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The main goal for this research was to evaluate the effectiveness and practicality of deploying and operating selected WZIA systems in California work zones. The objective was to provide recommendations and guidance to Caltrans on implementing such systems in real-world conditions through field observations and feedback provided by the Caltrans maintenance staff. Selected WZIA systems were procured and tested in active work zone conditions after two crews of Caltrans maintenance workers were provided an opportunity to train with the systems. Worker feedback on the performance and effectiveness of the systems was collected before and after testing in active work zone conditions. The selected WZIA systems were tested in a variety of active work zone conditions to ascertain their capabilities related to deployment, operation, retrieval; and effectiveness in varying work zone conditions while considering potential for worker exposure to traffic during deployment and operation, besides other practical considerations. Based on the outcomes of this research, some general guidance and recommendations related to the use of WZIA systems were also developed that can help highlight and ensure best practices for future use and implementation of WZIA systems.

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Work Zone Safety, Work Zone Intrusion Alarm, Testing and Evaluation

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PILOT TESTING OF WORK ZONE INTRUSION ALARMS

FINAL REPORT

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ABSTRACT

The main goal for this research was to evaluate the effectiveness and practicality of deploying and operating selected WZIA systems in California work zones. The objective was to provide recommendations and guidance to Caltrans on implementing such systems in real-world conditions through field observations and feedback provided by the Caltrans maintenance staff. Selected WZIA systems were procured and tested in active work zone conditions after two crews of Caltrans maintenance workers were provided an opportunity to train with the systems. Worker feedback on the performance and effectiveness of the systems was collected before and after testing in active work zone conditions. The selected WZIA systems were tested in a variety of active work zone conditions to ascertain their capabilities and practicality related to deployment, operation, retrieval, and overall effectiveness in improving work zone safety, while considering potential for worker exposure to traffic during deployment and operation besides other practical considerations. Based on the outcomes of this research, some general guidance and recommendations related to the use of WZIA systems were also developed that can highlight and ensure best practices for future use and implementation of WZIA systems.

EXECUTIVE SUMMARY

Highway maintenance and construction remains one of the most dangerous jobs in California, with more than 7,000 work zone intrusions resulting in more than 3,200 injuries and 53 fatalities in 2019 (Caltrans, 2020). Even though Caltrans maintains high worker safety standards through its operations and equipment standards, the need for further work zone safety improvement persists. A Work Zone Intrusion Alarm (WZIA) system is a set of equipment designed to provide highway workers with additional warning of errant vehicles that may enter a work zone. In a previous study (Caltrans Contract 65A0643: Evaluation of Work Zone Intrusion Alarms: Report Number CA19-3038) (Khan et al., 2019), researchers evaluated selected WZIA systems available at that time in closed-to-traffic conditions to verify and validate manufacturer specifications.

The main objective of this research was to evaluate the effectiveness, benefits, practicality, and shortcomings of selected WZIA systems through testing in active work zone locations with the help of Caltrans maintenance staff. Furthermore, this research aimed to provide Caltrans with recommendations on the capabilities, deployment, practicality, effectiveness, and reliability of the selected WZIA systems in real-world conditions.

A literature review and market survey were conducted to identify updates to available systems and identify any new systems not previously evaluated. Specifications, system types, procurement status, and other necessary details were collected. Additionally, some relevant studies conducted from other states were also reviewed that related to the performance of selected WZIA systems. In consultation with the Project Advisory Panel, the following five systems were initially selected for evaluation in active work zone conditions in this research:

1. Traffic Guard Worker Alert System
2. SonoBlaster
3. Intellicone
4. Intellicone Single Sentry Beam
5. AWARE Sentry

In the later stages of this research, the following two new systems recently introduced in the market were identified:

1. Guardian Cone
2. Alpha SafeNet Overwatch

The research team, in consultation with the Project Advisory Panel, procured these two systems and conducted a limited series of tests in non-work zone locations, due to time limitations. The aim was to evaluate the capabilities and performance of these systems, at least at a minimum, for inclusion in this report for posterity and as guidance to Caltrans.

A detailed evaluation framework developed in the prior study was adopted to effectively assess the performance of each system and understand their capabilities, issues, and limitations (Khan et al., 2019). The framework consisted of a set of goals, objectives, evaluation criteria, data collection sources, and a detailed survey questionnaire that were modified to evaluate the selected WZIA systems in active work zone conditions.

Two Caltrans maintenance crews were invited to training sessions in closed-to-traffic conditions at the Caltrans Maintenance Equipment Training Academy (META) facility, to practice safely deploying, operating, and retrieving the selected WZIA systems in active work zone locations. The training sessions were followed by six days of active work zone testing by the crews at six different locations utilizing multiple selected WZIA systems at each location. The active work zone locations included lane, shoulder, and ramp closure on different types of roadways with varying conditions. The selected WZIA systems were tested in a variety of active work zone conditions to ascertain their capabilities related to deployment, operation, effectiveness, and retrieval and potential to improve work zone safety.

The final results included a comparison of worker surveys before and after active work zone testing. The survey results captured the maintenance workers' feedback on device effectiveness, deployment, sound distinctiveness, and perceptions of effectiveness and practicality. It was noted that the survey responses after testing in active work zone locations were generally more positive compared with before.

Outcomes of active work zone testing showed that the WAS performed effectively in both shoulder/lane closure and ramp closure work zones given the flexibility of deploying the pneumatic hoses and ease of operation. Different deployment recommendations were provided in addition to the number of systems for coverage in a typical work zone based on crews' experience of testing in active work zones and exposure to traffic considerations.

The SonoBlaster system was considered better in low-speed conditions vs. high-speed conditions, primarily due to worker exposure concerns. The system has the benefit of requiring no batteries and has one of the loudest alarm sounds. Recommendations were provided to address maintenance workers' concern regarding the time and effort required to install SonoBlaster units to cones and drums. During the training sessions, issues were observed during deployment of SonoBlaster cones from a standard Caltrans cone body truck, which could result in accidental activation of the alarm. The SonoBlaster performed well during testing at ramp closures.

The overall performance of the Intellicone system was similarly effective in low-speed conditions vs. high-speed conditions. The main concern was worker exposure, especially in high-speed conditions when deploying cone lamps on foot. Recommendations by the maintenance crew included deploying the cone lamps from a cone body truck to potentially reduce worker exposure. Similar to the SonoBlaster system, deployment configurations were developed based on the intermittent coverage provided by the Intellicone system due to gaps in the cones with deployed lamps that are required to be hit to activate the alarm.

The Single Sentry Beam system performed effectively in both shoulder/lane closure and ramp closure work zones, with limitations due to limited range and inability to tether with additional devices to extend its range. As such, deployment was mainly recommended in smaller and low-speed work zones. The advantages of this system were flexibility in laser deployment/detection range and the continuous coverage provided by the laser beam that allowed for effective use in ramp closures and novel applications, e.g., pedestrian/bicyclist intrusion detection.

The AWARE Sentry system, primarily designed to be used in a flagging operation, performed effectively in active work zone testing given its intended range and capabilities in warning workers. However, deployment is not recommended near intersections or diverging roadways, and careful consideration should be given to setting the speed threshold values for detecting potential vehicle intrusions.

Based on this research, general guidance and recommendations related to the use of WZIA systems, and roles and responsibilities of maintenance supervisors and workers were also developed that can highlight and ensure best practices for future use and implementation of WZIA systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHU	Auxiliary Horn Unit
AWARE	Advanced Warning and Risk Evasion
Caltrans	California Department of Transportation
CO_2	carbon dioxide
dBA	A-weighted decibels
FHWA	Federal Highway Administration
GPS	global positioning system
MASH	Manual for Assessing Safety Hardware Evaluation
META	Maintenance Equipment Training Academy
mph	miles per hour
NCHRP	National Cooperative Highway Research Program
PSA	portable site alarm
PSD	personal safety device
RF	radio frequency
SIM	Subscriber Identity Module
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

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1 INTRODUCTION

1.1 INTRODUCTION AND BACKGROUND

California has the largest population and economy of any state in the nation, with over 39 million citizens relying on the transportation infrastructure to support the state's $3.6 trillion economy (Bureau of Economic Analysis, 2022). With the highest population and largest economy in the nation, California has increased demand for a safe and efficient transportation system with decreasing quality due to age and use. The California Department of Transportation (Caltrans) is responsible for maintaining and repairing California's transportation infrastructure that is essential for the state's growth. It is estimated that the state will require about $57 billion in repairs of state roads in the coming decade, which will increase the presence of work zones and Caltrans workers on roadways.

A work zone is an area of roadway under construction, maintenance, or utility-work activities typically marked by signs, barriers, cones, and/or work vehicles. The work zone area extends from the first warning sign or flashing lights from an attenuator truck to the "End of Road Work" sign (Federal Highway Administration, 2022). Highway maintenance and construction remains one of the most dangerous jobs in California, with more than 7,000 work zone intrusions resulting in more than 3,200 injuries and 53 fatalities in 2019 (Caltrans, 2020). Despite signs, signals, and barricades already in place to promote work zone safety, the need for further work zone safety improvement persists.

Work Zone Intrusion Alarm (WZIA) systems were introduced in 1995 as a response to persistent concerns about improving work zone safety by the Strategic Highway Research Program (Awolusi & Marks, 2019). The purpose of WZIA systems is to alert workers within a work zone, usually through audible or vibratory alarms, of a work zone intrusion caused by an errant driver. The WZIA systems typically consist of a detection indicator, transmitter, and receiver. WZIA systems are designed to improve work zone safety by providing the workers adequate time to react and clear away from errant vehicles. WZIA systems are meant to supplement safe work zone practices and standards already set and not be used in substitution.

1.2 RESEARCH NEEDS

A previous research project completed in 2019 explored the viability of using selected WZIA systems available in the market at that time in California. Three selected WZIA systems were tested and evaluated in closed-to-traffic conditions to validate manufacturer specifications and compare the outcomes with varying findings from other research studies (Khan et al., 2019). The outcomes of the previous research indicated some promise in the use of WZIA in California work zones. This research aimed to test and evaluate the effectiveness and practicality of the previously selected WZIA systems, and any new systems available on the market in real-world conditions, to promote the integration of WZIA systems into policy and practice.

1.3 OBJECTIVES AND TASKS

The main objective of this research was to evaluate the effectiveness, benefits, and shortcomings of selected WZIA systems through deployment in active work zone locations. Furthermore, this research was intended to provide Caltrans with recommendations on specific WZIA systems with regards to their capabilities, deployment, practicality, effectiveness, and reliability in real-world conditions. The research objective also included documenting and evaluating new WZIA systems that have recently become available in the market since the previous research study. 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 invoices, and scheduling meetings with Caltrans staff.

Task 2: WZIA Market Assessment and Literature Review

A brief literature review and market survey was conducted as a broader supplement of the literature review conducted in the prior research (Khan et al., 2019). The literature review identified updates made to the previous WZIA systems and any new systems/products not already listed in the final report of the previous research. Specifications, system types, procurement status, costs, and other necessary details were included.

Task 3: WZIA Training for Maintenance Staff and Workers

Training sessions with Caltrans maintenance staff were conducted in closed-to-traffic conditions at the Caltrans META facility in Sacramento. The Caltrans maintenance staff were trained to safely deploy, operate, and retrieve selected WZIA systems independently in active work zone locations while also providing initial feedback through a survey. Training plans and material specific to each selected WZIA system were developed in view of observations and limitations found during the current and prior research.

Task 4: Identification of Active Work Zone Locations

A list of active work zone locations was identified for selected WZIA systems to be deployed and tested in real-world conditions. Details of the locations, type of work zones, and choice of WZIA system tested were provided.

Task 5: System Procurement, Development of Active Work Zone Testing and Data Collection Plans

The required number of selected WZIA systems were determined and procured based on deployment recommendations developed during the prior research, and the size, type, and characteristics of active work zone locations. The testing protocols and worker surveys developed during the prior research were modified and utilized to obtain data for the performance evaluation of specific WZIA systems in active work zones. Deployment plans from the prior research displaying set up and implementation details for the selected WZIA systems were also modified and utilized as part of the WZIA evaluation.

Task 6: Active Work Zone Testing and Evaluation

Based on the testing protocols, the selected WZIA systems were deployed and tested by Caltrans maintenance staff at select active work zone locations. Video, usage, and worker crew survey data from each deployment were documented and analyzed as part of the evaluation results provided.

Task 7: Additional Testing and Evaluation

Additional testing was conducted to evaluate two new WZIA systems that were introduced in the market towards the end of the research project and could not be evaluated in conjunction with the Caltrans maintenance crews. The research team evaluated these two new systems through limited testing to provide information related to the devices' capabilities, deployment, practicality, effectiveness, and reliability as intrusion alarm systems.

Task 8: Documentation and Final Report

A final report was prepared documenting all findings of the research and final recommendations to Caltrans. A guide of best practices for each WZIA system was provided based on feedback provided by the Project Panel and observed system performance in active work zones. Revised supplements from prior research of Caltrans Standard Plans (T-10 through T-13) were provided for the deployment and implementation of selected WZIA systems in active work zone conditions.

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 systems and detailed updates made to previously selected WZIA systems. Chapter 2 also provides a brief literature review that includes existing, new, and emerging WZIA technologies, along with Manual for Assessing Safety Hardware (MASH) evaluations of the selected WZIA systems.
- 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 surveys used to evaluate the systems.
- Chapter 4 presents details and outcomes of the training sessions using the selected WZIA systems that were organized at the Caltrans Maintenance Equipment Training Academy (META) facility.
- Chapter 5 presents the details of the active work zone testing and the outcomes of the trials using the selected WZIA systems.
- Chapter 6 presents the results of the maintenance workers surveys conducted during the training sessions and active work zone testing.
- Chapter 7 presents details of additional testing and evaluations performed on new WZIA systems.
- Chapter 8 presents a summary and discussion for each selected WZIA system. Conclusions and recommendations are also presented in this chapter.

2 LITERATURE REVIEW

This chapter presents details on the various types of WZIA systems evaluated in this research and serves as a supplement to the broader review of the literature in the prior research (Khan et al., 2019). Details on specifications, type of system, procurement status, cost, and updates since the prior research are included. Additionally, some relevant literature and studies conducted in other states related to the performance of selected WZIA systems are also discussed in this chapter.

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

An extensive survey of the market and 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) (Figure 2.1)	Microwave and Pneumatic			

Table 2.1 lists current commercially available WZIA systems and Table 2.2 lists emerging WZIA systems that are expected to become commercially available based on information provided by the vendors. Table 2.1 and Table 2.2 also includes a summary of the detection technology and the alert mechanisms of each device. A detailed description, specifications, operation, and related information from the literature are presented in subsequent sections.

2.2 COMMERCIALLY AVAILABLE WORK ZONE INTRUSION ALARM SYSTEMS

The following section presents detailed information and updates to commercially available WZIA systems since the previous research. Although the previous research provided detailed information about some of these systems, a few details are presented here again in summarized form with updated and new information for convenience and quick referencing (Khan et al. 2019).

2.2.1 Traffic Guard Worker Alert System

2.2.1.1 Description and Specifications

The Traffic Guard Worker Alert System (WAS), shown in Figure 2.1, is a pneumatic/microwave device that comprises of a lightweight, portable trip hose and sensor assembly to trigger a wireless alarm unit and flashing lights. The WAS features the following components:

- Poly-Plastic Alarm unit with flashing LED alarm light and alarm horn speaker
- Single 12-foot pressure sensing hose (pneumatic tube) with hose sensor/transmitter
- Personal Safety Device (PDS) with vibration and audio warning alarms

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

2.2.1.2 Setup/Installation and Operation

The WAS alarm unit utilizes a rechargeable battery while the sensor attached to the pneumatic hoses utilize AA batteries for power. The senor hoses have the option to connect to multiple alarm units simultaneously. The WAS is deployed by laying the pneumatic hoses across the pavement of the desired coverage area inside the closure in a work zone. The following deployment steps should be followed for operating the WAS (Khan et al. 2019):

1. Deploy trip hoses on the pavement in the closure. Press the power button on the hose pressure sensor. The LED on the sensor box will flash red several times until the pressure hose is calibrated.
2. The alarm unit has a magnet that can be attached to a vehicle, structure, or equipment in a work zone. Set the alarm unit in a suitable location and switch on the power button under the handle on. Be sure the LED on the side of the unit is visible and showing green.
3. Turn on all Personal Safety Devices (PSD) distributed to the workers and verify the green LED is visible.
4. Step on a pneumatic hose to test the connection to an alarm unit and activate the alarm to verify the system is functioning properly.

Once a vehicle passes over a pneumatic hose, the WAS alarm unit and PSDs will activate the auditory and vibratory alarms. The manufacturer specified a maximum range of 1,000 feet; however, the previous research found that to be unattainable. To reliably maintain a connection, the following maximum distances were recommended from the prior research (Khan et al. 2019):

- 225 feet between a hose sensor and an alarm unit
- 175 feet between two alarm units
- 75 feet between a PSD and an alarm unit

2.2.1.3 System Updates

WAS had previously been manufactured by Astro Optics LLC. but was acquired by TAPCO. Updates to the device since the previous research include the following features:

- A trigger button on the Personal Safety Device is now optional.
- A hard case to protect the alarm and trip hose is now available upon purchase.
- Only the 12-foot trip hose is available; the 33-foot trip hose has been discontinued.

2.2.2 SonoBlaster

2.2.2.1 Description and Specifications

The SonoBlaster is a kinematic device that utilizes a built-in carbon dioxide (CO_2) cartridge to sound a 125 dBA alarm upon impact. Once impacted, the CO_2 cartridge is punctured which causes the escaping gas to produce sound through an air-pressure horn. The device can be mounted on traffic cones, drums, and other work zone barriers. The main components of the SonoBlaster, shown in Figure 2.2, include:

- SonoBlaster alarm unit
- Disposable CO_2 cartridge
- Mounting bracket for traffic cone attachment

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

2.2.2.2 Setup/Installation and Operation on a Traffic Cone

The following are specific steps for deploying and operating the SonoBlaster system as specified in the previous research (Khan et al. 2019):

1. Install the mounting bracket to the base of a traffic cone as per the instructions by the manufacturer. Attach the device unit to the mounting bracket. After installation, turn the knob located on the device unit 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 SonoBlaster mounted cone on the roadway while the knob is still in the locked position.
5. Arm the device by rotating the control knob from the locked position to the unlocked position.

The SonoBlaster will activate the alarm if the mounted cone is tilted more than 70 degrees and sounds the 125-dBA alarm for a minimum of 15 seconds (Khan et al. 2019). After alarm activation, the spent CO_2 cartridge must be replaced with a new cartridge. The system does not require batteries or other power sources since it uses a disposable CO_2 cartridge.

2.2.2.3 System Updates

Updates to the SonoBlaster system since the previous research include the device being commercially available through TAPCO as opposed to previously being available through Transpo Inc. The device is Federal Highway Administration (FHWA) National Cooperative Highway Research Program (NCHRP) 350 crash-tested and accepted.

2.2.3 Intellicone System

2.2.3.1 Description and Specifications

Intellicone is a kinematic and radio-based device that is digitally driven and designed to monitor the work zone. The system protects users from harm by creating a layer of protection, called a geozone, around a work zone to prevent intrusions and to improve the safety of workers and road users alike, as illustrated in Figure 2.3.

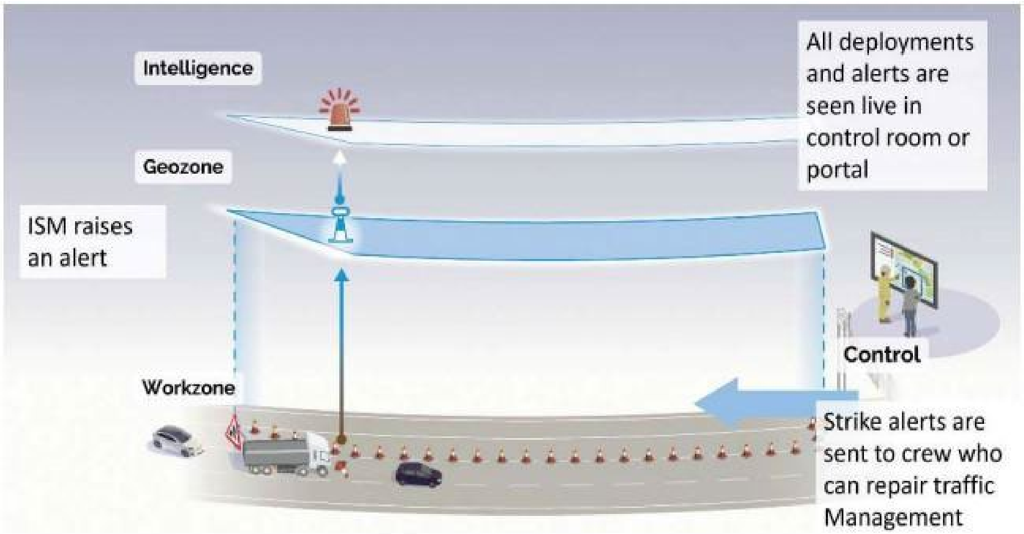


Figure 2.3 Intellicone System Geozone Overview
(Source: Highway Resource, 2021c)

The Intellicone system uses a cone and vehicle mountable audio-visual Portable Site Alarm (PSA), shown in Figure 2.4, to notify workers of errant vehicles. The PSA connects to the nearest cellular network to communicate with other Intellicone products and can also utilize short range radio frequencies to communicate with motion sensitive cone lamp sensors (Figure 2.5). The Intellicone system offers a wide variety of communication devices that can be operated from a central location or portal. Further details of the Intellicone system's components and features can be found in Appendix A.

Figure 2.4 Intellicone System Portable Site Alarms
(Source: transcanadatraffic.ca, 2021)

Figure 2.5 Intellicone System Cone Lamp
(Source: transcanadatraffic.ca, 2021)

A variety of Portable Site Alarms are available for use depending on the type of work zone closure as shown in Figure 2.6.

Figure 2.6 Intellicone System Updated Portable Site Alarms
(Source: Highway Resource, 2021c)

The PSA has a three-tone audio alarm that is designed to be highly effective in alerting users. The PSA may be used with up to 200 Intellicone lamp sensors at a maximum range of 100 feet between sensors. When activated, the PSA will emit red flashing lights along with a three-tone siren to warn against a vehicle intrusion, and a single-tone siren along with a blue light to indicate a controlled vehicle entry or pedestrians. Other technical specifications of the device include (Highway Resource, 2021c):

- 3.5 kg (about 8 lbs.) weight
- An internal battery option that includes a rechargeable battery for 28 hours of operation or an external battery option that provides an additional 400 hours of operation and is recommended for long term applications

2.2.3.2 Setup/Installation and Operation

The following are specific steps for deploying and operating the Intellicone system as specified in the previous research (Khan et al. 2019):

1. Deploy the Intellicone lamps on cones in the work zone.
2. 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 the alarm once a deployed cone lamp is pushed, impacted, or tilted beyond 45 degrees. The lamps have the capability to transmit signals from one lamp to another, within the maximum 100-foot range, until the signal reaches a PSA, and an alarm is triggered. The PSA can connect to the nearest cellular network that theoretically allows an unlimited range between the PSA and a cone lamp.

2.2.3.3 System Updates

Updates to the system since the previous research include the renaming of the system from “Intellicone” to “Intellicone Incursion Prevention & Warning System (IIPAWS).” The manufacturers have also expanded the range of products with varying traffic management capabilities to include warnings that alert workers in a work zone, road users, and/or pedestrians when applicable. (Highway Resource, 2021a).

2.2.4 Single Sentry Beam (Portable Laser)

2.2.4.1 Description and Specifications

The Single Sentry Beam uses a portable continuous laser beam to detect incursions by pedestrians/workers or vehicles within its range, depending on the desired settings (Figure 2.7). The Single Sentry Beam system utilizes the Intellicone PSA units to warn workers in a work zone. The Portable Laser can communicate wirelessly with the PSAs from Intellicone System at a maximum distance of 246 feet as specified by the manufacturer.

It should be noted that the performance of the laser is subject to light conditions and may vary depending on the approach angle and vehicle size. It is recommended that the detection range be tested before use. Technical details of the device include (Highway Resource, 2021b):

- 18 kg (45 lbs.) weight with batteries
- No reflector required

- Typical lifespan of 5 years
- Operating lifetime of about 120 hours

Figure 2.7 Intellicone Single Sentry Beam
(Source: Highway Resource, 2021b)

2.2.4.2 Setup/Installation and Operation

In order to set up the Single Sentry Beam, the device is turned on and it emits a beeping sound for 10 seconds indicating the laser is ready to be configured for a distance range based on user desired distance. The detection range of the device can be set by pointing the laser at an object at a maximum desired range distance in the direction of the desired monitoring area. The detection range can be reset after restarting the device.

