Y for tangent segment or Z for conflict situations, as appropriate, per Table 1, unless X, Y, or Z cone spacing is shown on this sheet.

All temporary warning signs shall have black legend on fluorescent orange background.

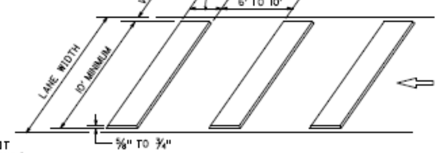
California codes are designated by (CA). Otherwise, Federal (MUTCD) codes are shown.

TYPICAL LANE CLOSURE WITH REVERSIBLE CONTROL



NOTES:

1. Each advance warning sign in each direction of travel shall be equipped with at least two flags for daytime closure. Each flag shall be at least 16" x 16" in size and shall be orange or fluorescent red-orange in color. Flashing beacons shall be placed at the locations indicated for lane closure during hours of darkness.
2. A G20-2 "END ROAD WORK" sign, as appropriate, shall be placed at the end of the lane control unless the end of work area is obvious, or ends within a larger project's limits.
3. If the W20-1 sign would follow within 2000' of a stationary W20-1 or G20-1 "ROAD WORK NEXT ____ MILES", use a W20-4 sign for the first advance warning sign.
4. All cones used for lane closures during the hours of darkness shall be fitted with retroreflective bands (or sleeves).
5. Portable delineators, placed at one-half the spacing indicated for traffic cones, may be used instead of cones for daytime closures only.
6. Additional advance flaggers may be required. Flagger should stand in a conspicuous place, be visible to approaching traffic as well as approaching vehicles after the first vehicle has stopped. During the hours of darkness, the flagging-station and flagger shall be illuminated and clearly visible to approaching traffic. The illumination footprint of the lighting on the ground shall be at least 20' in diameter. Place a minimum of four cones at 50' intervals in advance of flagger station as shown.
7. Place C30(CA) "LANE CLOSED" sign at 500' to 1000' intervals throughout extended work areas. They are optional if the work area is visible from the flagger station.
8. When a pilot car is used, place a C37(CA) "TRAFFIC CONTROL-WAIT AND FOLLOW PILOT CAR" sign with black legend on white background at all intersections, driveways and alleys without a flagger within traffic control area. Signs shall be clean and visible at all times. Where traffic can not be effectively self-regulated, at least one flagger shall be used at each intersection within traffic control area.
9. An optional C29(CA) sign may be placed below the C9A(CA) sign.
10. Either traffic cones or barricades shall be placed on the taper. Barricades shall be Type I, II, or III.
11. The color of the portable transverse rumble strips shall be black or orange. Use 2 arrays, each array shall consist of 3 rumble strips.
12. Portable transverse rumble strips shall not be placed on sharp horizontal or vertical curves nor shall they be placed through pedestrian crossings.
13. If the portable transverse rumble strips become out of alignment (skewed) by more than 6 inches, measured from one end to the other, they shall be readjusted to bring the placement back to the original location.
14. Portable transverse rumble strips are not required if any one of the following conditions is satisfied:
    A. Work duration occupies a location for four hours or less
    B. Posted speed limit is below 45 MPH
    C. Work is of emergency nature
    D. Work zone is in snow or icy weather conditions



PORTABLE TRANSVERSE RUMBLE STRIP ARRAY DETAIL

SIGN PANEL SIZE (Min)

A	48" x 48"
B	30" x 30"
C	36" x 18"
D	36" x 42"
E	20" x 7"

LEGEND

- TRAFFIC CONE
- TEMPORARY TRAFFIC CONTROL SIGN
- PORTABLE FLASHING BEACON
- FLAGGER

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

TRAFFIC CONTROL SYSTEM FOR LANE CLOSURE ON TWO LANE CONVENTIONAL HIGHWAYS

NO SCALE

T13