An object is detected once the beam is interrupted. Once detected, the Single Sentry will alert all nearby and connected PSAs and activate the audible warning alarm. The detection range of the laser is up to 10 meters (33 feet) for pedestrians wearing black, up to 20 meters (66 feet) for vehicles traveling at a speed of 60 miles per hour (mph,) and up to 35 meters (115 feet) for workers wearing florescent vests (Figure 2.8)

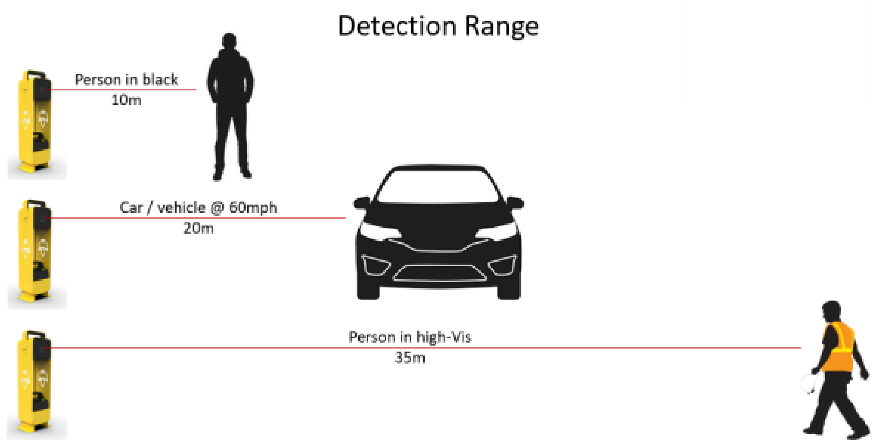


Figure 2.8 Intellicone Single Sentry Beam Detection Range
(Source: Highway Resource, 2021b)

2.3 EMERGING WORK ZONE INTRUSION ALARM SYSTEMS

The systems presented in the following sections provide detailed information and updates about emerging WZIA systems. Some of these systems are expected to become commercially available based on information provided by the vendors (e.g., Advanced Warning and Risk Evasion [AWARE]). Other systems (Guardian Cone, Alpha SafeNet Overwatch) just recently became available on the market. These systems were also included in the evaluation process during this research.

2.3.1 Advanced Warning and Risk Evasion

2.3.1.1 Description and Specifications

The Advanced Warning and Risk Evasion (AWARE) system utilizes radar and position/orientation sensors to continually track traffic surrounding an active work zone. The AWARE system can intelligently detect potential vehicle intrusion threats and provide timely warnings to workers and drivers.

The AWARE system was developed by CRH Inc. for internal use and is currently in development and testing phase for future commercial applications. CRH Inc. has developed two types of AWARE systems that may be used depending on the work zone operation.

1. **AWARE Lane Intrusion System:** Used for high-speed applications but is currently unavailable due to reliability issues.

2. **AWARE Sentry System:** Primarily used for flagging “stop” and “slow” operations. The sentry system can be used for one lane closures on two lane roadways and flagging operation. The sentry system cannot be used on highways and interstates where flaggers are not used, and when traffic is being slowed instead of stopped (CRH Inc., 2021).

The AWARE system is comprised of the following main components as shown Figure 2.9:

- High tech mountable radar sensor (The Raven)
- Global Positioning System (GPS) based personal safety unit (WorkTRAX)
- Threat deterrent unit that includes visible and audible warnings
- Mobile application (Base Station)

Figure 2.9 AWARE System Components
(Source: Oldcastle Video Team, 2021)

The components of AWARE are packaged in a portable box (base station) and configured as the AWARE Sentry system as shown in Figure 2.10 and Figure 2.11. The Raven, mounted in the AWARE Sentry box, monitors and detects vehicles that have a possibility of intruding the work zone at a distance of up to 600 feet. The AWARE Sentry system is activated if the Raven detects a potential intrusion within the coverage area through the assessment of up to 64 approaching vehicle speeds, locations, and trajectories (CRH Inc. Video Team, 2021). Once activated, the sentry unit will sound an audible alarm through the alarm speaker on the base station and visual flashing white and amber LED lights warning drivers and adjacent workers, as seen in Figure 2.11. Haptic and auditory alerts can also be produced by the WorkTRAX devices worn by the workers either on an armband or in the pockets of a safety vest. Other details of the AWARE Sentry System include:

- The Raven capabilities: 600 feet range, speed, location, and trajectory monitoring of 64 vehicles simultaneously.
- Data from vehicle traffic behaviors and unsafe events, including video recordings of intrusion incidents, are continuously collected, and automatically uploaded once the device is within a known Wi-Fi range.
- Battery life of 15 hours.

Figure 2.10 AWARE Sentry System Device
(Source: CRH Inc. Video Team, 2021)

Figure 2.11 AWARE Sentry System Components
(Source: CRH Inc. Video Team, 2021)

2.3.1.2 Setup/Installation and Operation

The AWARE Sentry System (Figure 2.13) provides advanced warning to drivers, flaggers, and workers in the work zone of impending intrusion threats. For optimal use, the AWARE Sentry System should be placed in front of the flagger facing traffic, preferably down a straight section. A toggle switch on the base station turns the system on and is ready to detect vehicles almost instantaneously. The WorkTRAX devices can be turned on by pressing a button on the device for 2 seconds. Pressing the button for longer than 2 seconds will allow the WorkTRAX to go into Bluetooth connection mode for data transfer between the base station and a mobile device.

The base station can be used to configure and control basic functions of the system. Site supervisors may also use the Bluetooth connection capability of WorkTRAX to connect to the AWARE mobile application, which allows for setting the speed thresholds above which vehicles are detected and alarm triggered by AWARE Sentry, amongst other settings. The sentry system automatically activates the warning alarms if a driver is approaching at high speeds exceeding the threshold set by the user, or if an impatient driver pulls out of the stopped queue and is headed into direct conflict with incoming traffic (CRH Inc. Video Team, 2021).

2.3.2 Guardian Cone

2.3.2.1 Description and Specifications

The Guardian Cone is a radar-based device designed to alert workers based on the speeds of approaching vehicles. The device is designed to be used by a single or limited number of workers in remote locations with sporadic traffic. The Guardian Cone system consists of a cone sensor (Figure 2.12) and a wearable receiver (Figure 2.13) that controls the system's functions and emits auditory and vibratory alerts based on incoming vehicle speeds exceeding a preset threshold.

The Guardian Cone has a maximum range of 500 feet and utilizes USB- C power bank. The threshold speed of the system, along with other system functions, can be set with the wearable device from a minimum speed of 15 mph, and a maximum speed of 75 mph. There are various types of auditory and vibratory alerts that are dependent on vehicle speeds and the threshold set. If incoming vehicle speeds exceed 5 mph from the threshold, the wearable device will beep once. If vehicle speeds are between 5 and 15 mph above the threshold, the wearable device will emit an alert tone. If vehicle speeds exceed 15 mph of the threshold, the wearable device will emit a louder and more urgent alarm tone. Vibratory alerts will occur for all vehicles detected, regardless of incoming speeds.

Figure 2.12 Guardian Cone Sensor
(Source: Site20/20, 2023)

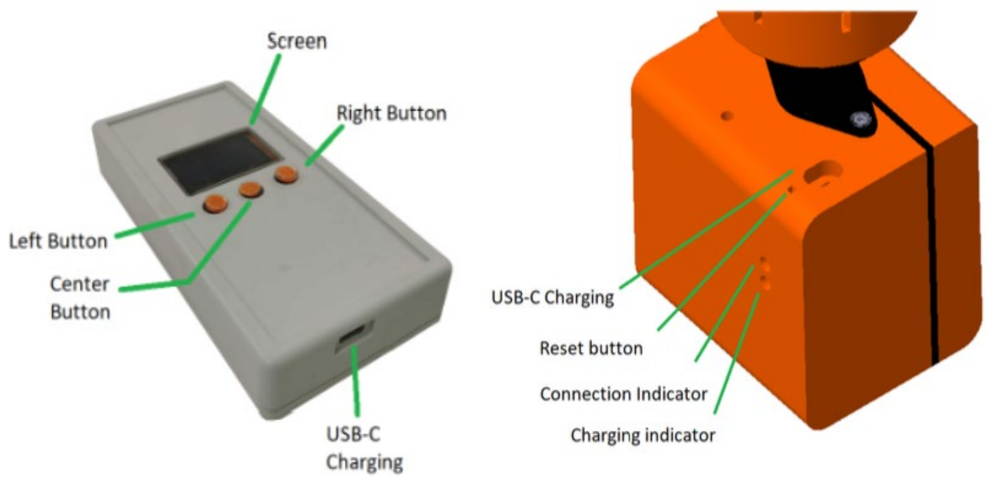


Figure 2.13 Guardian Cone System Mechanics

(Source: Site 20/20, 2023)

2.3.2.2 Setup/Installation and Operation

The sensor fits directly atop a standard traffic cone, with the sensor facing oncoming traffic while a lone worker attaches a receiver to their vest. The cone sensor should be deployed as close to traffic as safely possible but can be deployed up to 16 feet from the road centerline. When a vehicle passes the Guardian Cone sensor, a signal is sent to the worker's receiver utilizing long-range Bluetooth technology, that a vehicle is approaching. As fixed objects near the deployed sensor may affect the radio signal, a clear line of sight should be maintained between the wearable device and the cone sensor. It should be noted that one wearable device can be connected to one cone sensor at a time.

2.3.3 Alpha SafeNet Portable Overwatch Device

2.3.3.1 Description and Specifications

The Alpha SafeNet Overwatch Device (Figure 2.14) utilizes LiDAR laser technology to provide work zone coverage by creating an invisible barrier between the work zone and traffic. When activated, the system will emit flashing LED lights along with an auditory siren alarm. The Overwatch system provides two modes of coverage.

1. Targeting mode: May set the detection range up to about 300 feet. To set the desired detection range, the manufacturer specifications recommend that the LiDAR laser beam be terminated against a solid object at the desired range. This setting is suitable for providing short distance coverage.
2. Infinity mode: Provides an option where the LiDAR laser beam is not terminated against a solid object. This setting is suitable for providing long distance coverage up to 700 feet. However, it should be noted that even a slight movement of the detachable and mountable LiDAR device atop the box may result in a large shift in the direction of the laser beam at long distances.

The Overwatch system also includes an Auxiliary Horn Unit (AHU) that acts as a portable speaker placed near the workers as an additional warning device. The AHU as shown in Figure 2.15 is paired with the main system unit and provides an additional alarm once the system unit is activated. Depending on the model purchased, the AHU has a connection range between 200 and 1,000 feet. The manufacturer specifications indicate the alarm sounds is at 135 dBA.

Figure 2.14 Overwatch Device and LiDAR Head Unit
(Source: Alpha SafeNet, 2023)

Figure 2.15 Overwatch Auxiliary Horn Unit
(Source: Alpha SafeNet, 2023)

2.3.3.2 Setup/Installation and Operation

The following are specific steps to deploy and operate the Alpha SafeNet Overwatch device:

1. Connect the LiDAR head unit to the Overwatch device unit.
2. Place the Overwatch device on the border of the work site with the LiDAR head facing towards the area of desired coverage.
3. Connect the video targeting display to the LiDAR head and Overwatch device unit. Select the target or infinity mode depending on the desired coverage.
4. Flip the Power switch on. Target the system for the desired coverage by adjusting the LiDAR head using the video targeting display.
5. Verify that the LED display numbers on the Overwatch device are stable and within the ranges for the mode selected. When the values displayed are stable, press the Arm button to arm the device and flip the Horn switch on for an audible siren when activated.
6. The video targeting display may be detached at this point.
7. Open the AHU case and flip the power switch on for additional warning within the work site.

The Overwatch system will activate when the LiDAR detects any interference within the detection range. Once interference is detected, the Overwatch device and the AHU will sound a 135 dBA siren, along with flashing LED lights from the Overwatch device unit. The alarm continues to sound as long as the interference (person or vehicle) is in the line-of-sight of the laser and discontinues as soon as the interference moves away from disrupting the laser beam. The Overwatch system has a 20-hour battery life in idle mode, which may diminish depending on how often the alarm is triggered.

2.4 RELATED LITERATURE

2.4.1 Texas A&M Transportation Institute (2016)

Texas A&M Transportation Institute conducted a study in a simulated work zone to assess driver responses to an activated AWARE system alarm compared to a simulated work zone without the activated AWARE alarm. Test drivers included 63 participants varying in age and gender. The study observed driver responses in day vs. night conditions and white flashing warning lights vs. red/amber flashing warning lights. Approximately 15 percent of participants showed signs of being startled by the activation of the AWARE alarm. Overall, the study concluded that the AWARE alarm did not have an adverse effect on driver behavior (Ulman, Trout, and Theiss, 2016). The response survey of the participant drivers indicated that a majority thought that an emergency or police vehicle was nearby when the warning lights were flashing amber and contemplated pulling over, though none did. Researchers recommended using the white flashing warning lights as opposed to amber, and suggest the alarm be modified as it resembles emergency vehicles sound.

2.4.2 Texas/Georgia (2019)

Awolusi conducted a study to evaluate the potential and effectiveness of WAS and Intellicone as WZIA technologies. The study found the alarm duration of WAS to be 5 seconds, much shorter than the Intellicone alarm at 60 seconds. The levels of the two technologies were similar at various distances, with the Intellicone system having louder sound levels (Awolusi and Marks, 2019). The workers had a faster reaction time to Intellicone than WAS, which may have been amplified by the intruding vehicles impact to the designated impact activated cone upon which the sensor was placed. The worker's reaction time was also found to be faster the closer the alarm is placed to the workers and the faster a vehicle is intruding into the work zone, with a 0.02-0.05 second margin (WAS having the higher margin) (Awolusi and Marks, 2019).

The provided Personal Safety Devices proved ineffective with an average delay of 0.37 seconds. Table 2.3 displays the recommendations for the tested work zone intrusion alarm devices. Intellicone is recommended to be used for longer taper work zones where long-term temporary devices are deployed, and WAS is recommended for short tapers and short term and mobile work zones (Awolusi and Marks, 2019). During the Awolusi study, limitations such as lengthy set up times, false alarms, misfires, and alignment difficulty resulted in the team's inability to evaluate the system along with WAS and Intellicone (Awolusi and Marks, 2019).

Table 2.3 Selection Guide for Work Zone Intrusion Detection Devices

Situations	Intellicone	WAS	AWARE
> 1 day	X		X
≤ 1 day		X	
Mobile operations			X
Taper ≥1500 feet	X		X
Taper < 1500 feet		X	

(Source: Adapted from Awolusi and Marks, 2019)

2.4.3 Minnesota Department of Transportation (2019)

Based on the 2015 Texas A&M Transportation Institute's study of the AWARE system, Oldcastle sent representatives to conduct a new study during a Minneapolis paving project to evaluate the system's capabilities and future potential as shown in Figure 2.16 and Figure 2.17.

Figure 2.16 Work Zone Equipment Vehicle Used for AWARE System Testing in Minneapolis
(Source: Ullman and Theiss, 2019)

Figure 2.17 AWARE System Sensor Placement on Work Zone Equipment
(Source: Ullman and Theiss, 2019)

The results of the recent study concluded that the AWARE system was successful in detecting work zone intrusions and alerting motorists and workers (Ullman and Theiss, 2019). The study also reported some issues with data storage, and retrieval of raw data that may be processed and analyzed regarding vehicle intrusion behaviors. As of February 2019, Oldcastle anticipates the system's continued use in beta testing and is currently working to identify a manufacturer/distributor to license the technology once all issues have been addressed and the system is deemed acceptable to be commercialized (Ullman and Theiss, 2019).

2.4.4 Tennessee Department of Transportation

A recent study was conducted for the Tennessee Department of Transportation to identify and recommend the most effective and promising WZIA system between WAS, Intellicone, and AWARE Sentry. These three systems were evaluated using controlled and live conditions. During the controlled conditions, AWARE Sentry proved to be the most accurate of the three technologies, while WAS and Intellicone had a higher likelihood of false alarms and delayed signal transmissions (Mishra et al., 2021). The study recommended that AWARE Sentry be used for medium tapers and when flagging is required, as the Sentry device is designed primarily for flagging purposes.

During the live conditions testing, AWARE Sentry was used during a bridge repair, Intellicone was used during a pothole repair as well as two asphalt resurfacing projects, and WAS was used during a curb ramp repair. Table 2.4 summarizes the considerations based on the live conditions test. Table 2.5 provides implementation recommendations for each WZIA system based on the controlled and live conditions test. According to recent correspondence to the manufacturer, COVID-19 delayed the plans to undergo completion of the AWARE Lane Intrusion System.

Table 2.4 Summary of Key Considerations Needed

System	Benefits	Drawbacks
Intellicone:	• Good work zone coverage. • Distinct, loud alerts. • Low life cycle cost.	• Time consuming setup. • Frequent false positive and false negative alarms. • Issues with network connectivity in the US. • Currently not available in the US.
AWARE:	• Good work zone coverage. • Distinct, loud alerts. • Accurate detection of intrusions. • Quick set up.	• Primarily designed for flaggers. • Frequent alarms could be an issue when vehicles drive too close to the work zone at higher speeds. • Requires a smartphone application to configure system settings. • High life cycle cost.
WAS:	• Low life cycle cost. • Alerts produced from multiple sources-Portable Alarm Case and PSD. • Quick and easy set up.	• Limited Transmission range. • Lag in signal transmission could render it useless for workers working close to traffic. • Does not support live tracking of devices.

(Source: Adapted from Mishra et al., 2021)

Table 2.5 Recommended Implementation for WZIA Technologies

Work zone set up and duration	Short tapers or speed limits < 30 mph (< 500 feet)	Medium tapers or speed limits < 40 mph (500-1000 feet)	Long tapers or speed limits > 30 mph (> 1000 feet)
Short duration (≤ 1 day)	AWARE or WAS	AWARE	AWARE
Long duration (> 1 day)	Intellicone or AWARE	Intellicone	Intellicone
Mobile operation	WAS	AWARE	AWARE

(Source: Adapted from Mishra et al., 2021)

2.5 ADDITIONAL WORK ZONE SAFETY SYSTEMS AND TECHNOLOGY

During the market survey and literature review, a number of systems and devices were discovered that did not have alarm or vehicle intrusion detection capabilities. However, the devices may have the ability to enhance safety in work zones through other ancillary means. Therefore, information on these systems and devices was collected and is presented in Appendix A.

2.6 MANUAL FOR ASSESSING SAFETY HARDWARE EVALUATION

The NCHRP Report 350 sets guidelines and procedures for evaluating highway safety devices and specifies that any devices influencing the flow of traffic needs to be crash tested to promote public safety by minimizing the crash impact for the public. Temporary Traffic Control Devices are placed in one of four categories (Hiatt, 2019):

- Category 1: Small devices weighing 100 lb. or less that are crash certified by the device manufacturer based on crash testing or crash testing of similar devices. Such devices include traffic cones, plastic traffic drums, portable delineators, etc.
- Category 2: Small devices weighing 100 lb. or less that are not expected to significantly affect vehicular velocities but may cause some damage to vehicles once impacted. Such devices include barricades, portable sign supports, etc.
- Category 3: Devices weighing 100 lb. or more and are expected to significantly affect vehicular velocities once impacted. Such devices include impact attenuator vehicles, temporary railing, temporary barriers, etc.

- Category 4: A subset of Category 3 that includes portable devices such as area lighting supports, temporary traffic signals, changeable message signs, etc.

The Manual for Assessing Safety Hardware (MASH) is an extension of the NCHRP Report 350 as a formal manual with new guidelines that has been incorporated and implemented by state DOTs nationwide. Caltrans has established sunset dates for all categories of temporary traffic control devices manufactured before December 31, 2019, that are compliant with NCHRP Report 350 guidelines. All Category 2 and 3 devices deployed on the State Highway System after December 31, 2026, must be MASH 2016 certified. Temporary traffic control devices that are compliant with NCHRP Report 350 guidelines will not be permitted on the State Highway System after December 31, 2026 (Binns and Keever, 2020).

The selected WZIA systems have varying status regarding the certification of MASH evaluations. The research team was able to obtain the following details on the status of each selected WZIA system regarding the MASH certification:

- WAS: No MASH evaluation has been conducted. The manufacturer indicated that the device was used by Missouri DOT and Oregon DOT as a "temporary product" safe to use in work zones. Since the pneumatic hoses do not have a significant impact on changing the flow of traffic, MASH certification was not deemed necessary by the manufacturer.
- Intellicone: Since the Intellicone manufacturer is based in the UK, no MASH evaluations have been conducted on any Intellicone products. However, the manufacturer has conducted crash tests on cone lamps in the UK (Transport Research Laboratory, 2013) similar to MASH testing. The manufacturer stated they are looking into the requirements for MASH certification since the Intellicone products are planned to be commercially available in the United States sometime in the future.
- SonoBlaster: The SonoBlaster device was NCHRP 350 certified in 2002 (Jacoby, 2002).
- AWARE: MASH evaluation has been conducted on the AWARE Sentry device and has met the performance criteria for a MASH TL-3 work zone traffic control device (Bligh et al., 2020). However, Utah DOT reported that FHWA has verified that the AWARE Sentry device does not fall under Manual on Uniform Traffic Control Devices requirements for traffic control devices and is instead considered part of Personal Protection Equipment.

3 WZIA SYSTEMS PROCUREMENT AND TESTING PROTOCOLS

This chapter presents details on the systems selected by the Project Advisory Panel to be evaluated in this research and the development of a comprehensive evaluation framework that guided the evaluation of the selected WZIA systems in active work zone locations. Detailed information regarding each WZIA system procured is presented in Chapter 2. However, some specific details with respect to each system as observed during the procurement process are discussed in further detail in the following sections.

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 five systems were selected and procured to be evaluated in active work zone locations in this research:

1. Traffic Guard WAS
2. SonoBlaster
3. Intellicone
4. Intellicone Single Sentry Beam
5. AWARE Sentry

The research team procured four WAS alarm units and pneumatic hoses along with six PSDs. Additional older units of WAS were also made available on standby to be used in active work zones depending on the size of the closure and specific conditions at each work zone.

The SonoBlaster system procured from the manufacturer was the same as described in Chapter 2. The research team procured 25 units of SonoBlaster in addition to 30 units from the prior research (Khan et al. 2019). However, some of the units from the previous research were unusable. 100 CO_2 cartridges were procured in this research.

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). In the previous research, the research team procured three units of the Y-series Intellicone PSA and 10 units of the Intellicone Dorman ConeLITE lamps, determined to be best suited for

Caltrans' needs (Khan et al. 2019). However, these units were no longer operational due to battery deterioration and updates to the GSM technology rendering them unable to connect with cell phone networks.

In this research, the research team procured an additional two units of the new and updated Y-series PSA and 10 new units of the Dorman ConeLITE lamps. It should be noted that the previous version of the Dorman ConeLITE lamps was programmed for different sensitivity levels to prevent false alarms due to vibrations and high-speed traffic effects ("very high," "high," "medium," "low," and "very low"). However, the updated cone lamps now offer a single sensitivity level to ensure greater consistency in performance.

Two units of the Intellicone Single Sentry Beam were procured from the manufacturer along with accessories for proper charging of the batteries. Two units of the AWARE Sentry system were also procured. It should be noted that the two units of the AWARE Sentry systems procured from the manufacturer were not new systems and had been in use prior to this research at other locations across the United State (confirmed from the logs in online dashboard). Although the research team made efforts to procure all systems new from the market, it was not possible in the case of the AWARE Sentry system since it is not yet available for sale by the manufacturer. Hence, the research team had to settle for what was made available by the manufacturer.

In the later stages of this research, the research team was made aware of two new systems recently introduced in the market. These were:

1. Guardian Cone
2. Alpha SafeNet Overwatch

The research team, in consultation with the Project Advisory Panel decided to procure these systems and conduct a limited series of tests in non-work zone locations due to time limitations. The aim was to evaluate the capabilities and performance of these systems at least at a minimum for inclusion in this report for posterity and some level of guidance; details of which are presented in Chapter 7.

3.2 EVALUATION FRAMEWORK, METHODOLOGY, AND TESTING PROTOCOLS

The methodology framework and testing protocols developed during the previous research were modified to evaluate the performance of the selected WZIA systems in active work zones (Khan et al. 2019). Figure 3.1 illustrates the methodology framework that guided the steps undertaken this research.

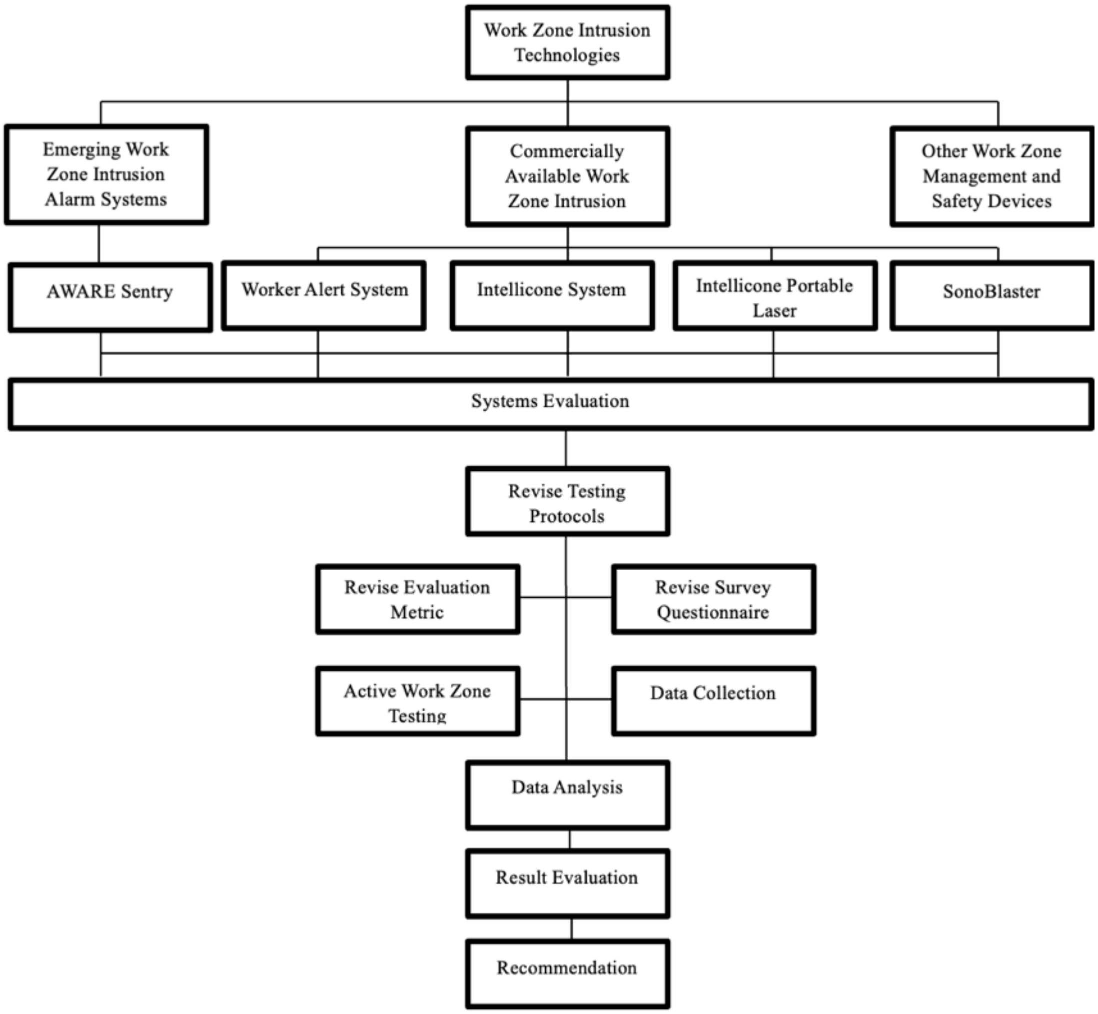


Figure 3.1 Methodology Framework

3.2.1 Development of Testing Protocols

Based on the research framework presented in Figure 3.1, the set of goals, objectives, evaluation criteria, and data collection sources developed during the previous research were modified to evaluate the selected WZIA systems in active work zone conditions. Despite modifying the testing protocols to accommodate the active work zone testing conditions, the three main goals defined for evaluating the WZIA systems in the previous research remained the same as listed below:

- Goal 1 focused on documenting device information and general work zone conditions where the tests were conducted.

- Goal 2 focused on documenting the functional characteristics considering the efficiency of deployment, effectiveness, practicality, reliability, worker risk of exposure to traffic hazards, and ease of retrieving devices from the work zone.
- Goal 3 focused on documenting feedback provided by the maintenance staff during the training sessions and active work zone testing.

The methods for data collection that were identified through the set of goals and objectives set for this research were sourced from the following (Khan et al., 2019):

- 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 during the prior research was frequency of false results. Two types of false results that were identified in the previous research were "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 (Khan et al., 2019). Since false negative results jeopardize worker safety, they pose a more serious concern. In contrast, frequent false positives can desensitize workers to alerts and partake as an acceptance and adoption barrier for implementing WZIA systems. Table 3.1 shows the four possible outcomes identified in the previous research as part of the 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.

(Source: Adapted from Khan et al., 2019)

3.2.2 Development of a Work Zone Workers Survey

The purpose of the worker survey questionnaires was to gage the needs, concerns, impressions, and overall experience of the Caltrans construction and maintenance staff with the selected WZIA systems. The survey questionnaires developed during the previous research were modified to include the newly obtained WZIA systems and any relevant information pertaining to this research. The survey questions consisted of a mixture of open-ended and standardized questions that captured the maintenance workers' perception of the effectiveness, practicality, and impressions of the WZIA systems as an alert mechanism for active work zone use. Due to the differences in characteristics between the selected WZIA systems, each survey was developed to be separate and contained questions specific to each of the selected WZIA systems. The questions aimed to gather detailed responses from the maintenance staff to increase the reliability, objectivity, and validity of recommendations provided in this research (Khan et al., 2019). Sample survey forms with all the questions are presented in Appendix C

4 TRAINING SESSIONS FOR MAINTENANCE STAFF AND WORKERS

Chapter 4 presents details of the training sessions conducted with two crews of Caltrans maintenance staff at the Caltrans META facility.

4.1 TRAINING SESSION BACKGROUND AND DETAILS

The purpose of the training sessions was to train the Caltrans maintenance staff, in closed-to-traffic conditions, to safely deploy, operate, and retrieve the selected WZIA systems. The training sessions were also meant to allow the maintenance staff to practice with the systems before testing in active work zone locations. Two maintenance teams from different Caltrans maintenance areas were selected by the Project Advisory Panel to participate in the training sessions.

The research team conducted preliminary tests on the performance of some of the newly acquired WZIA systems (Single Sentry Beam and AWARE) that had not been evaluated in the prior research, to better understand and verify their capabilities and manufacturer specifications. The research team then proceeded to collect data on the observations and feedback provided by the maintenance staff on the selected systems. The general layout in which the training sessions occurred, including a mock T-13 lane closure set up implemented by the maintenance staff within the META facility, is shown in Figure 4.1. The details of each training session are presented in Table 4.1.

Figure 4.1 Overview of the Training Session Setup

Table 4.1 Training Session Tentative Schedule

Day	Date	Time	WZIA System	Number of Maintenance Crew Members
1	March 29, 2022	7 AM – 5 PM*	Worker Alert System, Intellicone System, Single Sentry Beam, and SonoBlaster	8
2	April 4, 2022	7 AM – 3 PM*	AWARE Sentry	6

Since the prior research showed that not all systems met the guidelines and specifications detailed by the manufacturer (e.g., range limitations, transport, and deployment issues, etc.), specific training materials were developed for each WZIA system in view of the limitations observed during the prior and this research. Detailed training session plans and personalized training guides and best practices for each selected WZIA system are presented in Appendices D and E.

4.2 FIRST TRAINING SESSION

The first training session was conducted on March 29, 2022 at the Caltrans META facility. The WZIA systems demonstrated during the first training session included the Worker Alert System, Intellicone System, Intellicone Single Sentry Beam, and SonoBlaster. A total of eight maintenance crew members participated in the first training session. The research team briefed the participants on the set up, deployment, operation, and retrieval of the WZIA systems selected for the day. After the briefing, the maintenance staff and research team proceeded to the maintenance yard for the demonstration and training session of each WZIA system. Once the maintenance staff understood the set up, deployment, operation, and retrieval of each system, all the participants were asked to fill out the survey to provide feedback based on their initial assessment of each system. In addition to the survey feedback, the research team also observed the maintenance staff during the training sessions to document any unique observations and issues that were encountered; details of which are summarized in the subsequent sections.

4.2.1 Training Session - Worker Alert System

4.2.1.1 Setup and Deployment

During the WAS demonstration, two pneumatic hoses, three alarm units, and five PSDs were distributed to the maintenance staff to familiarize themselves with the operation of the system. When discussing deployment strategies for the system, the crew members debated the most effective placement for the pneumatic hoses within the work zone. One crew member wished to place hoses on the inside of the taper. A few members were worried about false alarms since equipment vehicles pass in and out of work zones frequently, stating "Place them right behind resting work vehicles." One crew member stated, "It doesn't matter if [the alarm] activates while deploying since the system resets on its own." Another crew member suggested placing the hoses last to reduce potential false alarms. The consensus was to place both hoses along the cones inside of the taper parallel to the flow of traffic, with one hose placed where the first hose ended for continuous coverage. The hose sensors were placed on the ground despite efforts to attach the sensors to or around nearby cones. The PSDs were placed inside the maintenance crew's pockets.

Due to some of the workers' skepticism whether the alarm units would be heard over equipment vehicles during work zone operations, one crew member decided to bring over one of the stationed Caltrans equipment vehicles with generators to test the sound effectiveness with loud background noise. The crew members then attached the three alarm units onto the equipment vehicle using the magnet located on the alarm devices and had the equipment vehicle generators running while the alarms were tested against the noise. The alarm units' placement on the equipment vehicle is presented in Figure 4.2. The maintenance crew felt the WAS alarm unit sound was sufficient (for the three units used) and would be most effective if one alarm unit was placed on the passenger side of the equipment vehicle and the remaining two units were placed under the truck bed, above the vehicle's tires, with all unit speakers pointing toward the direction of the work activity area.

Figure 4.2 WAS Alarm Units' Sound Test using Caltrans Generator Vehicle

4.2.1.2 Operation and Retrieval

During the operation of WAS, a few alarm unit activations occurred despite no one being near the hoses. The cause for the alarm unit activations was found to be the result of the PSDs worn by the maintenance crew. The button located on the PSDs were accidentally being pressed through the clothing of the maintenance staff. One crew member noted that the button located on the PSDs was "too sensitive," since simply placing the device in a pocket or vest may cause an activation. Despite the accidental triggers, the maintenance crew noted that the PSD's haptic feedback could be felt through their clothing with every alarm activation.

Once the WAS demonstration concluded, the crew member then retrieved the alarm units from the equipment vehicle and rolled both hoses individually for easier transport. Further details of the general feedback and recommendations provided by the maintenance crew during the WAS demonstration are presented in Table 4.2

Table 4.2 WAS – General Feedback and Observations from Maintenance Staff

	Maintenance Staff Feedback from WAS Training Session
Comments/Concerns:	● Multiple crew members noted the alarm sound was loud especially when multiple units (three alarm units) were deployed and triggered at the same time. Despite the equipment running and the use of ear plugs, the alarm was easily heard. ● One crew member liked that the PSDs and alarms (once activated) draw attention to the end of the taper, where hoses were placed. Stating that in an actual work zone, the crew members are more likely to be looking down. ● Many crew members liked the flexibility of the hoses, to be placed wherever they desire. ● Placement of the hoses would be an issue if vehicles were frequently entering and leaving the closure. ● One crew member noted that the placing the devices on the sides of work truck is fine (most likely placement to be used by crew members).
Recommendations:	● Provide a hook or zip ties attached to the pneumatic hose sensor to easily place it around cones and above the ground. (Note: the WAS system was found to operate optimally when the hose sensor or the alarm units were placed 4 feet above the ground in the prior research (Khan et al, 2019). ● Provide Velcro straps to help keep hoses organized after retrieval and for easier transport. ● Provide a weight to be placed at the end of the hoses to be more stationary.

4.2.2 Training Session - Intellicone system

4.2.2.1 Setup and Deployment

During the Intellicone System demonstration in the maintenance yard, two PSAs and 10 cone lamps were distributed to the maintenance crew. The crew were asked to share their opinion on the most effective deployment strategy for the lamps, considering lamps must be deployed manually on each cone. The crew discussed and employed two deployment strategies, both involving a Caltrans standard cone body truck. As the first option, a crew member deploying the cones installed the lamp on the cone before placing it on the ground from the cone body truck. As the second option, a crew member deployed all the cones on the ground in one pass and then repeated the pass deploying the lamps on each cone. Figure 4.3 demonstrates the crew members practicing the deployment of Intellicone lamps from a standard cone body truck. The deployment strategy for Intellicone lamps was important because concern was shown in the prior research by maintenance staff regarding exposure to traffic while manually deploying lamps, especially in long and high-speed work zones close to traffic flow.

Figure 4.3 Intellicone Lamps Deployment from Caltrans Standard Cone Body Truck

The maintenance crew also discussed deployment strategies for the PSA with consensus that deployment would be most optimal on a cone as near as possible to the activity area.

4.2.2.2 Operation and Retrieval

There were no issues observed during the operation of the Intellicone System and the system performed as expected. The retrieval of the cone lamps was quick and easy, with crew members carrying multiple lamps simultaneously. Further details of the general feedback and recommendations provided by the maintenance crew during the Intellicone System demonstration are presented in Table 4.3.

Table 4.3 Intellicone System – General Feedback and Observations from Maintenance Staff

	Maintenance Staff Feedback from Intellicone System Training Session
Comments/Concerns:	• One crew member liked the idea of having the PSA within the work zone. • Crew members liked the flashing lights during the alarm which would be useful in nighttime operation. • A few members questioned the possibility of wind and passing vehicles disturbing the cones resulting in alarm activation. This was noted by the research team for observation during active work zone testing. • One crew member noted the ease of placing the lamps while another member did not like the idea of cone retrieval and possible exposure to traffic.

4.2.3 Training Session – Single Sentry Beam

4.2.3.1 Setup and Deployment

During the Intellicone Single Sentry Beam demonstration, two devices were used to first demonstrate the detection range set up of the system. Many maintenance crew members liked the ease of setting the detection range to a desired distance and deployment of the laser devices. The maintenance crew were asked to share their opinion on deployment strategy for the Single Sentry Beam. Most crew members agreed that the best deployment strategy would be to place the device at the end of the initial taper or on the shoulder of the closure. The detection range would most likely be set to the maximum distance from the lane closure sign, with the laser pointing parallel to traffic and towards the start of the taper. Some concerns were raised about placing the device close to traffic flow and the possibility of a collision with a vehicle given the weight of the system.

4.2.3.2 Operation and Retrieval

Since the Single Sentry Beam system was new, the maximum range between the laser device and PSA was tested during deployment and operation by the crew (Figure 4.4). The maximum range between the laser device and a PSA was observed to be 175 feet and not 75 meters (246 feet) as specified by the manufacturer. This meant the device would have to be placed much closer to the PSA in the activity area, thus reducing the coverage distance of the laser device. Although manufactured by the same company, the Single Sentry Beam device does not communicate with the Intellicone lamps to extend range or pass signal on to a PSA.

During the retrieval of the laser devices, one crew member noted that retrieving multiple laser devices after a job could be cumbersome due to the weight of the device. Further details of the general feedback and recommendations provided by the maintenance crew during the Intellicone Single Sentry Beam demonstration are presented in Table 4.4.

Figure 4.4 Single Sentry Beam Detection Range Test

Table 4.4 Intellicone Single Sentry Beam – General Feedback and Observations from Maintenance Staff

	Maintenance Staff Feedback from Intellicone Single Sentry Beam Training Session
Comments/Concerns:	• The size and weight of the battery may be the biggest issue, that could fly out and cause serious damage if impacted. • The crew liked the flexibility in setting the laser detection range at multiple desired distances for specific work zone conditions. • Most crew members agreed that multiple laser units would be required to provide adequate coverage between the work zone and a lane closure sign. • Another crew member noted that the lasers would have to be placed too close to the work site to provide adequate warning.
Recommendations:	• Have the laser be removable to be placed elsewhere such as the back of a shadow truck.

4.2.4 Training Session - SonoBlaster

4.2.4.1 Assembly

At the start of the SonoBlaster demonstration in the maintenance yard, the maintenance crew members were asked to assemble one SonoBlaster bracket and alarm unit to a cone. Initially three crew members volunteered to try the bracket assembly, though one crew member soon gave up assembling and passed the task to another crew member. It was noted that while assembling the SonoBlaster unit, none of the crew members referred to the instructions provided by the research team or the manufacturer, but instead used a preassembled SonoBlaster cone as a reference. The crew members also proceeded to use their own tools and methods in installing the device utilizing a hammer to insert screws into the base of the cone shown as shown in Figure 4.5. The time for the maintenance crew to fully assemble and install a SonoBlaster unit was 20 minutes. It was also noted that some difficulty assembling the SonoBlaster device to a cone may depend on the type of cone used, since the bracket cannot be assembled to cones that have a cleated base.

Figure 4.5 Crew Members Installing the SonoBlaster Unit

4.2.4.2 Setup and Deployment

The maintenance crew discussed various deployment strategies given the SonoBlaster requires pre-installation on cones before being deployed in a work zone. The crew members agreed that SonoBlaster units would most likely be pre-assembled at the maintenance yard before use. The previous research noted that standard cones with a SonoBlaster unit installed cannot be stored in two rows side-by-side on a Caltrans standard cone body truck (Khan, et al. 2019). The crew was presented with this information and asked for alternative suggestions. One suggestion was to stack and deploy the cones from the front of a shadow truck as shown in Figure 4.6.

The crew were mindful of the instructions that an unlocked SonoBlaster unit may be triggered if the cone is tilted by more than 70 degrees during deployment. However, concern was shown by the crew about false alarms since cones get knocked over frequently in a work zone, especially in high-speed traffic conditions. For this reason, it was determined that the SonoBlaster devices are not ideal for testing in high-speed traffic conditions.

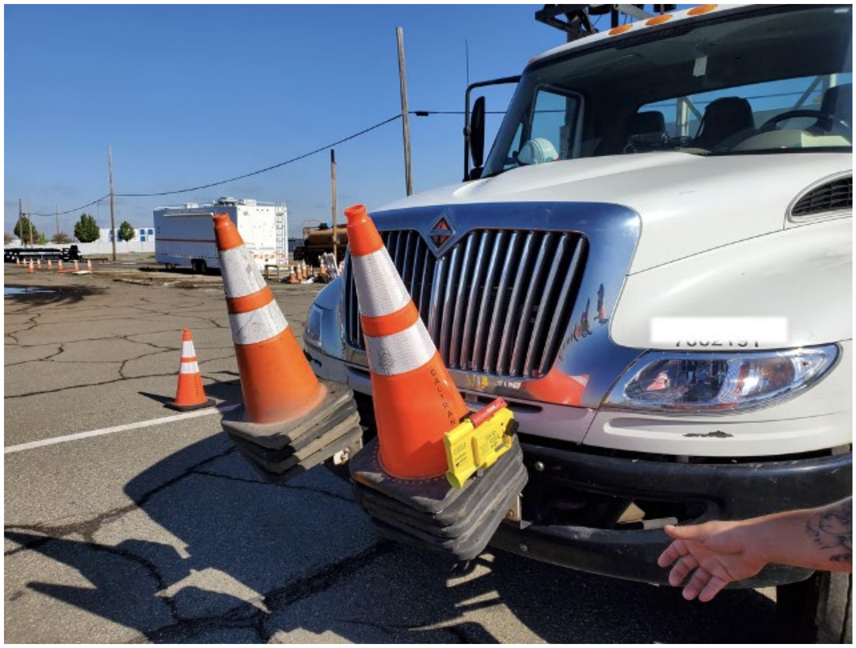


Figure 4.6 SonoBlaster Cone Stacking and Deployment from Shadow Truck

4.2.4.3 Operation and Retrieval

There were no issues observed during the operation and retrieval of the SonoBlaster units. Further details of the general feedback and recommendations provided by the maintenance crew during the SonoBlaster demonstration are presented in Table 4.5.

Table 4.5 SonoBlaster – General Feedback and Observations from Maintenance Staff

	Maintenance Staff Feedback from SonoBlaster Training Session
Comments/Concerns:	● The short bolts worked well for assembling the bracket to the cone base. ● A few crew members were worried about false alarms occurring due to tilting of the cone during deployment or cones getting knocked over in high-speed traffic conditions. ● One crew member noted the alarm was loud despite being next to an equipment truck. ● One crew member was completely against the device, stating "It will never work." Another member noted "it's too much work," regarding the hassle of placing and replacing spent cartridges. He was also worried about the exposure time for deploying the device.
Recommendations:	● Provide self-tapping screws when attaching the bracket to the cone. ● If possible, link the cones together using a chain or tie to activate multiple units if a vehicle intrudes between cones or hits a single cone. ● Use clips, instead of a bracket, that go over the protruding parts of the cone base. Can easily be removed as well. ● Provide a way for the bracket and unit to be rotational. ● Provide an assembly for the unit to be "dropped" on top of the cone to allow for quick and easy installation and deployment.

4.3 SECOND TRAINING SESSION

The second training session was conducted on April 4, 2022 at the Caltrans META facility, demonstrating the AWARE Sentry system to a different Caltrans seven-member maintenance crew. The research team began the day by briefing the crew on the set up, deployment, operation, and retrieval of the AWARE Sentry system. After the briefing, the maintenance staff and research team proceeded to the maintenance yard for the demonstration, training, and testing of the AWARE Sentry system. Once the maintenance staff understood the set up, deployment, operation, and retrieval of the AWARE Sentry system, all parties then filled out the survey and the training session concluded.

4.3.1 Training Session - AWARE Sentry b

4.3.1.1 Setup and Operation

During the demonstration of the AWARE Sentry system, two devices were displayed but only one device was used for the demonstration. Four WorkTRAX (personal safety devices) were also distributed to the crew members. After the device was setup and placed at the edge of a mock single lane closure, the alarm was manually triggered from the dashboard app to gage the maintenance crew's reaction. The most frequent comment about the alarm was that it "sounds like the police." One crew member also stated that "the lights are blinding," which led to a discussion about how the lights would impact the lead driver in the queue. One crew member noted that the flagger would need to get the lead driver's attention to proceed if they turned away from the lights. When discussing the maintenance crew members' deployment strategy, it was stated that the optimal distance for setting the device would be 200 feet ahead of the flagger, about eight to ten vehicles away from the flagger, and about 200 feet behind the "work zone ahead" sign. However, since the flagger needs to be within reach of the foot pedal attached to the device, the device would most likely be deployed on the shoulder of the roadway.

4.3.1.2 Operation and Retrieval

After the AWARE Sentry system was set up and deployed, the vehicle speed detection and range of the device were tested. Vehicle speeds were tested from 10 mph to 45 mph with the threshold speed set at 5 mph. It was observed that with increasing vehicle speeds, the frequency of the WorkTRAX alerts also increased. The device's ability to detect and activate the alarm if a vehicle driver decided to leave the queue was also tested, shown in Figure 4.7. The detection for out-of-queue vehicles proved successful as the device did activate the alarm every time one of the three vehicles pulled out of the queue.

Figure 4.7 AWARE Sentry Setup and Vehicle Out of Queue Test

The crew tested the range between the AWARE Sentry base unit and the WorkTRAX personal safety device. At a distance of 500 feet between the base station and the WorkTRAX, the system was triggered resulting in a successful alarm trigger on the WorkTRAX unit. The crew noted that at distances of 500 feet or greater, the base station siren was more useful to warn drivers intruding into the work zone whereas the WorkTRAX personal safety device was useful in alerting the workers in the activity area.

The crew also tested the range at which the base station was able to detect a speeding vehicle. It was observed that the AWARE Sentry unit was successful in detecting a vehicle approaching at 45 mph (exceeding the 35-mph speed threshold set) at approximately 500 feet. This distance was close to the maximum range specified by the manufacturer of 600 feet.

The last feature tested on the Sentry device was the foot pedal. It was observed that no matter the speeds of an approaching vehicle, the siren and PSDs would not activate if the foot pedal remained pressed. Once the foot pedal was released, the siren immediately activated if the approaching vehicle speed exceeded the set threshold. Further details of the general feedback and recommendations provided by the maintenance crew during the AWARE Sentry demonstration are presented in Table 4.6.

Table 4.6 AWARE Sentry – General Feedback and Observations from Maintenance Staff

	Maintenance Staff Feedback from the AWARE Sentry Training Session
Comments /Concerns:	• The crew liked the ability to alert both the drivers and the workers. • Concerns were raised about drivers with epilepsy given the brightness and flashing lights. • Better as an early warning system rather than at the flagging station given that most drivers do not slow/stop until they are close to the flagger. • One crew member did not want the pedal to be a momentary switch. Would most likely place a cone on the pedal (when needing traffic to proceed) due to flaggers moving around/directing/talking to drivers. The flagger would have to adjust their stance, keep balance, etc. One member did not like the idea of the pedal being wired/attached to the device. • Concerns were raised about the effectiveness of the WorkTRAX PSD to alert workers in high noise work zones even though the device provides haptic feedback which can be felt through clothing. • The device would be most useful at 25-30 mph thresholds. • The crew was impressed with the range of the system in detecting vehicles. • With the radio turned on inside the vehicle, the siren was slightly faint but audible. • Crew members liked that the siren shuts off automatically after the driver's speed is adjusted.
Recommendations:	• Remove the use of the app and instead set the configurations on the device manually. • Provide an option to dim the lights on the Sentry Box. • The option of a wireless remote for the flagger to manually control the alerts and sirens to warn the other crew members. • The option for the device to be held on a tripod for monitoring since some shoulders do not allow enough space to set up. • Increase the sound level of the siren.

4.4 TRAINING SESSION SURVEYS

At the end of the training sessions, survey questionnaires specific to each WZIA system were distributed to the crew members. The survey consisted of 19 questions divided into four sections relating to device effectiveness, deployment, durability, and sound distinctiveness. The survey questions were developed to capture the maintenance staff's perception of the effectiveness, practicality, and impressions of each WZIA system as an alert mechanism for active work zone use and in improving safety in work zones. The survey form is provided in Appendix C. The survey results from the training sessions are further discussed in Chapter 6 alongside results from the same survey also conducted after the active work zone testing sessions.

5 ACTIVE WORK ZONE TESTING

Chapter 5 presents the details of the active work zone testing conducted on various days with the trained Caltrans maintenance crews. Details of the observations and outcomes of active work zone testing are presented in the following sections.

5.1 ACTIVE WORK ZONE TESTING BACKGROUND AND DETAILS

The research team, in consultation with the Project Advisory Panel and the two trained Caltrans maintenance crews, identified a list of possible work zone locations for active work zone testing. Efforts were made to select different types of work zones to evaluate the selected WZIA systems in a variety of conditions. Two rounds of active work zone testing on six days were conducted during May and October of 2022. Based on the characteristics of each work zone location, the research team pre-assigned the best suited WZIA systems for testing at each location. On the day of testing, the research team provided a brief refresher on the systems to the crew. The research team then handed the devices over to the maintenance crew for deployment and use. Details of the active work zone locations, testing schedule, and other general work zone information are presented in Table 5.1, Table 5.2., and Table 5.3.

Table 5.1 Active Work Zone Locations and Testing Schedule

Day	Date	Time	Location	WZIA System	Type of Closure
1	May 16, 2022	8 AM – 2 PM	US Hwy 50 WB (between Mather and Bradshaw Interchanges)	Worker Alert System, Intellicone System	Shoulder Closure
2	May 17, 2022	8 AM – 12:30 PM	US Hwy 50 EB (near Eldorado Blvd. off ramp)	SonoBlaster, Single Sentry Beam	Lane Closure
3	May 18, 2022	5:30 AM – 10:30 AM	Highway 16 near Woodland	AWARE Sentry	Lane Closure, Flagging Operation
4	Oct. 24, 2022	8 AM – 11:30 AM	CA Hwy 113 in Robbins	Intellicone System, AWARE Sentry	Lane Closure, Flagging Operation
5	Oct. 26, 2022	8 AM – 11:15 AM	CA Hwy 113 & E Main St Interchange (NB On Ramp)	SonoBlaster, Single Sentry Beam	On Ramp Closure
6	Oct. 27, 2022	8 AM – 11:30 AM	CA Hwy 113 & E Gibson Rd Interchange (SB On Ramp)	Worker Alert System	On Ramp Closure

Table 5.2 Active Work Zone Testing Sites Detailed Information - 1

Work Zone Information	WAS/Intellicone System	SonoBlaster/Single Sentry Beam	AWARE Sentry
Location	US Hwy 50 WB	US Hwy 50 EB	Highway 16 near Woodland
Date:	05/16/2022	05/17/2022	05/18/2022
Time Start:	9 A M / 12:10PM	9 AM / 10 AM	6 AM
Time End:	12:05 PM / 1:45 PM	12:15PM	10:30 AM
No. of Lanes:	5	4	2
No. of Lanes Closed:	N/A	1	1
Work Zone Speed Limit (mph):	55	65	35
Weather description (Temperature, Wind):	85 °F, Sunny	90 °F, Sunny	95 °F, Sunny
Type of Work Zone:	T-10	T-13	T-13
Taper Length:	N/A	1,000 feet	N/A
Taper Cone Spacing:	N/A	75 feet	N/A
Work Area Length:	300 feet / 350 feet	4,700 feet	2,300 feet
Tangent Spacing:	N/A	500 feet	N/A

Table 5.3 Active Work Zone Testing Sites Detailed Information - 2

Work Zone Information	AWARE Sentry/Intellicone System	SonoBlaster/Single Sentry Beam	Worker Alert System
Location:	CA Hwy 113 in Robbins	CA Hwy 113 & E Main St Interchange	CA Hwy 113 & E Gibson Rd Interchange
Date:	10/24/2022	10/26/2022	10/27/2022
Time Start:	8 AM	8 AM	8 AM
Time End:	11:30 AM	11:15 AM	11:30 AM
No. of Lanes:	2	1	1
No. of Lanes Closed:	N/A	1	1
Work Zone Speed Limit (mph):	35	N/A	N/A
Weather description (Temperature, Wind):	60 °F, Sunny	63 °F, Sunny 12 mph winds	55 °F, Sunny
Type of Work Zone:	T-13	T-14	T-14
Taper Length:	50 feet	N/A	N/A
Taper Cone Spacing:	25 feet	N/A	N/A
Work Area Length:	450 feet	800 feet	600 feet
Tangent Spacing:	N/A feet	N/A feet	N/A

To evaluate the five selected WZIA systems in active work zone conditions, the data collection plans and forms from the previous research were revised in view of the methodology framework discussed in Chapter 3. Data were collected on:

- General Work Zone Information and Conditions,
- Deployment of Devices,
- Operation of Devices,
- Retrieval of Devices, and
- Miscellaneous Observations and Worker Survey/Feedback

The details of testing protocols, data collection plans and forms, and survey questionnaires are presented in Appendices B and C. The details of Caltrans standard plans for T-13 lane and T-14 ramp closures are presented in Appendix F.

5.2 DAY 1: US HIGHWAY 50 WESTBOUND

The Worker Alert System and Intellicone system were tested on Highway 50 Westbound near Sacramento, CA on shoulder closure operation to repair roadside fence. Details of the work zone are presented in Table 5.2. The work zone was located on a high-speed high-traffic segment of Highway 50 with five lanes in the direction of flow of traffic. The WAS trial started at 9:00 AM and ended at 12:05 PM, followed by the Intellicone system trial which started at 12:10 PM and ended at 1:45 PM. Figure 5.1 shows the general layout of the work zone along with the placement of various WZIA systems.

5.2.1 Setup and Deployment - WAS

During the WAS trial, three 33-foot sensor hoses and four alarm units were deployed, and seven PSDs were distributed to the workers. The sensor hoses were placed by the crew in a line parallel to traffic on the edge of closure, starting from the location of the shadow truck and downstream of the closure (Figure 5.2). It should be noted that while the recommendations for deploying the WAS pneumatic hoses suggested placing the hoses inside the closure diagonally to capture any intruding vehicles venturing into the closure, the crew preferred to deploy the hoses parallel to the traffic flow direction. The worker deploying the sensor hoses had to be reminded to turn on one of the sensor hoses, since he forgot to do so.

Figure 5.1 General Layout of Work Zone on US Highway 50 WB
(Source: Google Earth™)

Figure 5.2 Placement of WAS Pneumatic Hose

Two alarm units were placed on the shadow truck and the other two devices were placed on two work vehicles near the activity areas shown in Figure 5.3. The set up and deployment time for the devices was about 5 minutes. No physical requirements were identified for deploying the devices as they were very easy to set up.

Figure 5.3 Location of WAS Alarm Units on Vehicles Near Activity Area

5.2.2 Operation - WAS

During operation of WAS, five false alarms were recorded by the research team. Four of the five false alarms were triggered from the same worker through the worn PSD. Originally the worker had placed the PSD in a front vest pocket, however it was observed that while lifting the heavier equipment for the fence repair, the equipment pressed the button of the PSD which triggered the alarm units. After placing the PSD from the front vest pocket to the back pocket of the worker's clothing, the PSD activated every time the worker bent forward. One false alarm occurred due to a different worker accidentally stepping on one of the sensor hoses placed on the pavement. The research team observed that every time an alarm was triggered, the workers would immediately pay attention to the oncoming traffic to look for possible intrusions.

At the end of the trial, the research team manually triggered the WAS alarm to record the workers' reaction time. Video footage recorded during the event showed that the crew looked in the direction of the pneumatic hoses with a reaction time less than 1 second.

5.2.3 Retrieval - WAS

The retrieval of the WAS alarm units and hoses was quick, with workers carrying multiple devices in one hand. The workers forgot to turn off the PSDs, alarm units, and hoses after retrieval and were reminded to do so to preserve batteries.

5.2.4 Setup and Deployment - Intellicone

During the Intellicone trial, seven cone lamps and two Portable Site Alarms (PSAs) were deployed. Due to the limited space between the shoulder closure cones and various vehicles present on the shoulder (Figure 5.4), the Intellicone lamps were manually deployed by a worker, since it was not possible to safely deploy the lamps from the cone body truck (Figure 5.5).

Figure 5.4 Deployment of Intellicone Lamps with Limited Space between Closure and Presence of Work Vehicles

Figure 5.5 Deployment of Intellicone Lamps by Maintenance Worker

One of the PSAs was placed on the bed of a work vehicle and the second PSA was placed on a cone near the edge of the shoulder close to the activity area (Figure 5.6). Both PSAs connected to a cellular network within 2 minutes of being turned on.

Figure 5.6 Location of Intellicone PSA Deployment on Highway 50 WB Active Work Zone

5.2.5 Operation - Intellicone

During the operation of Intellicone system, no false alarms or issues were observed or recorded by the research team. The roadway section near the work zone had a speed limit of 55 mph; however, it was clear that traffic was moving slightly above the speed limit. No lamps were disturbed, or cones knocked over, even with heavy vehicles passing in close proximity to the cones.

At the end of the trial, the research team deliberately triggered the Intellicone system by knocking over a cone with a lamp to observe the workers' reaction time as shown in Figure 5.7. Four workers reacted immediately to the Intellicone System alarm by halting the fence repair work and looking around for the reason of activation. After it was realized to be a false positive alarm, the workers continued to work without resetting the PSAs. By not resetting the Intellicone PSAs and continuing to work after the alarm has triggered, the workers may have assumed one of the other workers would reset the devices.

Figure 5.7 Manual Activation of Intellicone to Observe Worker Reaction Time

5.2.6 Retrieval - Intellicone

At the end of the trial, one of the maintenance workers was able to retrieve all the Intellicone lamps and PSAs as shown in Figure 5.8. The retrieval of the Intellicone system (lamps and PSAs) was quick, with worker being able to carry multiple lamps in one hand as shown in Figure 5.8. However, the retrieval did require the worker to walk close to the traffic flow with possible exposure concerns.

Figure 5.8 Retrieval of Intellicone Lamps by Maintenance Worker

5.3 DAY 2: US HIGHWAY 50 EASTBOUND

The SonoBlaster and Intellicone Single Sentry Beam systems were tested in a work zone on Highway 50 Eastbound near Sacramento, CA on a lane closure operation to repair roadside fence. Details of the work zone are presented in Table 5.2. The work zone was located on a high-speed traffic segment of Highway 50 with three lanes of traffic. The SonoBlaster trial started after 9:00 AM and ended at 12:15 PM, while the Intellicone Single Sentry Beam system trial started at 10:00 AM and ended at 12:15 PM. Figure 5.9 shows the general layout of the work zone along with the placement of various WZIA systems.

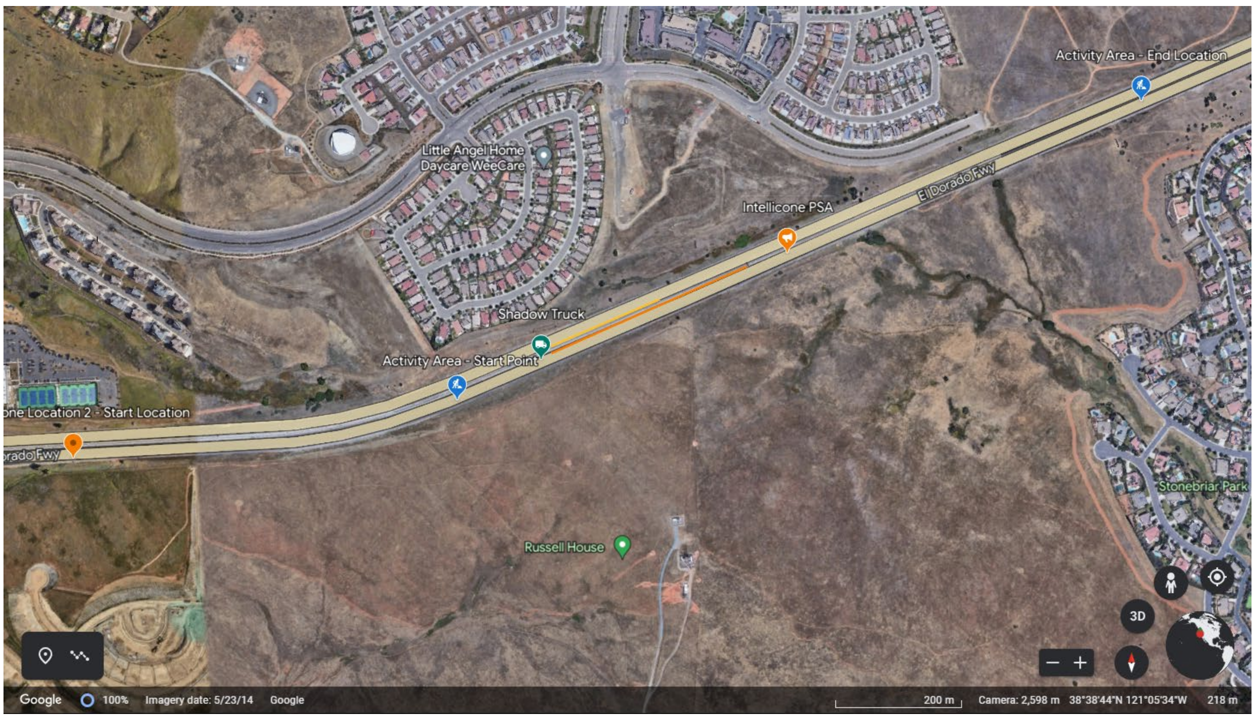


Figure 5.9 General Layout of Work Zone on US Highway 50 EB
(Source: Google Earth™)

The maintenance crew had originally planned to close down one of the on-ramps approximately 400 feet upstream of the start of the work zone due to visibility concerns for traffic on the on-ramp. The research team had initially intended for the maintenance crew to utilize the SonoBlaster in the ramp closure. However, after careful review by the crew supervisor in the field, the closure of the ramp deemed unnecessary given sufficient sight distance between the on-ramp and start of the work zone. Therefore, it was decided to use the SonoBlaster in the work zone itself.

5.3.1 Setup and Deployment - SonoBlaster

The SonoBlaster mounted cones were deployed from front mounted Truck Mounted Attenuators (TMA) vehicle as shown in Figure 5.10. The SonoBlaster cones were deployed at a spacing of approximately 50 feet apart, with the unit inside of the closure and the alarm horn facing parallel to traffic.

There were immediate safety and exposure concerns realized by the crew and the research team as the SonoBlaster mounted cones were being deployed in this particular work zone given the proximity of high-speed traffic (Figure 5.11). Therefore, further deployment of SonoBlaster cones was halted after three cones were deployed. Another concern exacerbating the exposure issue was that the worker needed to kneel down to unlock the SonoBlaster device after placing the cone on the ground. It should be noted, however, that the exposure concerns were primarily due to the high-speed traffic conditions.

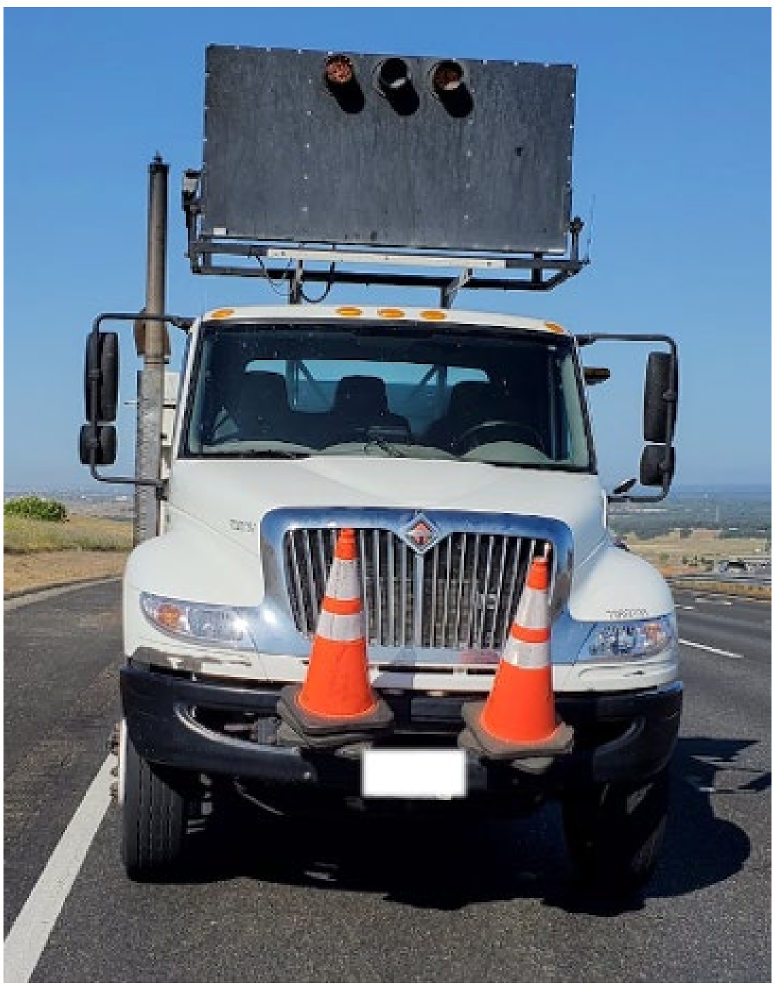


Figure 5.10 SonoBlaster Deployment from Front Mounted TMA Vehicle

Figure 5.11 Maintenance Worker Deployment of SonoBlaster in Work Zone

5.3.2 Operation - SonoBlaster

After limited deployment of three cones, the operation of the SonoBlaster system did not require any involvement from the maintenance crew. No false alarms or other issues were observed during the trial. It was noted that passing high-speed heavy vehicles did not affect the cones or result in accidental trigger of the SonoBlaster alarm.

5.3.3 Retrieval - SonoBlaster

At the end of the trial, a single worker was able to lock (disarm) the SonoBlaster units before retrieving the cones without any issues.

5.3.4 Setup and Deployment – Single Sentry Beam

During the Intellicone Single Sentry Beam trial, one device was deployed in the work zone near the shoulder inside the closure with the laser facing perpendicular to oncoming traffic as shown in Figure 5.12. The detection range of the laser device was configured to approximately 22 feet, which was the distance from the deployment location to the edge of the closure. One Intellicone PSA was deployed onto a maintenance vehicle that followed the maintenance workers as they made their way downstream in the activity area.

It should be noted that the total weight of a single unit with battery was approximately 45 lbs.; therefore, walking around with a unit for deployment in a work zone may not be feasible. In this trial, the unit was transported to the work zone and offloaded from the back of a truck at the point of deployment.

Figure 5.12 Location of Single Sentry Beam Deployment inside the Work Zone

5.3.5 Operation – Single Sentry Beam

The operation of the Intellicone Single Sentry beam did not require any involvement from the maintenance crew. No false alarms were observed during the trial, primarily due to the positioning of the laser device behind a vehicle that was following the workers in the activity area. At the end of the trial, the research team deliberately triggered the Single Sentry beam alarm to observe the workers' reactions. Five workers leisurely turned toward the direction of the laser device. The lack of urgency observed from the workers' reaction may have been attributed to the fact that the workers had ended working and it was the end of the workday.

5.3.6 Retrieval – Single Sentry Beam

The retrieval of the Single Sentry beam device after the trial was easy and quick as only one switch needed to be turned off before the device was loaded on to the back of a truck for transport. As noted earlier, given the weight of the device, maintenance crew would have to be careful about transport and deployment of the system in the work zone.

5.4 DAY 3: HIGHWAY 16 NEAR WOODLAND

The AWARE Sentry system was tested in a flagging operation on a two-lane rural highway near Woodland, CA during pavement repair and rehabilitation work. Two flaggers, one at each end of the work zone, were present with one lane closed down during the duration of the trial. The trial started at 6:00 AM and ended at 10:30 AM. Details of the work zone are presented in Table 5.2. The speed limit on the two-lane highway was 55 mph. One end of the work zone was located at the point of a horizontal curve with a diverging side road splitting off as shown in Figure 5.13. Figure 5.13 also shows the general layout of the work zone along with the placement of various WZIA systems.

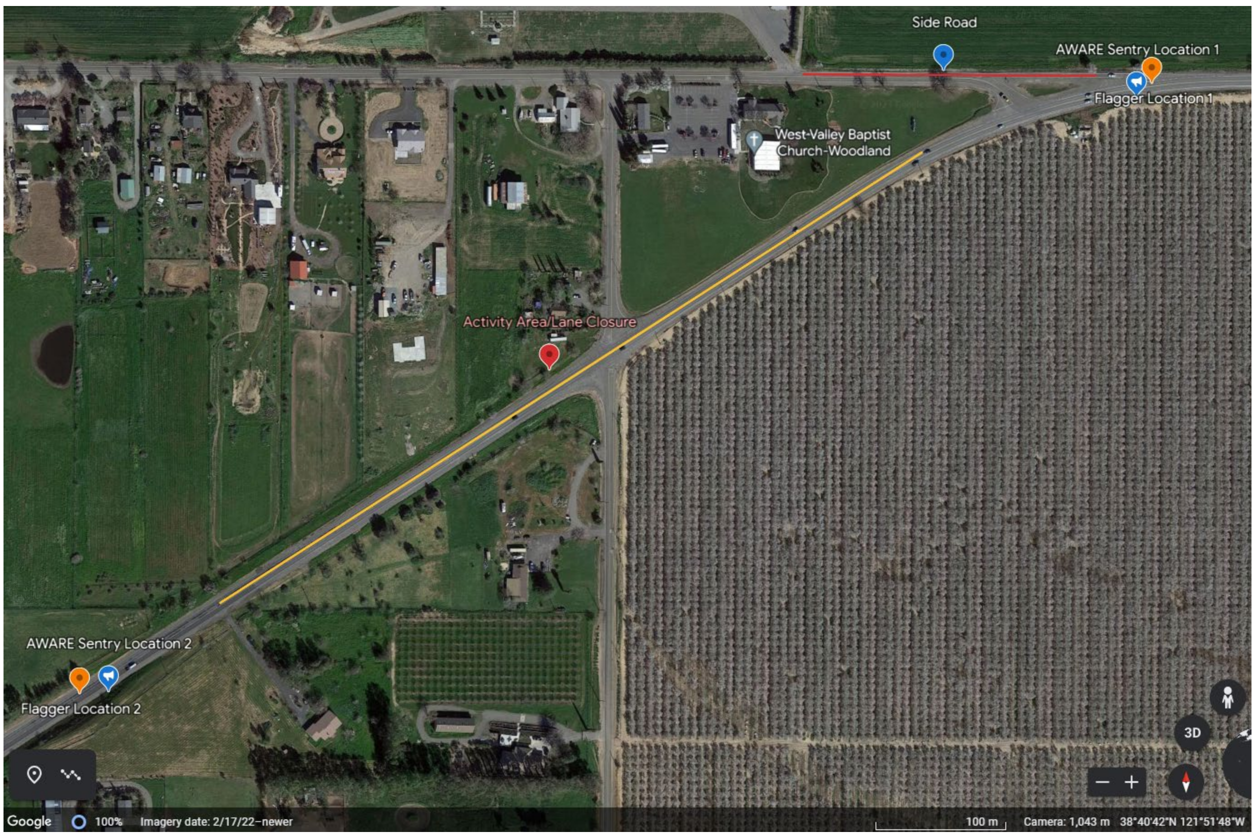


Figure 5.13 General Layout of Work Zone on US Highway 16
(Source: Google Earth™)

5.4.1 Setup and Deployment – AWARE Sentry

Although the research team had procured two AWARE Sentry units, it was decided to deploy one unit at a time at each flagger location and use the second system as a backup. This was also done to ensure the research team was always present while observing the operation of the AWARE Sentry unit at each location. Upon arriving in the work zone, it was noticed that the flagger at location 1 (as shown in Figure 5.13) was not part of the crew during the training sessions. The flagger was given a quick overview of the AWARE Sentry unit operation and use before deployment at “Flagger Location 1” as show in Figure 5.13 and Figure 5.14. Three of the four WorkTRAX PSDs were distributed to the workers, while the research team retained one to track alarm triggers. About halfway through the trial, the AWARE Sentry device was moved to the “Flagger Location 2” as shown in in Figure 5.13 on the other size of the work zone.

At deployment, the AWARE Sentry speed threshold was set at 35 mph in consultation with the maintenance supervisor in the work zone as that was the speed limit set for vehicles traversing through the work zone.

Figure 5.14 AWARE Sentry Deployment at Flagger Location on Highway 16 near Woodland, CA

5.4.2 Operation – AWARE Sentry

During the AWARE Sentry trial at the first flagger location, it was clear that the 35-mph speed threshold was too low because alerts were being generated with almost every approaching vehicle. A temporary sign placed approximately 400 feet upstream of the flagger location 1 warned drivers to slow down from 55 mph to 35 mph; however, it was clear that vehicles were not slowing down as quickly as intended. Furthermore, the AWARE Sentry unit detected vehicles and their speeds at a distance of 500 feet when vehicles had not yet started to slow down. Figure 5.15 shows a vehicle detected by the AWARE Sentry system traveling at 45.54 mph 519.49 feet away. Figure 5.16 shows another vehicle detected by AWARE Sentry that was traveling 38.63 mph 249.67 feet away but obscured by a vehicle waiting in queue. This meant that the AWARE system was able to detect vehicles without a direct line of sight. Given higher than expected approaching vehicle speeds, the speed threshold on the AWARE Sentry unit was raised from 35 mph to 45 mph.

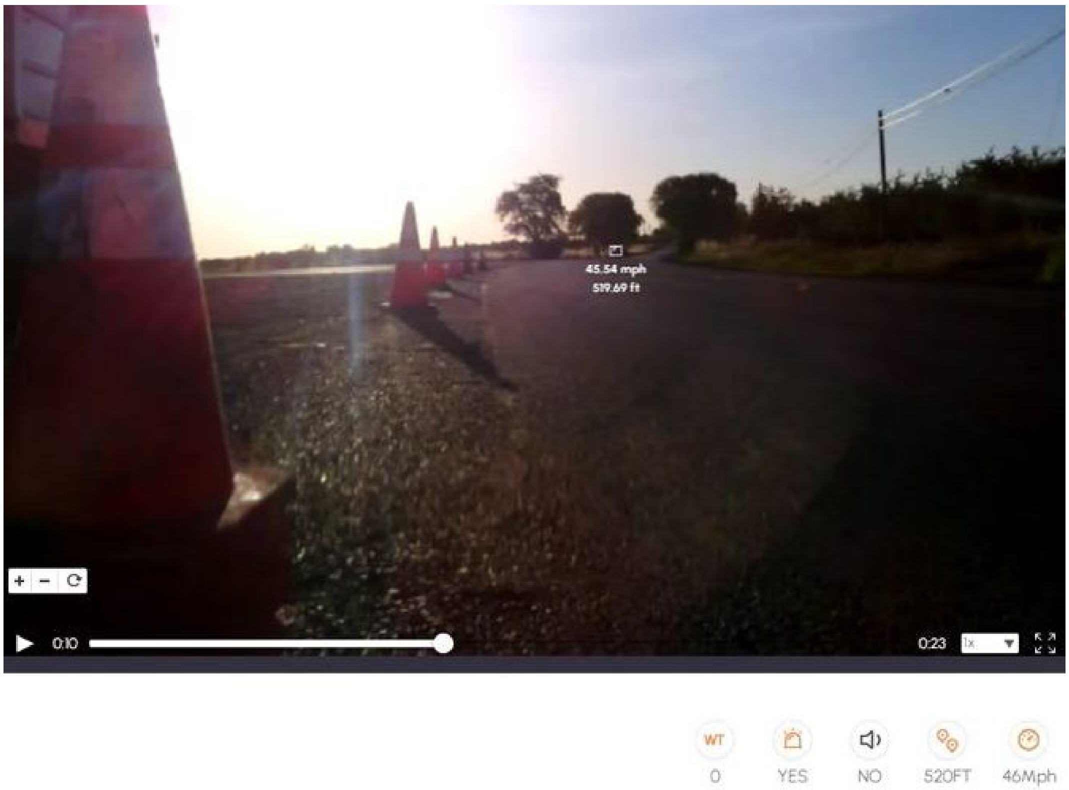


Figure 5.15 Vehicle Detection by AWARE Sentry at Greater than 500 feet Distance at Flagger Location 1

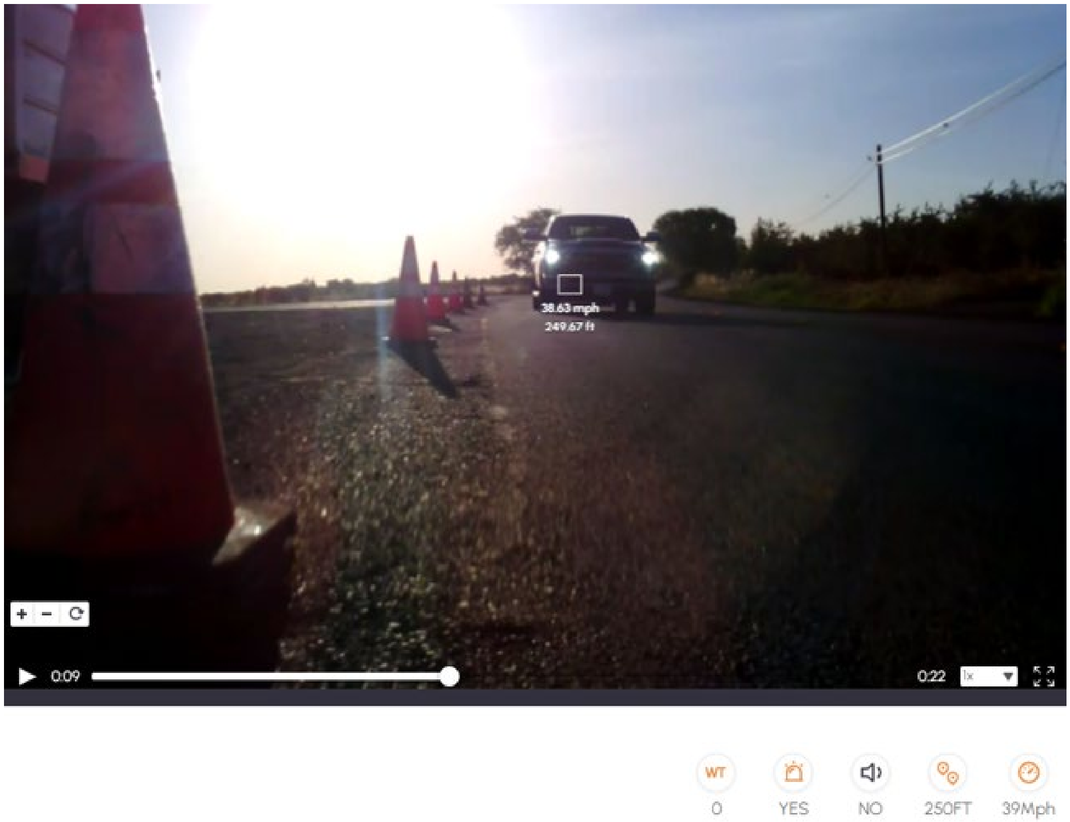


Figure 5.16 Vehicle Detection by AWARE Sentry Obscured by Another Vehicle in Queue at Flagger Location 1

Another issue observed at flagger location 1 was the presence of a diverging side road as shown by the red arrow in Figure 5.17. Some vehicles continued down the diverging road at normal speeds, resulting in the AWARE Sentry unit sounding an alarm (1) due to excessive speed or (2) detecting a vehicle coming out of the queue in front of the flagger. Figure 5.18 shows a screenshot from the video recorded due to one of the alarms where the AWARE Sentry unit detected a vehicle traversing on the diverging road at 35.01 mph and 98.10 feet away while there was a queue of vehicles before the flagger. It can be assumed the AWARE Sentry device was mistaking the vehicles traveling down the diverged road for vehicles driving out of the queue, as was tested during the training session at the META facility.

Figure 5.17 Diverging Side Road at Flagger Location 1 on Highway 16 near Woodland, CA

Figure 5.18 Screenshot of Detected Vehicle Traversing on Diverging Roadway near Flagger Location 1

Midway through the trial, the AWARE Sentry unit was shifted from flagger location 1 to flagger location 2 at the other end of the work zone. At flagger location 2, the initial speed threshold was kept at 35 mph to observe the performance of the system. After a few detections, the speed threshold was changed to 25 mph to observe the performance of the system under varying conditions. All detections at flagger location 2 were successful based on the speed thresholds set. No other issues were observed as this section of the approach to the work zone was a straight tangent section without any horizontal curves or diverging roadways. Figure 5.19 shows a vehicle detected by the AWARE Sentry system traveling at 29.8 mph 582 feet away, which was the furthest detection of all the trials observed on the day. It is interesting to note that at flagger location 2, one false alarm was generated when a vehicle travelling in the opposing direction was reflected off of the front of a semi-truck waiting in queue and was detected by AWARE Sentry as a moving vehicle exceeding the speed threshold of 25 mph set during that trial.

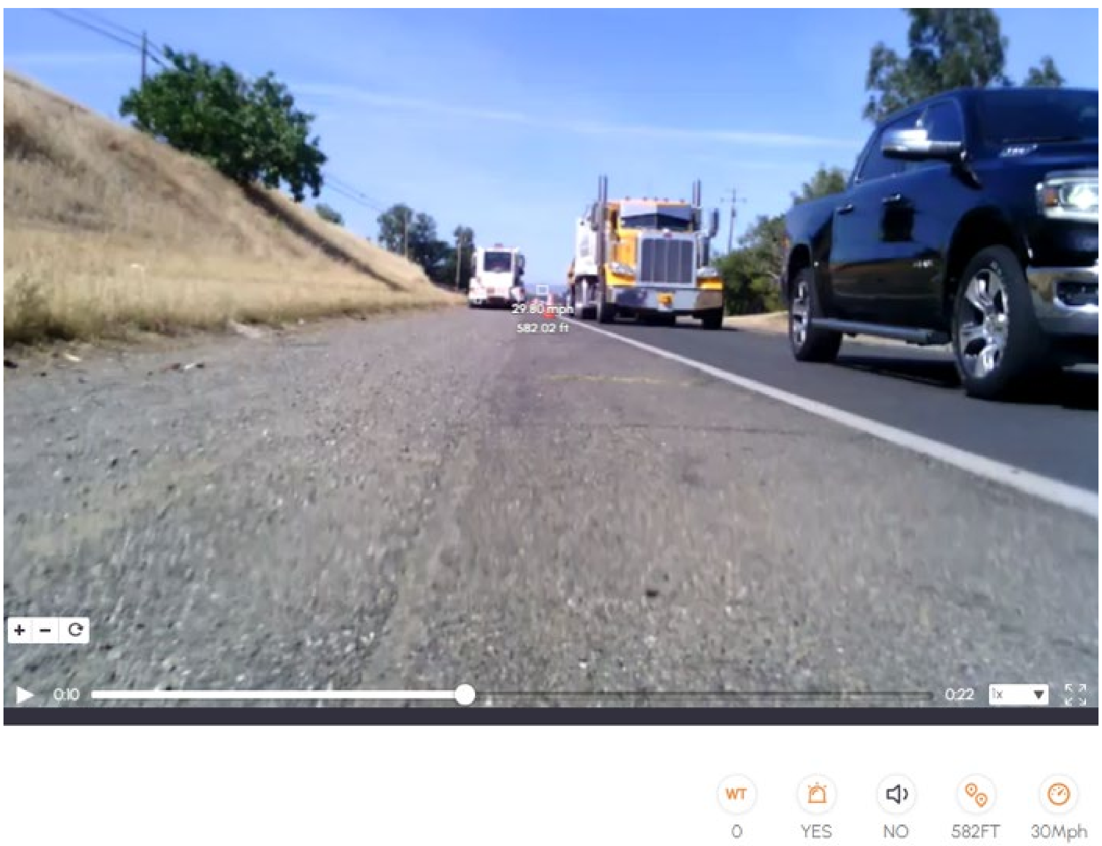


Figure 5.19 Vehicle Detection by AWARE Sentry at Flagger Location 2

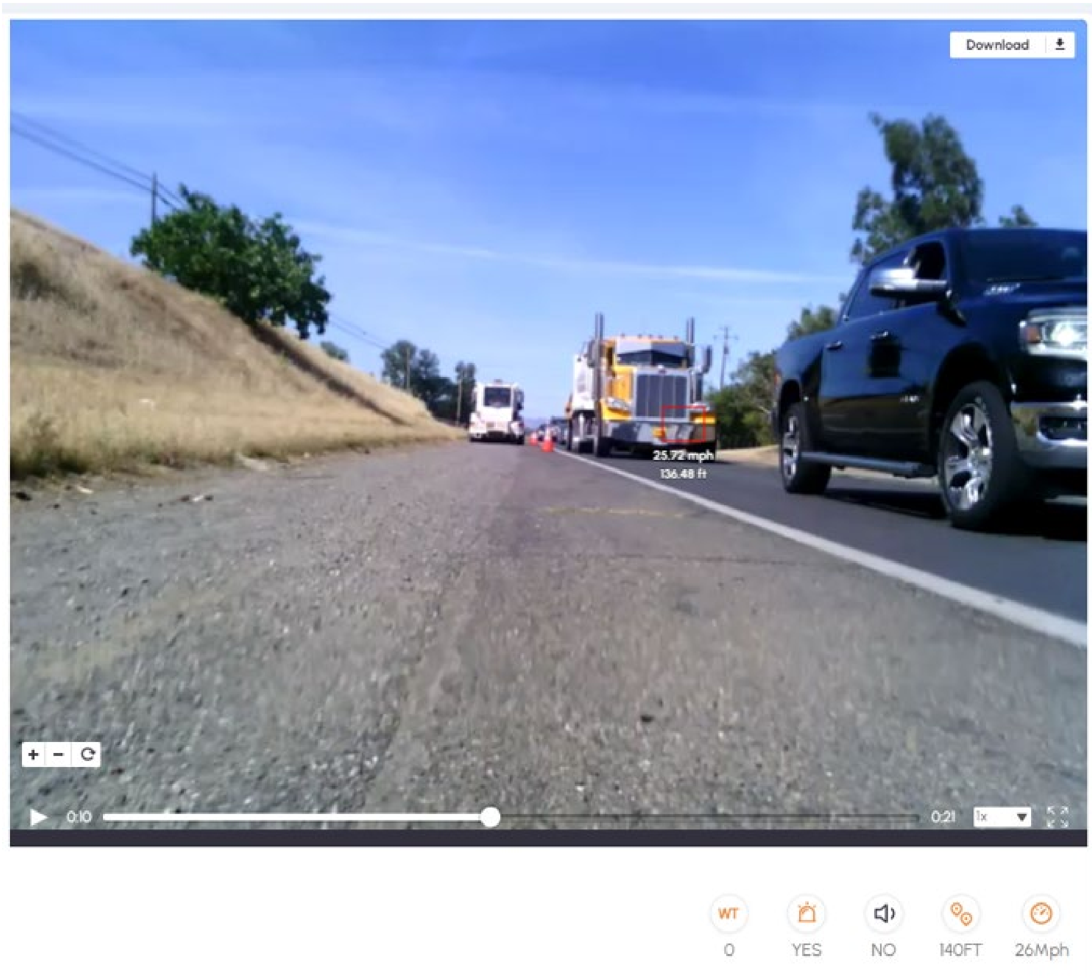


Figure 5.20 False Alarm Generated by AWARE Sentry at Flagger Location 2

5.4.3 Retrieval – AWARE Sentry

At the end of the trial, the retrieval of the AWARE Sentry system was quick as the system was shut down and loaded on to a truck for transport. No issues were observed.

5.5 DAY 4: CA HIGHWAY 113 IN ROBBINS

The AWARE Sentry system and the Intellicone system were tested at lane closure work zone on CA Highway 113 near Robbins, CA during a pavement crack sealing operation. The research team met with the maintenance crew at the Woodland maintenance yard near Woodland, CA at 8:00 AM. The crew were given a quick refresher on both the systems as shown in Figure 5.21. One of the AWARE Sentry units did not start properly and was not operational. It should be noted that both the AWARE Sentry units procured were not new systems as noted earlier in Chapter 3. Therefore, the research team proceeded with the use of a single AWARE Sentry system.

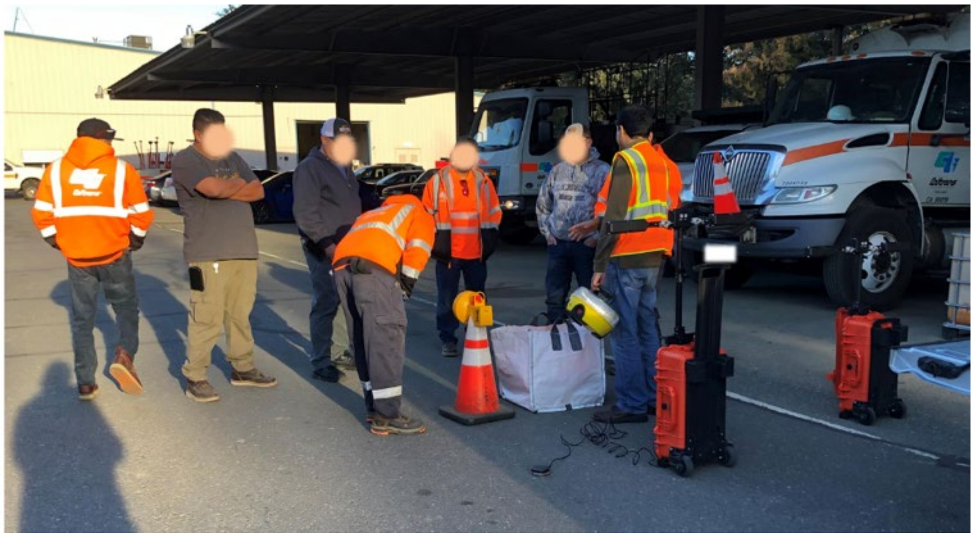


Figure 5.21 Review of AWARE Sentry and Intellicone Systems with Maintenance Crew at Caltrans Maintenance Yard

After the quick review, both the systems were handed over to the crew for transport to the work zone on CA Highway 113 near Robbins, CA during pavement crack sealing operation. The work zone was located on a section of CA Highway 113 which is a two-lane road with shoulders. Details of the work zone are presented in Table 5.2. The speed limit on the two-lane highway was 55 mph. Figure 5.22 shows the general layout of the work zone along with the placement of the two WZIA systems. It should be noted that there was a turn pocket in each direction, in the middle of the work zone, which was kept open for vehicles. The trial started at around 10:00 AM when the maintenance crew shut down one of the two lanes to set up a flagging operation, and was ended at 11:32 AM.

Figure 5.22 General Layout of Work Zone on CA Highway 113
(Source: Google Earth™)

5.5.1 Setup and Deployment – Intellicone

At around 10:05 AM the Intellicone lamps and Portable Site Alarms (PSA) were set up and deployed on the cones along the work zone. After placing the cones, the crew deployed 10 Intellicone lamps from the cone body truck on every other cone along the length of the work zone, each lamp spaced about 25 feet from the next, as shown in Figure 5.23. This was done to provide coverage throughout the work zone and because the cones were placed very close to each other.

Figure 5.23 Deployment of Intellicone Lamps in Active Work Zone on CA Highway 113

Two PSAs were initially deployed by the maintenance crew on cones along the closure; one on the cone before the turn pocket, the other on a cone at the end of the work zone. Upon further discussion with the crew supervisor, one of the cones with the PSA was moved to the shoulder to avoid being hit by turning vehicles, as shown in Figure 5.24. The other PSA was moved onto the crack filling machine to be closer to the group of workers in the work zone.

Figure 5.24 Placement of Intellicone PSA near Shoulder of the Work Zone

The set up of the devices was quick and relatively easy, taking about 15 minutes to deploy. Most of the 15 minutes was spent determining the deployment locations of the Intellicone System within the work zone. One of the PSAs connected to cellular data within 5 minutes. However, the second PSA was not able to connect to the cellular network for unknown reasons. Nevertheless, this did not impede the operation of the Intellicone System as the lamps and PSA connect using a radio signal and can function properly even without a cellular connection. However, certain additional features, e.g., the use of online dashboard to track system functions and data logging, may not work without the cellular network connection.

5.5.2 Operation – Intellicone

At the beginning of the trial, both Intellicone System PSAs activated three times within a span of 6 minutes. It was determined that the false alarms were triggered by the workers moving the cones to make space for the crack seal equipment vehicle moving through the closure. While the crews were instructed that any movement of the cones after deployment of the Intellicone lamps will trigger an alarm, this was ignored by the crew. Once the crew were informed of the reason for the false alarm, the Intellicone system was temporarily turned off and the cone locations were adjusted to make space for the maintenance vehicle moving through the closure. After the adjustments, no further false alarms occurred during the trial.

Towards the end of the trial, one of the lamps was intentionally knocked over for manual activation to observe the workers' reactions. Upon activation of the alarm, some of the workers immediately looked in the direction of the PSA without any visible delay, while others were also alerted to the sound of the alarm given the high intensity of the alarm sound level. The noise levels in the work zone were particularly high given the presence of a leaf blower and the crack filling equipment.

5.5.3 Retrieval – Intellicone

There were no issues noted with the retrieval of the Intellicone lamps and PSAs. The retrieval of the lamps and PSAs were quick and easy. Some maintenance workers collected multiple lamps at once as shown in Figure 5.22.

Figure 5.25 Retrieval of Intellicone System at the end of Trial

5.5.4 Setup and Deployment – AWARE Sentry

The AWARE Sentry system was deployed at around 10:20 AM at "Flagger Location 1" as shown in Figure 5.22 and Figure 5.26. All four WorkTRAX PSDs were distributed to four workers. The threshold speed for the AWARE Sentry device was set to 35 mph using the app dashboard. The set up and deployment of the AWARE Sentry device was about 10 minutes, most of that time being spent distributing the PSDs.

Figure 5.26 Location of AWARE Sentry Deployment at Flagger Location 1

5.5.5 Operation – AWARE Sentry

The AWARE Sentry system trial proceeded with the speed threshold set at 35 mph for the duration of the trial. One of the issues observed in the previous AWARE Sentry trial was also encountered at this trial, which related to the wired base pedal required to active/deactivate the base unit. The worker could not simultaneously place a cone to close down the lane while activating the foot pedal connected through a wire to the base unit. This issue was noted and would be shared with the manufacturer. During the trial, it was noted that the vehicle detection range of the AWARE system was accurate as per the manufacturer specifications, since the alarm triggered every time an approaching vehicle's speed exceeded the set threshold. There was also clear indication of vehicles reducing speeds when the AWARE alarm activated with flashing lights pointed towards the drivers. Figure 5.27 shows an example of a vehicle detection by AWARE Sentry system at approximately 520 feet with a speed of 38.95 mph.

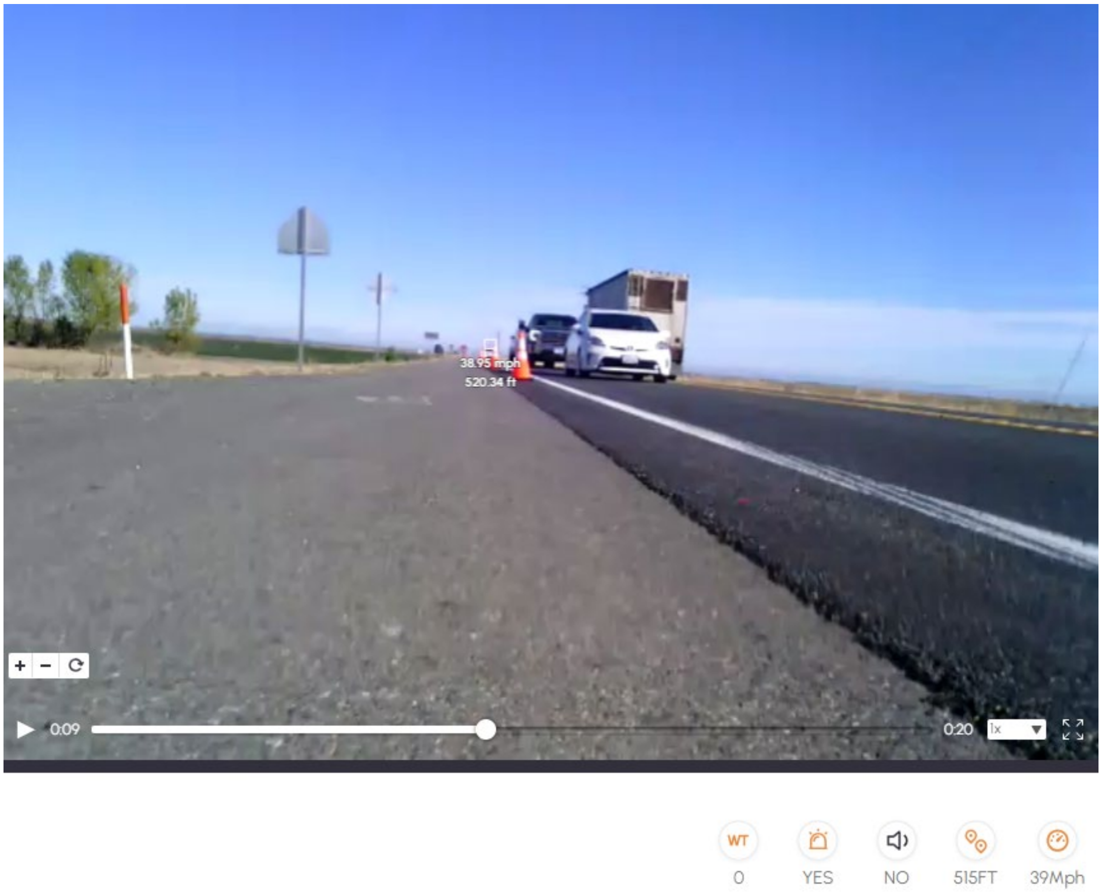


Figure 5.27 AWARE Sentry Detection of Vehicle at Flagger Location 1

During the trial, two heavy vehicles turned into the closed lane after passing the flagger at flagger location 1, in between the spacing of the deployed cones (Figure 5.28 and Figure 5.29). The vehicles intended to make a right turn at one of the turn pockets located in the middle of the work zone. The vehicles were moving at a very slow speed and were directed out of the closure by the supervisor. None of the alarms were activated, since the vehicles crossed into the closure after passing the AWARE Sentry system and none of the Intellicone lamps were hit. After this incident, the maintenance supervisor placed additional cones and reduced the spacing between the cones to prevent further intrusions.

Figure 5.28 Two Heavy Vehicles Intruding into the Work Zone near Flagger Location 1

Figure 5.29 Two Heavy Vehicles Exiting the Work Zone After Intrusion

5.5.6 Retrieval – AWARE Sentry

At the end of the trial, the AWARE Sentry base unit and WorkTRAX PSD were retrieved from the workers and placed in a truck without any issues observed.

5.6 DAY 5: CA HIGHWAY 113 & E MAIN ST INTERCHANGE (NB ON-RAMP)

The Intellicone Single Sentry Beam and SonoBlaster systems were tested at the closure of the Northbound ramp of CA Highway 113 and East Main St. interchange near Woodland, CA, during a pavement crack sealing operation. The research team met with the maintenance crew at the Woodland maintenance yard near Woodland, CA at 7:30 AM. The crew were given a quick refresher on both the systems at the maintenance yard as shown in Figure 5.30 and Figure 5.31. After the review, eight cones with pre-installed SonoBlaster devices and two Intellicone Single Sentry Beam units were handed over to the crew for transport to the work zone.

The work zone was located on an on-ramp at the interchange of CA Highway 113 and East Main St. near Woodland, CA. Details of the work zone are presented in Table 5.2. Figure 5.32 shows the general layout of the work zone along with the placement of the two WZIA systems. The Single Sentry Beam and SonoBlaster trials started at around 9:00 AM and ended at around 11:15 AM.

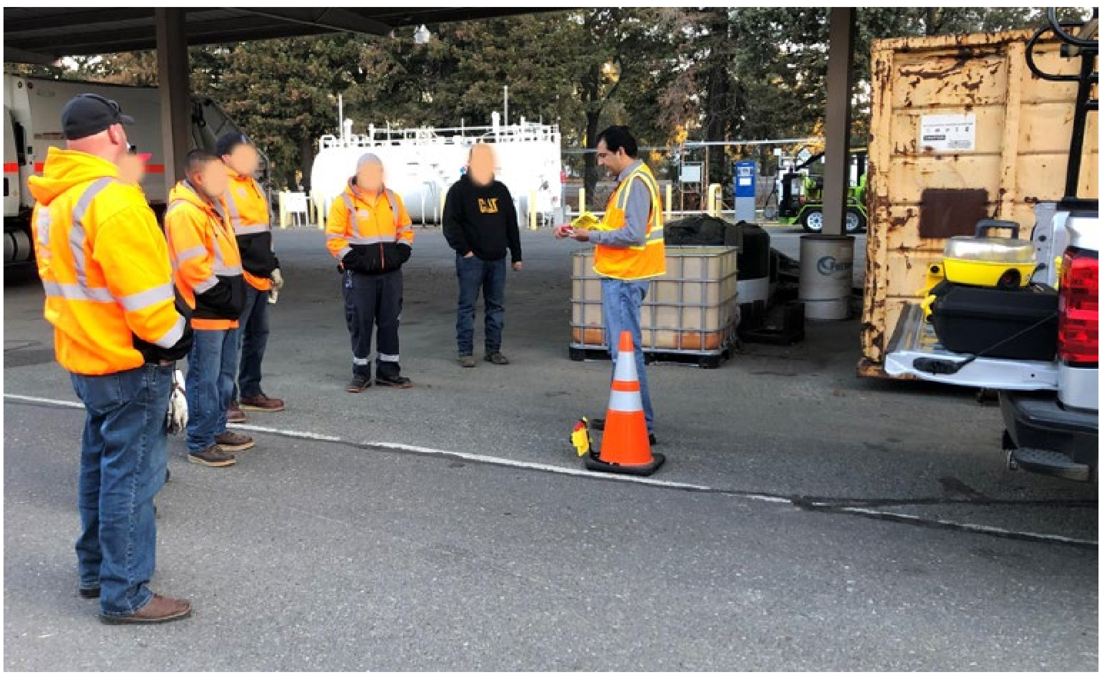


Figure 5.30 Review of SonoBlaster System with Maintenance Crew at Caltrans Maintenance Yard

Figure 5.31 Review of Intellicone Single Sentry Beam System with Maintenance Crew at Caltrans Maintenance Yard

Figure 5.32 General Layout of Ramp Closure at CA Highway 113 and E Main St.
(Source: Google Earth™)

5.6.1 Setup and Deployment – Single Sentry Beam

At 9:15 AM, both units of the Single Sentry Beam were deployed at the shoulder of the closed on-ramp lane with the laser detection range set equal to the width of the lane. One Laser device was deployed by the supervisor, between the ramp closure barrier at the on-ramp entrance behind the shadow truck. This device was deployed to detect any pedestrians that may try to enter the closure, as shown in Figure 5.33. The second Single Sentry Beam unit was deployed inside the closure between the location of the shadow truck and the workers' activity area to detect vehicle intrusions at the start of the on-ramp. Two Intellicone PSAs were set up and placed onto the crack filling machine as shown in Figure 5.35 either side of the vehicle. The set up and deployment time for both the Single Sentry Beam and Intellicone PSAs was less than 5 minutes, with both PSAs connecting to cellular network within 2 minutes.

Figure 5.33 Deployment Location of Single Sentry Beam Unit Behind Shadow Truck

Figure 5.34 Deployment of Single Sentry Beam within Closure on On-Ramp

Figure 5.35 Location of Intellicone PSA Deployment on Maintenance Vehicle

5.6.2 Operation – Single Sentry Beam

As the crack sealing work continued forward in the work zone, one worker moved the Single Sentry Beam unit, placed between the shadow truck and the workers further along the closure, maintaining an approximate distance of 75 feet. The alarm was not activated during this movement because the laser was not breached. The maintenance crew was concerned that the Single Sentry Beam unit behind the shadow truck may not operate because it did not have a clear line of sight with the Intellicone PSA. Therefore, the research team deliberately activated the Single Sentry Beam unit to check the connection status, which was successful despite no clear line of sight to the alarm units. During the trial, four false alarms were observed, details of which are as follows:

- 9:17 AM – false alarm detected when crew member walked within the Laser detection range when placing the SonoBlaster cone on taper parallel to closed lane
- 9:44 AM – false alarm detected when worker accidentally walked through the laser detection range while walking in the closure
- 10:49 AM – false alarm detected when worker accidentally walked through the laser detection range

Towards the end of the trial, the research team deliberately triggered the alarm to observe the workers' reactions. Three of the workers immediately turned toward the direction of the laser to look for the source of the alarm. Another visible worker cleaning debris parallel to the closed lane looked toward the laser in under 2 seconds, about 160 feet away from the Single Sentry Beam location.

5.6.3 Retrieval – Single Sentry Beam

At the end of the trial before the Single Sentry Beam units were retrieved, the research team conducted a quick range test at the request of the crew supervisor in the field. Both Intellicone PSAs activated their alarms after the laser was triggered at a distance of 200 feet and a clear line of sight. However, the alarm was not successfully triggered at a distance of 225 feet. It should be noted that this range was higher than what was observed during the training sessions (175 feet) but less than the manufacturer specified range of 246 feet.

5.6.4 Setup Up and Deployment - SonoBlaster

At 9:17 AM, six preinstalled SonoBlaster units were deployed in the on-ramp closure at the start of the ramp entrance. The crew supervisor placed the SonoBlaster-installed cones by hand from the back of a truck parked inside the closure. Although the cones were placed 25 feet apart, the supervisor decided to place the SonoBlaster-installed cones after every second cone (2 cones apart) to provide maximum coverage at the beginning of the ramp closure. The cones were originally placed with the horns facing into the opposing lane; however, this was later corrected so the horns were pointing in the direction of the activity area and the maintenance workers as shown in Figure 5.36.

Figure 5.36 Location of SonoBlaster Deployment in On-ramp Closure

All devices were successfully unlocked and deployed with no issues. The set up and deployment time of all six SonoBlaster units was about 10 minutes, with most of the time spent determining device placement within the work zone.

5.6.5 Operation - SonoBlaster

The operation of the SonoBlaster system proceeded without any issues or false alarms during the trial.

5.6.6 Retrieval - SonoBlaster

At the end of the trial, the workers successfully locked the SonoBlaster devices before retrieving them and placing them in the back of a truck for transport. No issues were observed during the retrieval process.

5.7 DAY 6: CA HIGHWAY 113 & E GIBSON RD INTERCHANGE (SB ON RAMP)

The WAS was tested at the closure of the Northbound ramp of CA Highway 113 and East Gibson Road interchange near Woodland, CA, during a pavement crack sealing operation. The research team met with the maintenance crew at the Woodland maintenance yard near Woodland, CA at 8:00 AM. The crew were given a quick refresher on the system at the maintenance yard as shown in Figure 5.37. During the review, the crew discussed strategies on most effective placement of the pneumatic sensor hose above the ground by inserting it in the top of the cone or tying it around the top of the cone as shown in Figure 5.38. After the review, the WAS was handed over to the crew and transported to the work zone.

The work zone was located on an on-ramp at the interchange of CA Highway 113 and East Gibson Road near Woodland, CA. Details of the work zone are presented in Table 5.2. Figure 5.39 shows the general layout of the work zone along with the placement of the WAS. The WAS trial started at around 9:00 AM and ended at around 11:25 AM.

Figure 5.37 Review of WAS with Maintenance Crew at Caltrans Maintenance Yard

Figure 5.38 Maintenance Crew Discussion on WAS Sensor Hose Placement

Figure 5.39 General Layout of Ramp Closure at CA Hwy 113 and E Gibson Rd.
(Source: Google Earth™)

5.7.1 Setup and Deployment – WAS

During the trial, six WAS alarm units, two pneumatic sensor hoses, and six PSDs were deployed. Two alarm units were placed on the equipment hauling vehicle and four alarm units were placed on the crack filling machine, as displayed in Figure 5.40 and Figure 5.41.

Figure 5.40 Placement of WAS Alarm Units on Side of Equipment Vehicle

Figure 5.41 Placement of WAS Alarm Units on Rear of Equipment Vehicle

Two 30-foot pneumatic hoses were deployed by a single worker. The first hose was deployed on the left pavement marking, parallel to the road between the ramp closure barricade and the shadow truck; the second sensor was wrapped around one of the ramp closure barriers (Figure 5.42). The second hose was placed in the gap between the front of the shadow truck and the island at the entrance to the on-ramp, with the hose sensor placed on the ground (Figure 5.43).

Figure 5.42 Location of First WAS Hose Deployment

Figure 5.43 Location of Second WAS Hose Deployment

Six PSDs were distributed to the workers: four at the start of work and two at 9:40 AM (when two additional workers arrived at the work zone). The research team kept two PSDs. The set up and deployment time for the WAS units, hoses and PSDs was less than 5 minutes.

5.7.2 Operation – WAS

During the WAS trial, the pneumatic hoses remained at the ramp entrance while the alarm units progressively moved further away from the hoses as the crack filling work moved forward. However, given the horizontal curvature of the ramp, the progressive increase in the distance between the alarm units and the pneumatic hoses was less relative to that on a tangent/straight section of roadway; ensuring that the alarm units were never out of range of the sensor hoses. This was confirmed with a deliberate activation of the alarm at a distance of 175 feet from the sensor hose, which was successful. The workers were pre-warned of the activation. A second activation at a distance of 335 feet between the hoses and WAS units was also conducted, which was successful. It should be noted that this range was much larger than the 225-foot range observed during closed-to-traffic trials. Another deliberate activation was conducted at 9:51 AM to observe workers' reactions. Two visible workers immediately looked up from their work despite considerable noise from equipment and traffic in the work zone. There were five false alarms that occurred during the trial that are detailed as follows:

- 9:40 AM – Two incoming workers were given the PSD, one of which accidentally activated as he was placing it in his pocket.
- 9:52 AM – False alarm (unknown reason, although a pedestrian was spotted crossing the street nearby the hoses and could have stepped on one of the active hoses).
- Twice at 10:22 AM – One worker accidentally activated the PSD when reaching into his pocket, causing back-to-back triggers.
- 11:00 AM – supervisor entering the work zone triggered the alarm to test whether it was working, at a distance of 200 feet from the alarm units.
- 11:12 AM – A worker accidentally triggered the PSD.

5.7.3 Retrieval – WAS

The retrieval of the WAS units was quick, with the supervisor carrying two units, one in each hand, and two other workers carrying one unit each. No issues retrieving the units and the pneumatic hoses were observed.

5.8 SUMMARY OF ACTIVE WORK ZONE TESTING OUTCOMES

5.8.1 Worker Alert System Testing Outcomes

The testing of WAS at two active work zones revealed several important observations. Overall, the deployment of WAS was easy and quick with very short set up time without any issues. The ability to deploy multiple pneumatic hoses that can provide continuous coverage in parts of the work zone provided additional flexibility to the maintenance crew to target vulnerable spots and locations in a closure. Furthermore, moving the hoses after deployment to new location depending on changing conditions or observations is also possible, easy, and without any issues. The alarm unit includes a magnet which allows it to be attached to a vehicle near the workers inside the closure. While a single WAS alarm unit may not be sufficiently loud, the ability of hoses to connect with multiple alarm units ensured the alarm sound was loud enough to be heard, despite high noise levels from equipment and traffic. The WAS is one of the few systems that offers a PSD with audio and haptic alarm. As such, individual workers in a work zone can be alerted to any intruding vehicles. The PSD alarm (audio and haptic) were found to be effective during the active work zone trials. The WAS utilizes AA and AAA batteries for operation; hence no real issues were observed with power source availability. The cost of the system is moderate in comparison with other systems procured during this research.

Given the maximum range of 225 feet for reliable connection between the hoses and the alarm units, the system requires multiple hoses and alarm units to be deployed to provide adequate coverage in larger work zones. Otherwise, workers may not be in range of a hose if the alarm unit deployed on a vehicle moves away from hoses. Redeploying the hoses in range of the alarm units may disrupt the workflow of the maintenance workers and increase the possibility of maintenance staff forgetting to redeploy the hoses, leaving a gap in work zone coverage. During closed-to-traffic-condition testing, the research team observed that the WAS performed optimally when the alarm units were placed at least 4 feet above the ground; or the sensor on the hose was some feet above the ground. As such, given the instructions to the workers, the workers instinctively tried to stick the hose sensor on top of a cone or tried to tie it to the top of the cone, sometimes unsuccessfully, leading to frustrations. It will be will recommended to the manufacturer to offer a zip tie or Velcro strap that will allow users to place the hose sensor above ground, as per the recommendation of the maintenance workers. During the placement of pneumatic hoses, the workers sometimes forgot to turn the hose sensor on. Although there is a small LED light indicating the status of the hose sensor, the size of the light is too small to be seen in daylight conditions easily.

Due to the nature of the manual activation buttons on the PSDs, a few maintenance workers triggered accidental false alarms during both rounds of active work zone testing. The manual activation buttons slightly protrude from the body of the PSD, with older devices more sensitive to touch, making it difficult to avoid accidental triggers. By having the PSDs inside the pockets of the maintenance staff's clothing, the manual activation button would be accidentally pressed against equipment or clothing as the maintenance crews were working. To avoid this issue, it is recommended that the manufacturer remove or disable the manual activation button to reduce the number of false alarms. Overall, the vibratory alerts provided by the PSDs were felt through clothing after every activation.

5.8.2 Intellicone and Single Sentry Beam Testing Outcomes

Both the Intellicone and the Intellicone Single Sentry Beam systems are offered by the same manufacturer. Both the systems utilize the same PSA unit. The Intellicone system uses cone lamps deployed on cones that connect with each other to pass on a signal to offer coverage (with gaps between cones) in a work zone. The maximum distance specified by the manufacturer between two lamps was 100 feet, which was confirmed during active work zone testing. Furthermore, even the furthest placed lamp, when activated, triggered the PSA (alarm unit) without any delay. The deployment of the cone lamps can lead to some exposure concerns as the lamps must be placed on top of the cones after the cones have been deployed. In the two active work zone trials, one crew operating in a high-speed work zone tried to utilize the cone body truck to deploy the lamps; however, it was made difficult due to limited space. At the second active work zone location with flagging operation, the maintenance supervisor walked inside the closure to install the lamps himself as exposure to high-speed traffic was less of a concern. Given the exposure concerns during deployment and retrieval of the cone lamps, it can be deduced that the Intellicone system should be deployed in low to medium speed traffic conditions, especially if there is insufficient space to deploy the lamps from a cone body truck. The cone lamp utilizes a "lantern type" battery, which was easily available at a hardware store. The duration of the battery depends on the duration of use and can last multiple days. The combined weight of the lamp with a battery and availability of a handle in each lamp, meant a worker could carry multiple lamps simultaneously.

The Single Sentry Beam uses a continuous laser beam pre-set to a fixed distance to offer continuous coverage. In this regard, the Single Sentry Beam performs somewhat similar to the WAS in offering continuous coverage in a work zone, with additional advantages in terms of coverage distance as compared with the length of the WAS pneumatic hose. The device laser must be configured to a pre-set distance for the laser to detect an object crossing its path. The setting is configured within the first 10 seconds of when the device is turned on. Once configured, the device can be moved around to point the laser in a desired direction. The range between the Single Sentry Beam unit and the Intellicone PSA was 175 feet for reliable operation, even though one of the active work zone sites tests revealed the system to work at a distance of 200 feet. An added benefit observed from the active work zone testing was the utilization of the Single Sentry Beam to detect potential pedestrian intrusion in an urban work zone environment. Although the Single Sentry Beam can trigger an alarm unit at 175 feet, it does not have the ability to tether to another Single Sentry Beam unit or pass on the signal to other devices to extend the range. As such, the deployment of the Single Sentry Beam system is limited by the range of 175 feet and can be utilized effectively in shorter work zones and ramp closures without significant consideration for high or low speed traffic (exposure concerns). Because the Single Sentry Beam system offers a continuous coverage area through the laser beam, it is prone to accidental triggers due to workers walking inside the closure or work zone with high vehicular activity inside the closure. The weight of the Single Sentry Beam unit with battery installed is approximately 45 lbs., making it somewhat cumbersome to carry around in a work zone. Therefore, deployment must be made from a truck as close as possible to placement location. The battery is a proprietary one which must be charged for at least 24 hours prior to deployment and uses an intelligent charger to display charge status.

The Intellicone PSA (alarm unit used by both the Intellicone and the Single Sentry Beam systems) deployment is easy, with the alarm units turning on at the touch of a button. It took approximately 2-5 minutes for the unit to connect to the cellular network, which is not required for in-field operation but necessary to connect to another alarm unit more than 100 feet away. Additionally, connection to the cellular network also allows the ability to view and control certain features of the PSA and other capabilities of the system related to work zone management from a centralized location through an online dashboard. The alarm unit has a three-tone alarm, which is quite distinctive in sound. With the use of two alarm units during active work zone testing, the sound was sufficiently loud to be heard by the workers, despite high noise levels from equipment and traffic. The PSA must be charged at least overnight and preferably for 24 hours before use. The duration of the charge depends on the conditions and strength of the cellular network but can easily last for multiple days. The PSA also offers an “alert” sound (different from the three-tone alarm sound) to be used by a supervisor to alert workers of vehicles entering the work zone for work purposes. However, this capability was not utilized or tested in active work zone locations given the nature of the conditions. The PSA unit also offers a visual (light) warning, which could be effective during night-time operation.

5.8.3 SonoBlaster Testing Outcomes

The performance of the SonoBlaster system was effective during trials at the two active work zone locations. No accidental triggers or issues were observed during operation nor were any devices triggered by a vehicle intrusion. Providing the maintenance workers with training and customized guides and instructions ensured that care was taken during deployment, unlocking, and locking the SonoBlaster system to prevent accidental trigger. The SonoBlaster system is installed on cones, offering the same type of protection and coverage as the Intellicone cone lamps. A vehicle intruding into the work zone must hit a cone installed with a SonoBlaster device to sound an alarm. Hence, the greater the number of deployed cones with SonoBlaster installed, the better the coverage in a work zone. The SonoBlaster system was the least expensive of all WZIA systems. Most of the concerns surrounding the use of the SonoBlaster system arise from the exposure to traffic while deploying the cones. While the cones installed with a SonoBlaster could not be deployed from a standard Caltrans cone body truck, the maintenance crew deployed the cones from the front of a shadow truck. However, since the SonoBlaster system must be unlocked after the cones are placed on the ground, there is additional exposure to the workers, especially in high-speed work zones as was encountered on Day 3 of active work zone testing. However, exposure was not a concern during the deployment of the SonoBlaster system on a ramp closure during Day 5 testing where speeds were much lower.

Other issues related to the SonoBlaster system installation on the cones were covered in detail in Chapter 4. During active work zone testing, the maintenance crew were provided with pre-installed cones, so installation issues were not encountered.

5.8.4 AWARE Sentry Testing Outcomes

The AWARE Sentry system is the only system with an active warning to workers before an intrusion occurs in a work zone. It also has the additional capability of warning drivers approaching a work zone if they are exceeding a set speed threshold or if a vehicle jumped a queue. Furthermore, the AWARE Sentry system offers personal safety devices (WorkTRAX) to warn individual workers of potential intrusions in a work zone. The outcomes of the active work zone testing at two locations clearly showed the effectiveness of the AWARE Sentry system in detecting vehicles at speed and distances as specified by the manufacturer. The system was reliable in its detection and offered significant range coverage. The WorkTRAX was effective in warning workers using audio and haptic feedback. The system can record a 30 second video of any vehicle detection or alarm activation to be reviewed by the user at a later date. The availability of an online dashboard offers additional maintenance and operational capabilities that could be useful in developing strategies for best deployment in a work zone. Deployment of the AWARE Sentry system is relatively easy as it can be transported and offloaded from the back of a truck and placed by the side of a flagger in a work zone.

The AWARE Sentry system is limited to use in only flagging operations, given its design. As such, it was tested at two active work zone locations, both with flagging operations. The flashing lights facing the driver are very bright LEDs and concerns were noted regarding the possibility of temporarily blinding and distracting the drivers in a queue. The alarm sound associated with the base unit is very loud and could be heard at least 500 feet away in a close cabin vehicle. In addition, the alarm sound is similar to that of a police car and may distract the drivers to search for a police vehicle rather than looking at the flagger. The most important element of the AWARE Sentry system is setting the speed threshold given the specific conditions of a work zone. As noted during the Day 4 trial, an incorrect speed threshold setting may result in too many alarms and triggers, desensitizing the workers causing them to pay less attention when an actual intrusion might occur. Therefore, close consultation and review of traffic conditions is required to ensure the proper speed thresholds are set from the start of operations to minimize false alerts. Diverging roads and reflective surfaces may cause the system to activate false alerts as well, as seen during Day 4 trials of active work zone testing. Some issues were also observed with the tethered foot pedal needed to operate the base unit and the location of the flagger in a work zone. There is a need to develop a wireless connection to the foot pedal or a hand-held wireless device to operate the base unit effectively.

5.9 ACTIVE WORK ZONE TESTING SURVEYS

The maintenance workers were given a survey at the end of active work zone testing on certain days. The survey was the same as the one conducted during the training sessions, as previously described in Chapter 4, with one change – the "Don't Know" response was removed from some questions. This change was made because of a high number of such responses in the previous surveys. It was thought that this change would encourage a definitive response from the crew on the performance of WZIA systems after active work zone testing. Refer to Appendix C for the detailed survey forms. The results of the active work zone testing compared with the training sessions are discussed in detail in Chapter 6.

6 RESULTS OF MAINTENANCE WORKERS SURVEYS

Chapter 6 presents a comparison of survey results conducted with the Caltrans maintenance workers during the training sessions at the Caltrans META facility and after WZIA system testing in active work zone locations. A copy of the survey can be found in Appendix C. The purpose of this survey was to solicit feedback from the Caltrans maintenance workers regarding their perception on the ease of use, effectiveness, and safety benefits of the selected WZIA systems. The survey results also served to better understand the adaptability and practicality of the selected WZIA systems and provided valuable feedback that would be communicated to the manufacturers to improve their systems. Lastly, a comparison of survey results during the training sessions and after trials in active work zones would shed light on any changes in perception of the workers regarding the selected WZIA systems.

6.1 SURVEY RESULTS - WORKER ALERT SYSTEM

6.1.1 Device Effectiveness

Figure 6.1 shows the survey responses, during the training sessions and active work zone testing, to questions regarding device effectiveness of WAS. The results show that the maintenance staff perceived the WAS to be an "Effective" device overall. Similarly, the responses during active work zone testing show predominantly "Effective" responses, with an increase in the number of "Effective" responses and no "Ineffective" responses. The predominant "Effective" responses correlate with maintenance staff's comments during the training session and general field observations of the system's ability to deploy multiple alarm units within the work zone while the PSDs are held by individual workers.

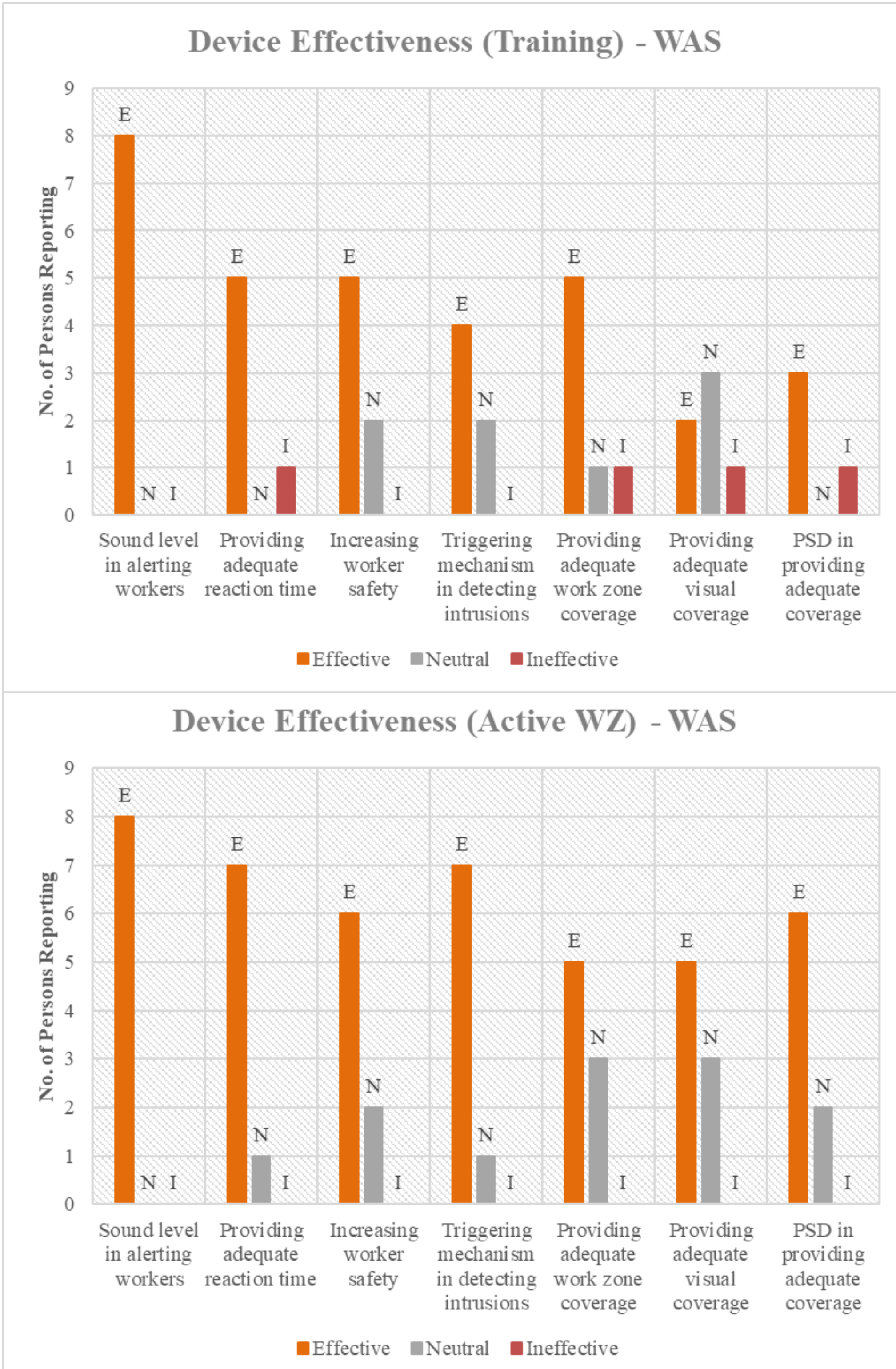


Figure 6.1 Comparison of Survey Results for WAS Device Effectiveness

6.1.2 Deployment

Figure 6.2 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the deployment of WAS. The results from training session show that the maintenance staff consider WAS generally easy to deploy. This aligns with the comments shared by the maintenance workers during the training session in which they liked the quick and easy deployment, along with the flexibility of hose and alarm unit placement. The time to set up received equal responses between "Easy" and "Neutral"; and depends on the time it takes to turn on the device and the number of hoses/alarm units being deployed. The results from active work zone testing show that a majority of the maintenance workers perceived WAS deployment to be overall "Easy" with the number of positive responses increasing compared with the results from training session. The perception of an "Easy" deployment is consistent to the field observations of quick deployment and set up times for the WAS.

6.1.3 Durability

Figure 6.3 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the durability of WAS. The results show mixed responses from the maintenance workers in both surveys, possibility due to the difficulty of assessing durability given the short timeframe of interaction with the system. Some maintenance workers did not respond to this question, indicating their uncertainty highlighted by the "Neutral" responses in both the surveys. More time interacting with the WAS may allow the maintenance crew to better assess the durability of the device.

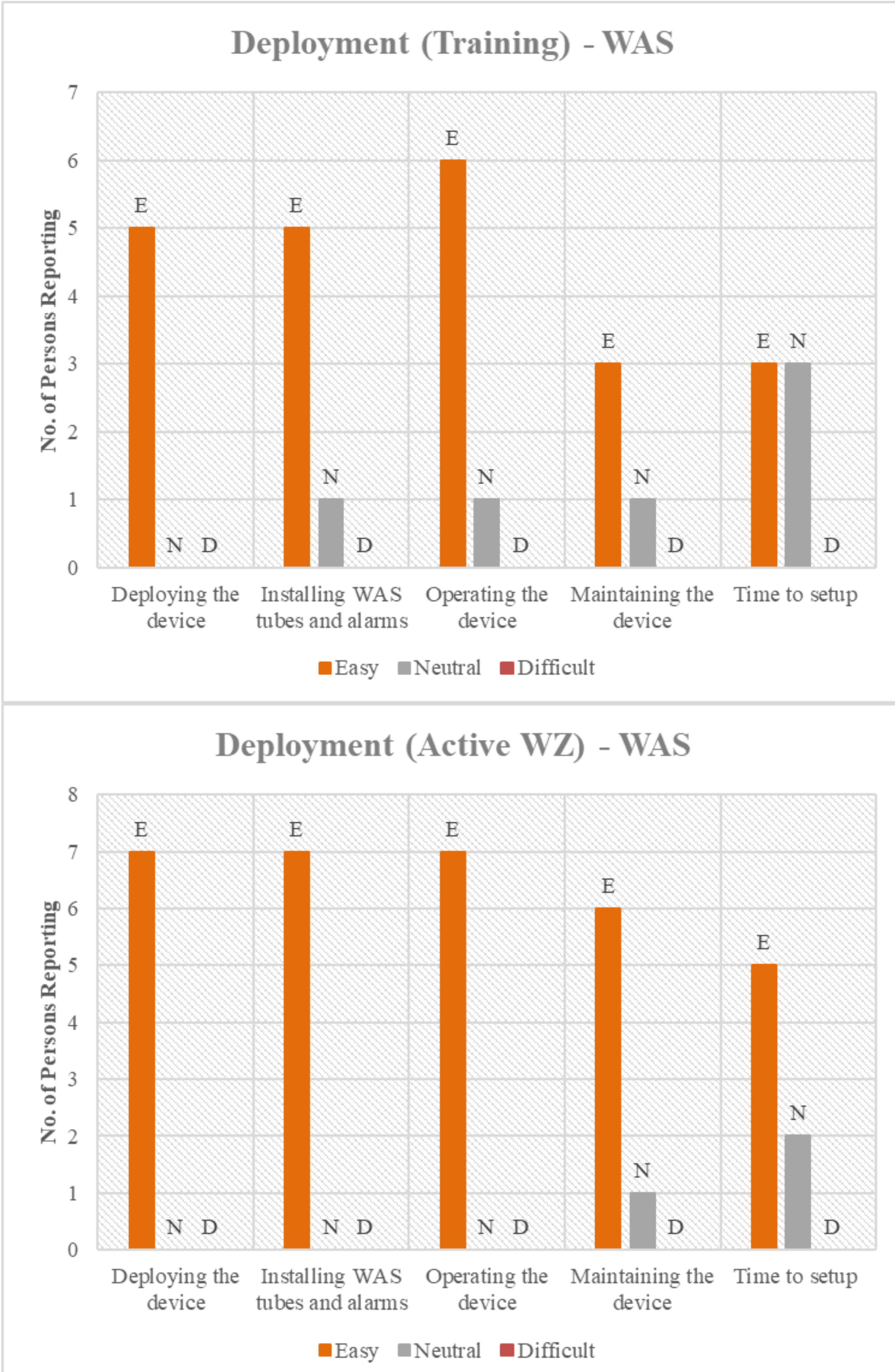
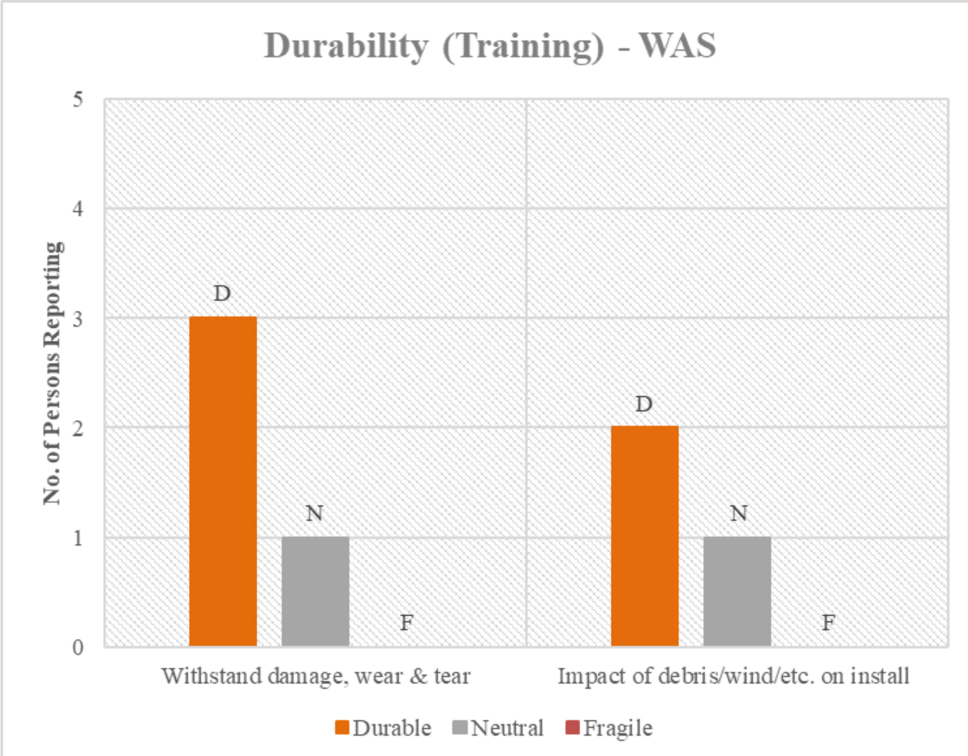


Figure 6.2 Comparison of Survey Results for WAS Deployment



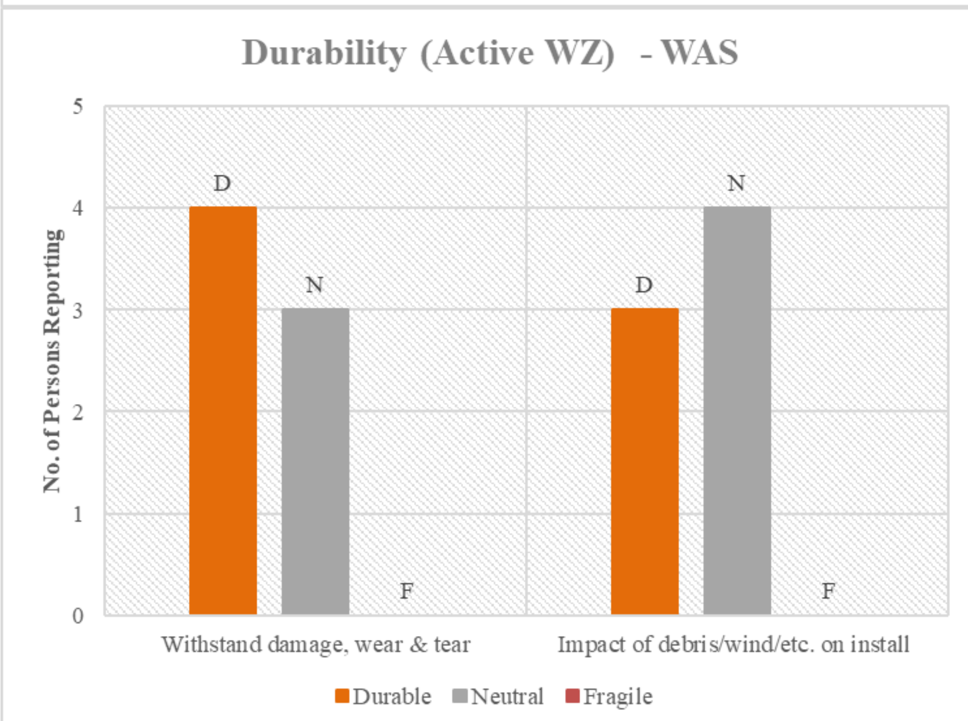


Figure 6.3 Comparison of Survey Results for WAS Durability

6.1.4 Sound Distinctiveness

Figure 6.4 shows the survey responses to questions regarding the sound distinctiveness of WAS during the training sessions and active work zone testing. The results from both the surveys clearly indicated that the maintenance workers considered the alarm sound to be distinctive relative to the background work zone noises. Additionally, the alarm sound was also effective in alerting the workers towards the possible direction of intrusion. The use of multiple alarm units in a work zone made the WAS alarm sound effective. The predominant "Distinctive" responses correlate with comments shared by the maintenance staff appreciating the ability to place multiple alarm units on vehicles near the activity area allowing the alarm sound to be amplified despite the noises due to the presence of running equipment.

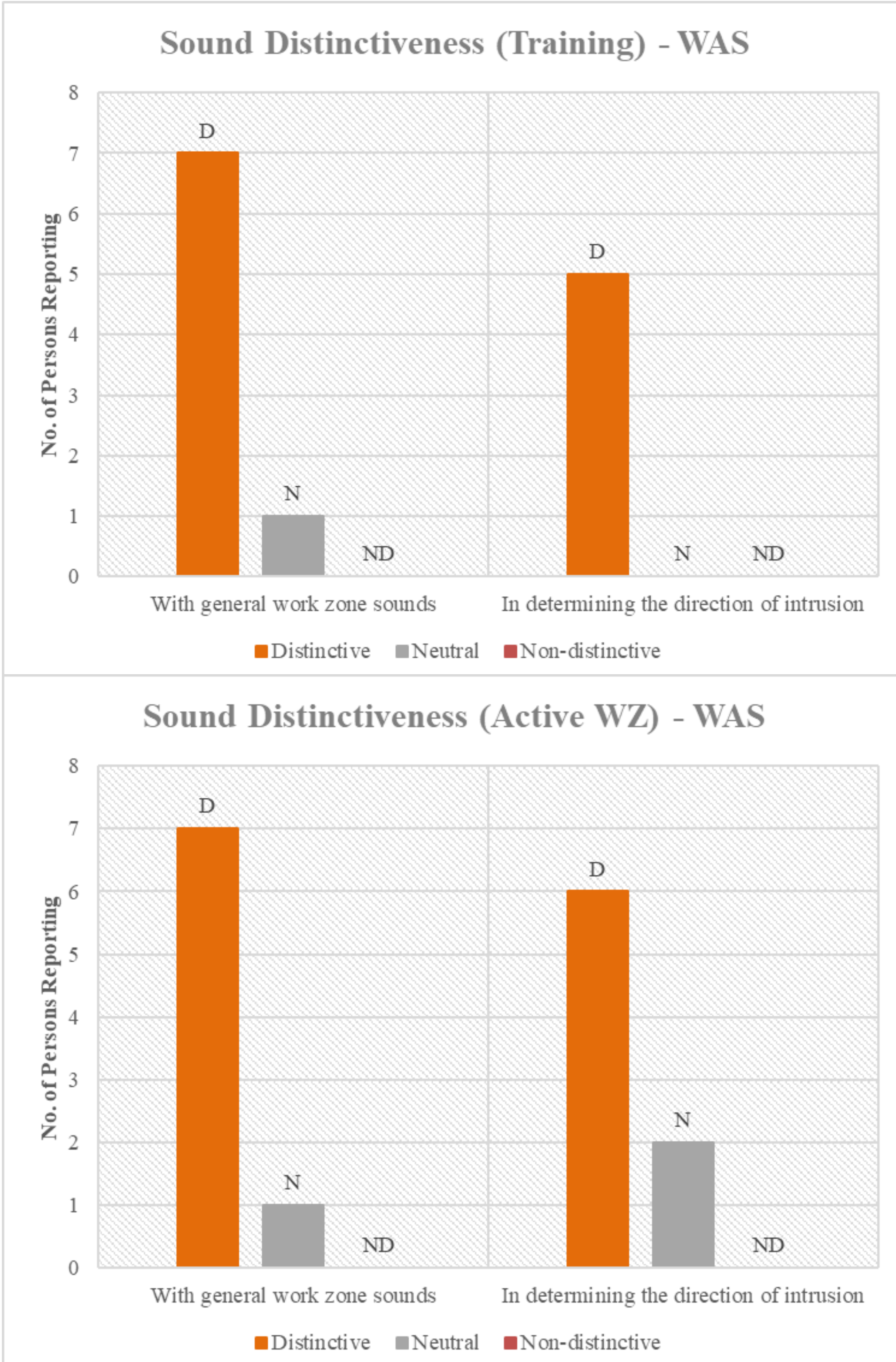


Figure 6.4 Comparison of Survey Results for WAS Sound Distinctiveness

6.2 SURVEY RESULTS – SONOBLASTER

6.2.1 Device Effectiveness

Figure 6.5 shows the survey responses, during the training sessions and active work zone testing, to questions regarding device effectiveness of SonoBlaster. The results from the training session show that the maintenance workers were mostly neutral on SonoBlaster device effectiveness with some concerns regarding adequate coverage in a work zone. It is interesting to note that although the SonoBlaster system has the loudest alarm sound (approx. 125 dBA), the response to the first question in this section during the training session was mixed. The research team assumes that some of these responses may be attributed to the number of SonoBlaster units needed for assembly to receive the desired work zone coverage and the general perception of the system given the issues surrounding installation, maintenance, and transport as discussed in detail in Chapter 4 and 5. Results of the survey responses after active work zone testing were more definitive, with the maintenance workers finding the SonoBlaster system to be mostly "Effective" in all areas. It should be noted that some of these survey responses were from the crew testing the system in a low-speed work zone on a ramp closure, eliminating some of the issues surrounding exposure to traffic in high-speed work zones.

6.2.2 Deployment

Figure 6.6 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the deployment of SonoBlaster. The results from both the surveys were generally mixed with a higher number of "Neutral" responses. Time to set up received a predominant response of "Difficult," which correlates with the comments shared by the maintenance staff in regard to the length of time and effort required to install the SonoBlaster unit on each cone. It is clear from both the survey responses that the deployment of the SonoBlaster system is a general concern with the maintenance workers, given the setup requirements, exposure issues during deployment, and issues with transporting the system (discussed earlier in Chapter 4).

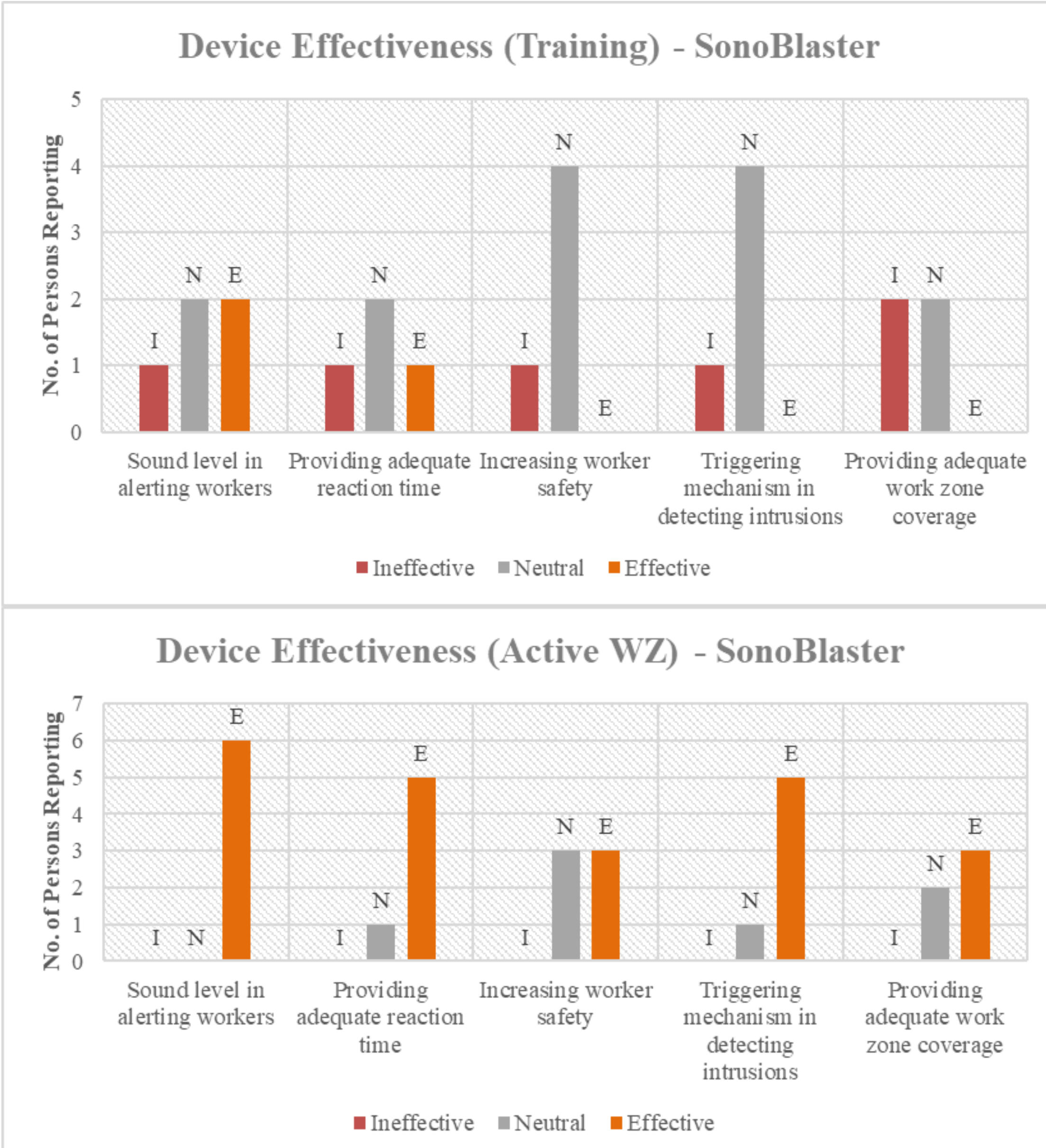


Figure 6.5 Comparison of Survey Results for SonoBlaster Device Effectiveness

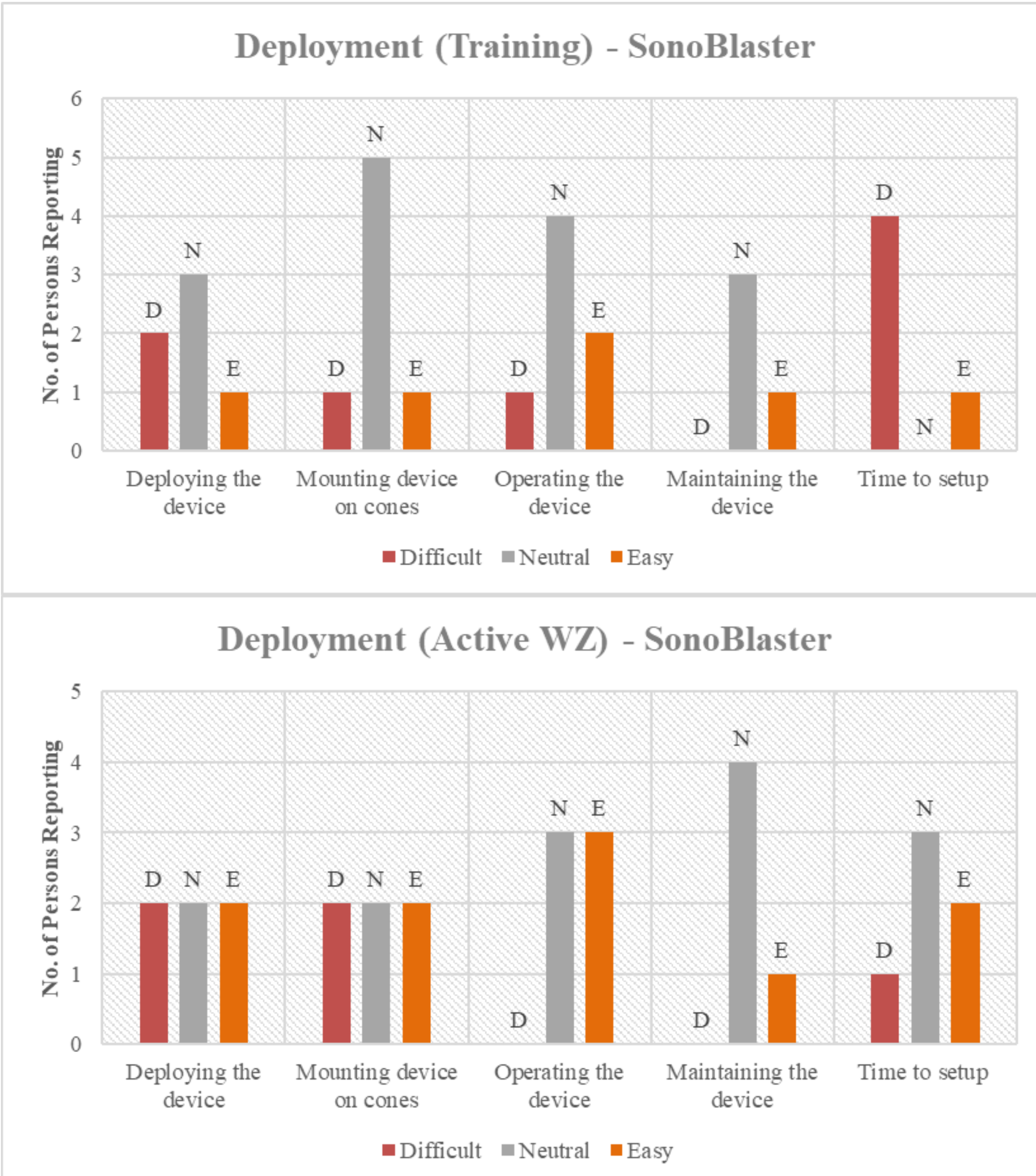


Figure 6.6 Comparison of Survey Results for SonoBlaster Deployment

6.2.3 Durability

Figure 6.7 shows the survey responses to questions regarding the durability of SonoBlaster during the training sessions and active work zone testing. The results from both the surveys show that the maintenance workers consider the SonoBlaster system to be fragile or had neutral responses on its durability. The SonoBlaster system is activated when the device with a cone is hit by a vehicle, resulting in possible damage to the device. Thus, the workers' responses may be attributed to the fact that the SonoBlaster system may not be able to withstand such damage. The "Neutral" responses may also be attributed to the limited interaction between the maintenance workers and the SonoBlaster system, given the training session and active work zone testing.

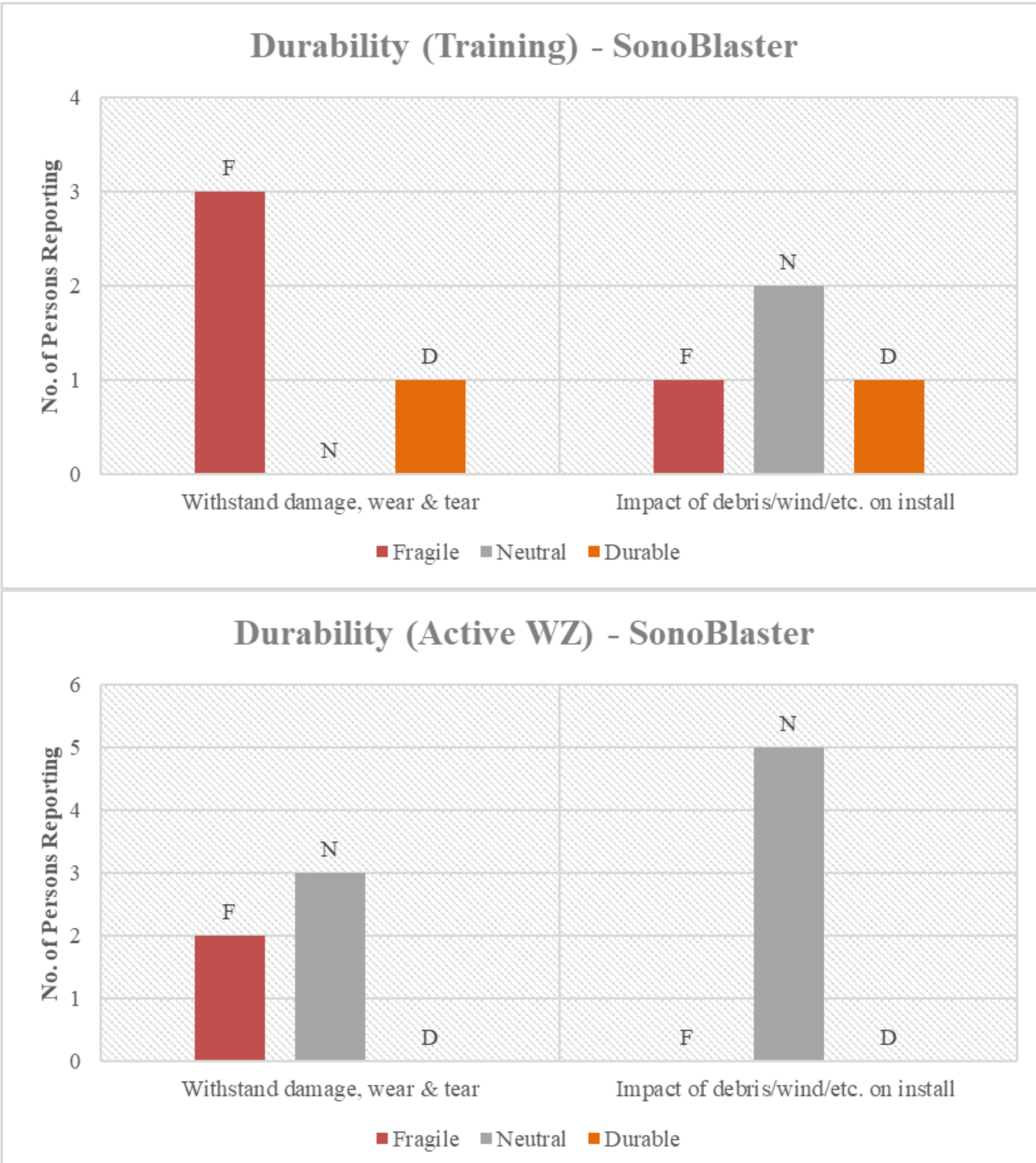


Figure 6.7 Comparison of Survey Results for SonoBlaster Durability

6.2.4 Sound Distinctiveness

Figure 6.8 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the sound distinctiveness of SonoBlaster. Given that the SonoBlaster was one of the loudest WZIA systems tested, the results from both the surveys were generally clear in finding the SonoBlaster sound to be distinctive and helping getting workers' attention towards the direction of an intrusion.

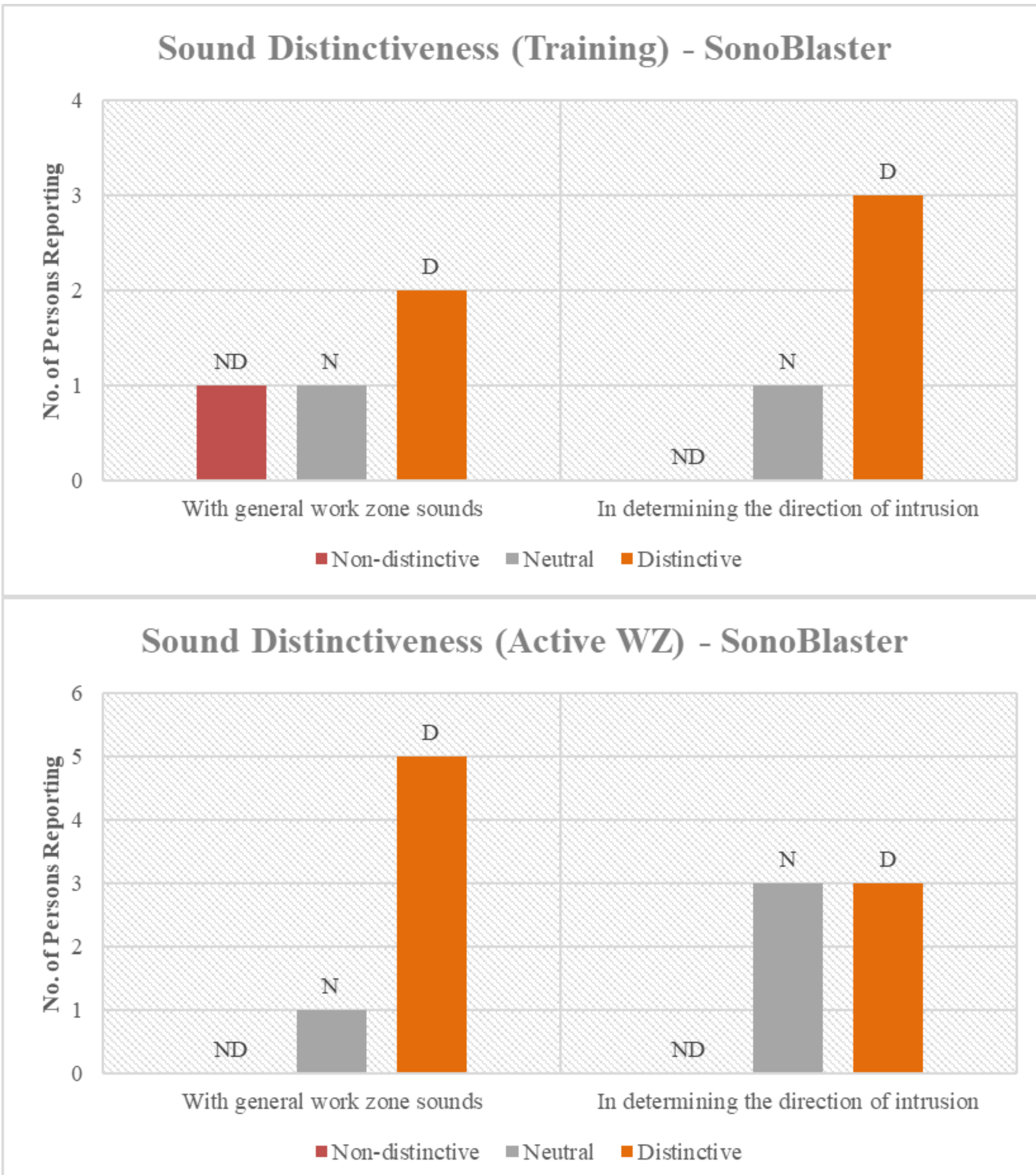


Figure 6.8 Comparison of Survey Results for SonoBlaster Sound Distinctiveness

6.3 SURVEY RESULTS – INTELLICONE SYSTEM

6.3.1 Device Effectiveness

Figure 6.9 shows the survey responses to questions regarding device effectiveness of the Intellicone system during the training sessions and active work zone testing. The results from both surveys show that the maintenance workers found the Intellicone system to be "Effective" in all aspects with a few "Neutral" responses. The only aspect standing out was the ability to provide adequate coverage, which could be attributed to the fact that the Intellicone system utilizes the cone lamps that only trigger an alarm when hit. Therefore, there may be gaps in the work zone where a cone is not present or not hit during an intrusion, potentially compromising the coverage of a work zone. The sound level clearly stood out as the most effective feature of the Intellicone system.

6.3.2 Deployment

Figure 6.10 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the deployment of the Intellicone system. The results from both the surveys show mixed responses. While there were many "Neutral" responses, the maintenance workers generally found the system deployment, cone installation, and time to set up to be difficult. These responses reflect the comments shared by the maintenance workers about deployment of the cone lamps to be a tedious process, especially in a large work zone. Additionally, the exposure to traffic while installing the cones was a concern shared by the maintenance workers, especially in high-speed traffic conditions. Once deployed, the responses show that the maintenance workers found operating the device to be easy; however, there were some "Neutral" responses to that question.

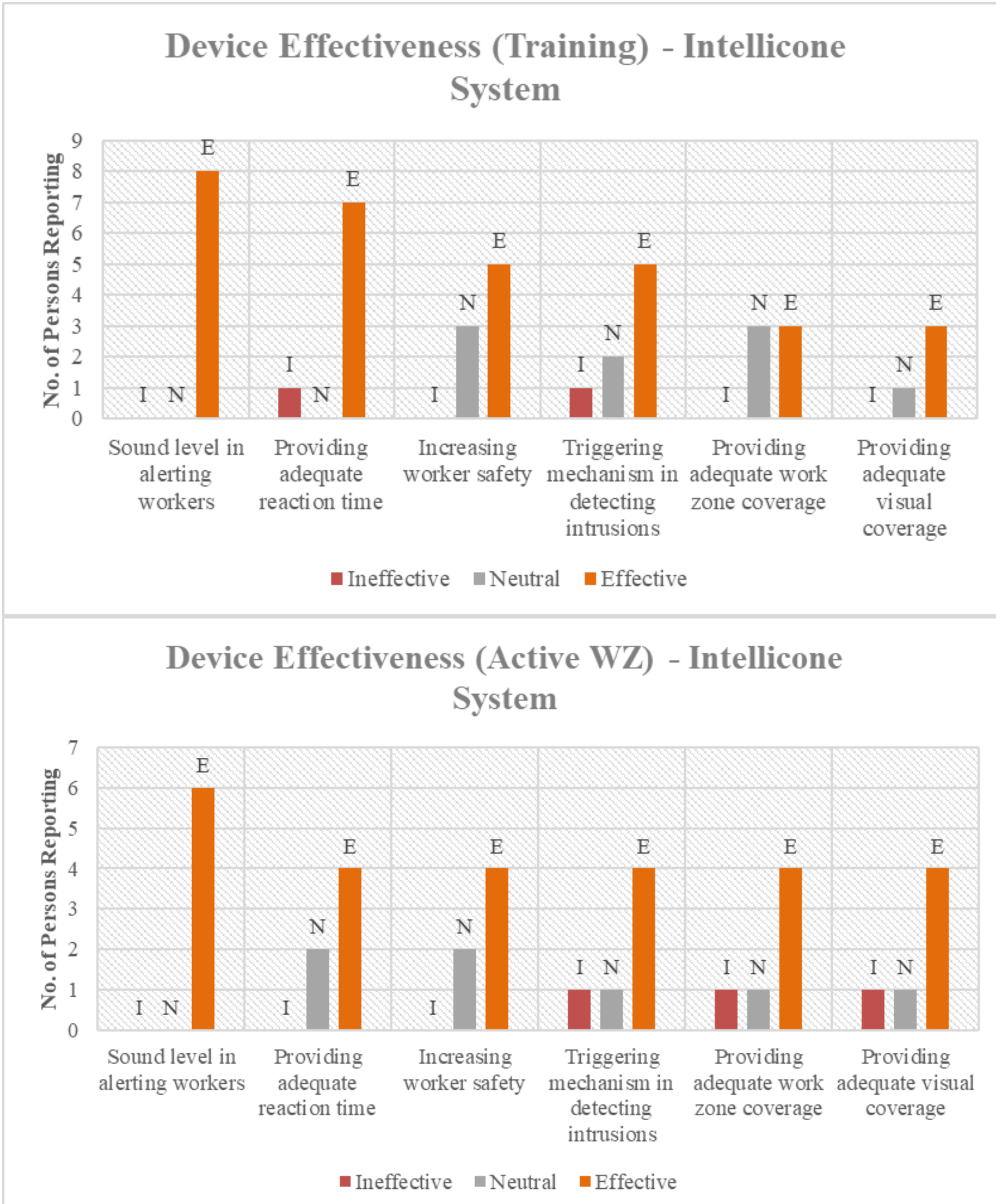


Figure 6.9 Comparison of Survey Results for Intellicone Device Effectiveness

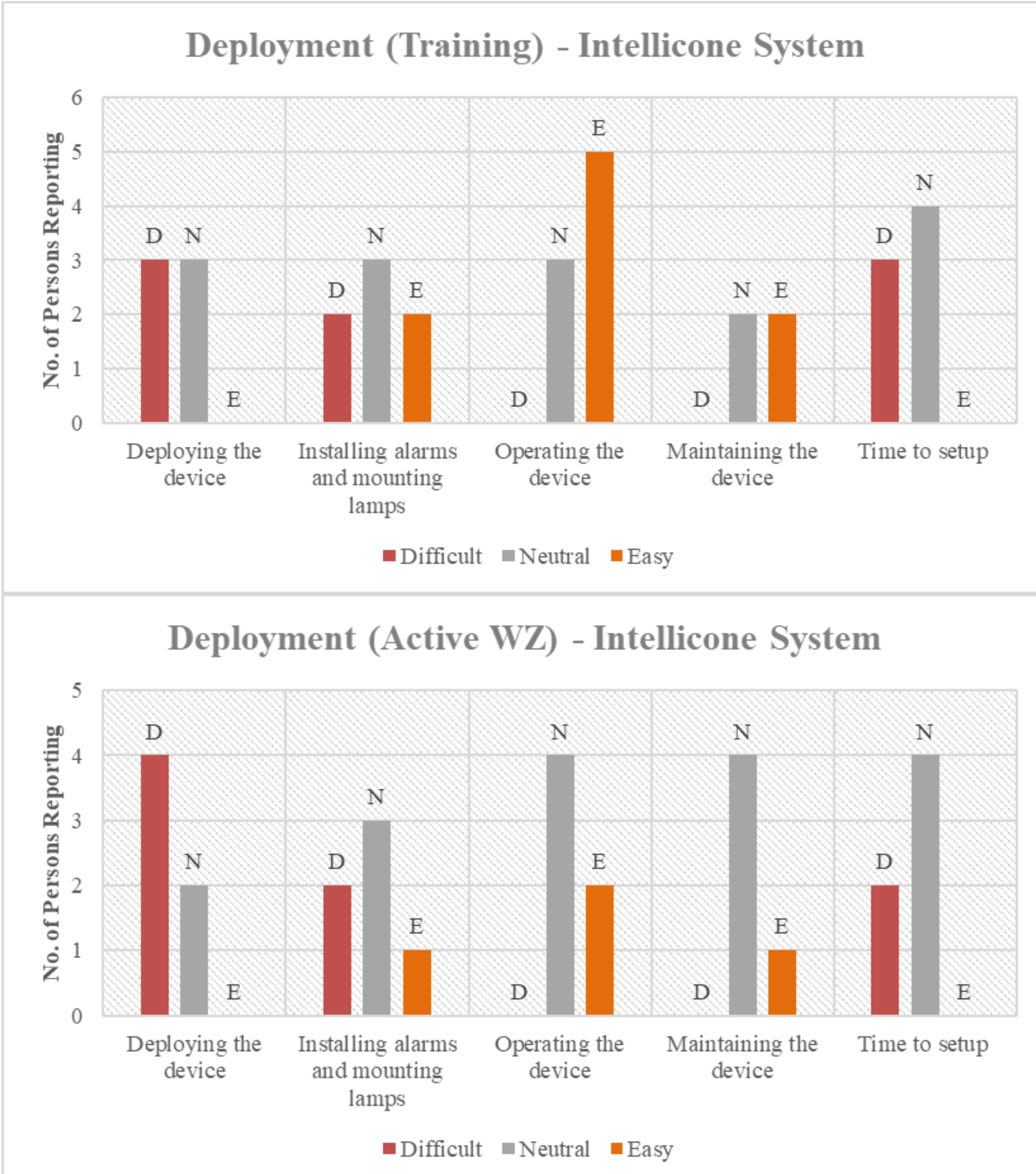


Figure 6.10 Comparison of Survey Results for Intellicone Deployment

6.3.3 Durability

Figure 6.11 shows survey responses, during the training sessions and active work zone testing, to questions regarding the durability of the Intellicone system. While the responses were generally mixed, the number of responses to questions relating to the durability of the Intellicone system in both the surveys was low. Therefore, it is difficult ascertain anything definitively from the responses. The research team explained to the respondents that answers to the durability related questions should be submitted based on their perceptions, given their experience working in a work zone environment, and associated factors that may impact a system's durability. However, it was clear that the workers were unable to provide feedback on the durability aspect of the Intellicone system, which could be attributed to their limited interaction with the system during the training session and active work zone testing.

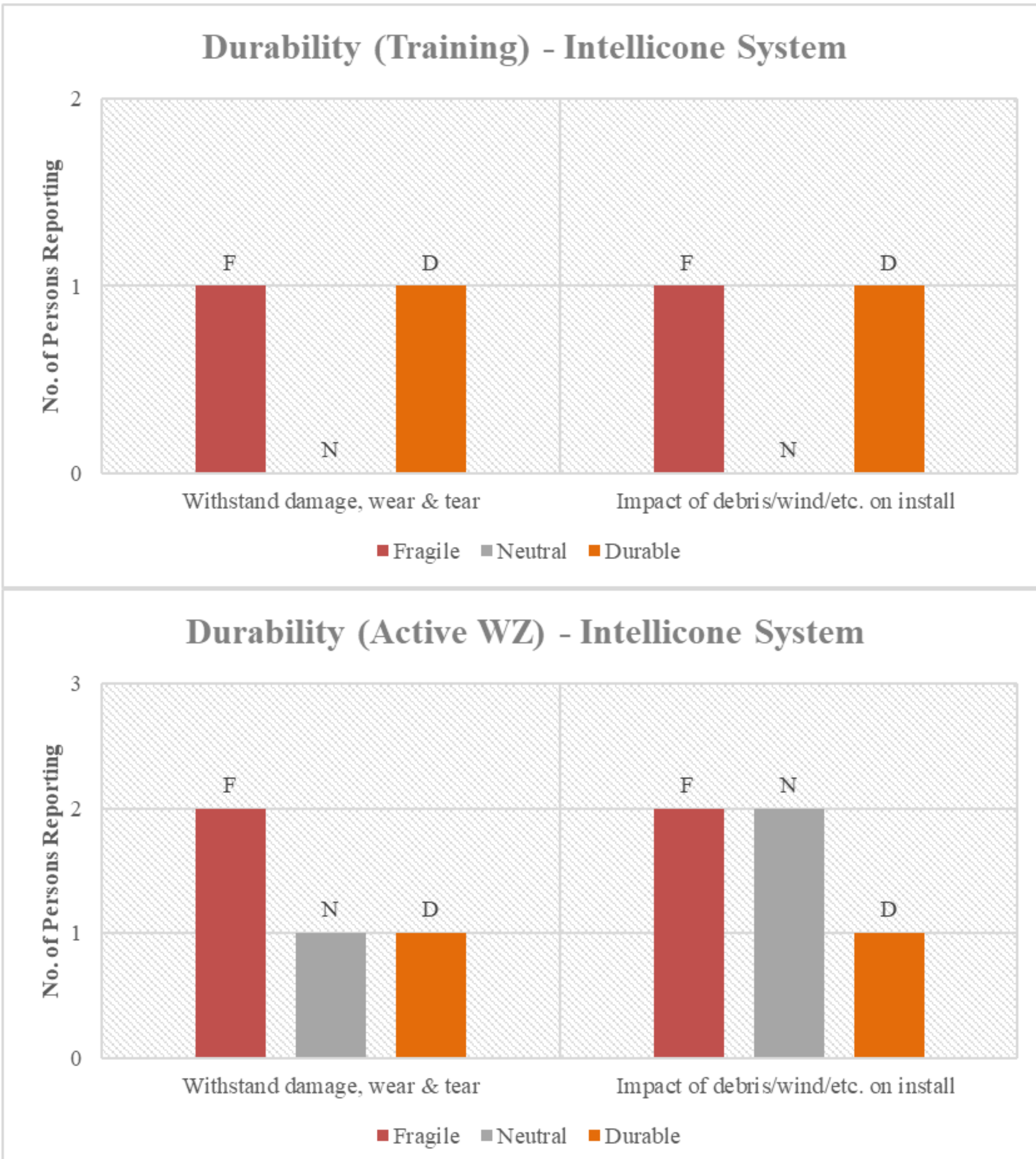


Figure 6.11 Comparison of Survey Results for Intellicone Durability

6.3.4 Sound Distinctiveness

Figure 6.12 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the sound distinctiveness of the Intellicone system. The results from both the surveys show that the Intellicone System alarm was perceived to be distinctive relative to the general noise levels in a work zone. The predominant "Distinctive" responses may be attributed to the system's ability to utilize multiple alarm units together for maximum effectiveness within the work zone and near the workers.

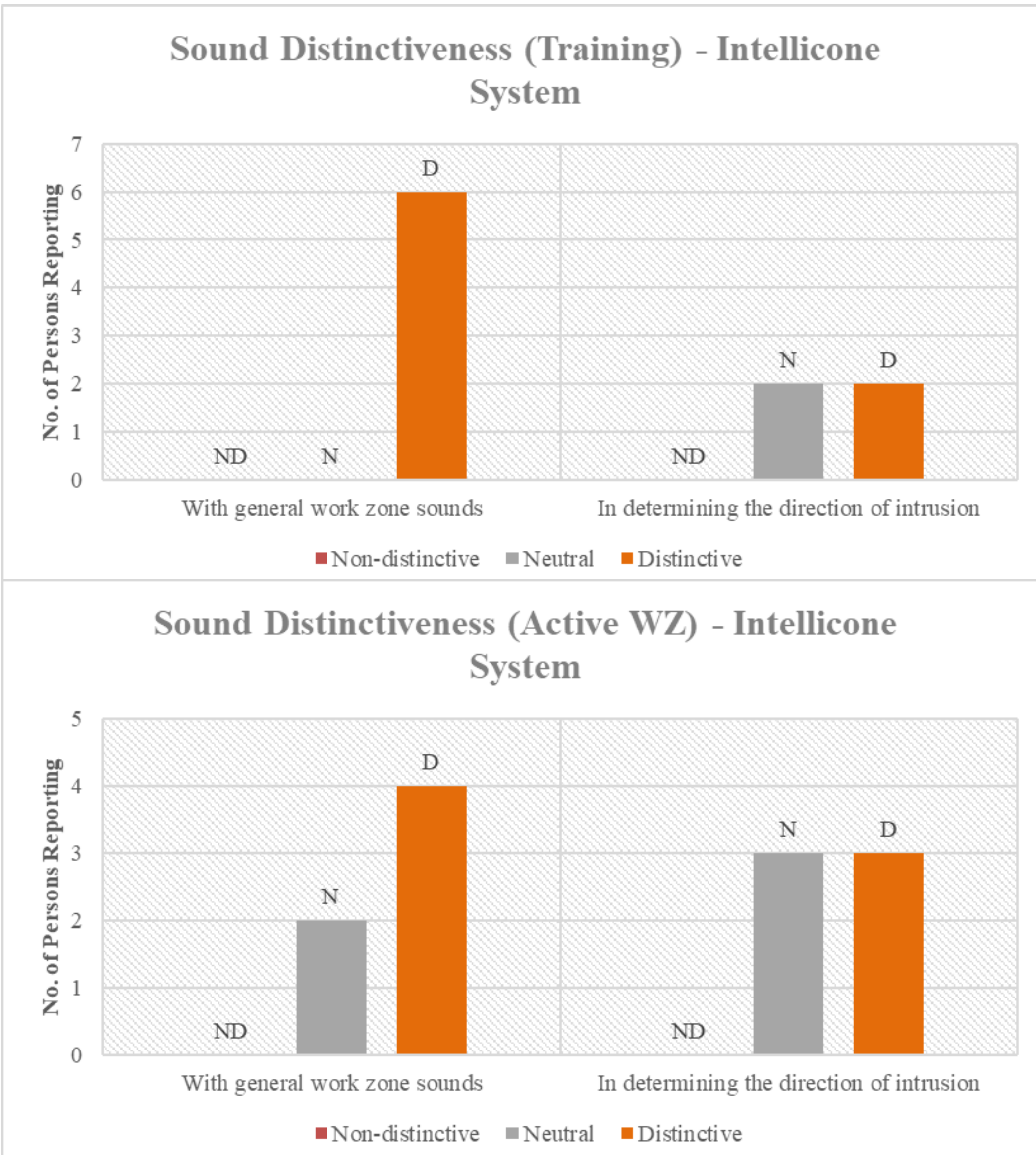


Figure 6.12 Comparison of Survey Results for Intellicone Sound Distinctiveness

6.4 SURVEY RESULTS - INTELLICONE SINGLE SENTRY BEAM

6.4.1 Device Effectiveness

Figure 6.13 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the effectiveness of the Single Sentry Beam system. The results from the training session show "Effective" to "Neutral" responses to various questions related to device effectiveness, with less positive responses surrounding adequate coverage and increasing worker safety. These results reflect the discussion surrounding the range of the Single Sentry Beam system, which is 175 feet when connecting to the Intellicone PSA. Discussion and comments from the maintenance workers during the training session showed that the range was inadequate in providing sufficient coverage, especially in larger work zones. Furthermore, the inability of the system to tether to another device to pass along the signal resulted in a limited range. Conversely, the results from the active work zone testing are mostly positive, with many "Effective" responses and some "Neutral" responses. The results could be attributed to the fact that the Single Sentry Beam system was deployed in two active work zone locations, where it performed well using the suggested deployment instructions provided by the research team, as discussed in detail in Chapter 5. Furthermore, the use of the Single Sentry Beam in the ramp closure work zone to detect possible pedestrian intrusions was a novel application of the system. Therefore, it is understandable that the responses from the active work zone testing surveys found the system to be effective in all aspects. Because the Single Sentry Beam system utilizes the Intellicone PSA, the response to the question on sound level was similar in both surveys as "Effective."

6.4.2 Deployment

Figure 6.14 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the deployment of the Single Sentry Beam system. The results from both the surveys were generally similar in all aspects of deployment with most responses as "Easy" or "Neutral." A few "Difficult" responses to the deployment question may relate to the weight of the system and difficulty in transporting it around a work zone. There were more "Easy" responses in the active work zone surveys, possibly due to the deployment of the system in a more suitable work zone given its limited range. In general, however, the system is easy to deploy, given the ease of configuring the laser detection range and system operation.

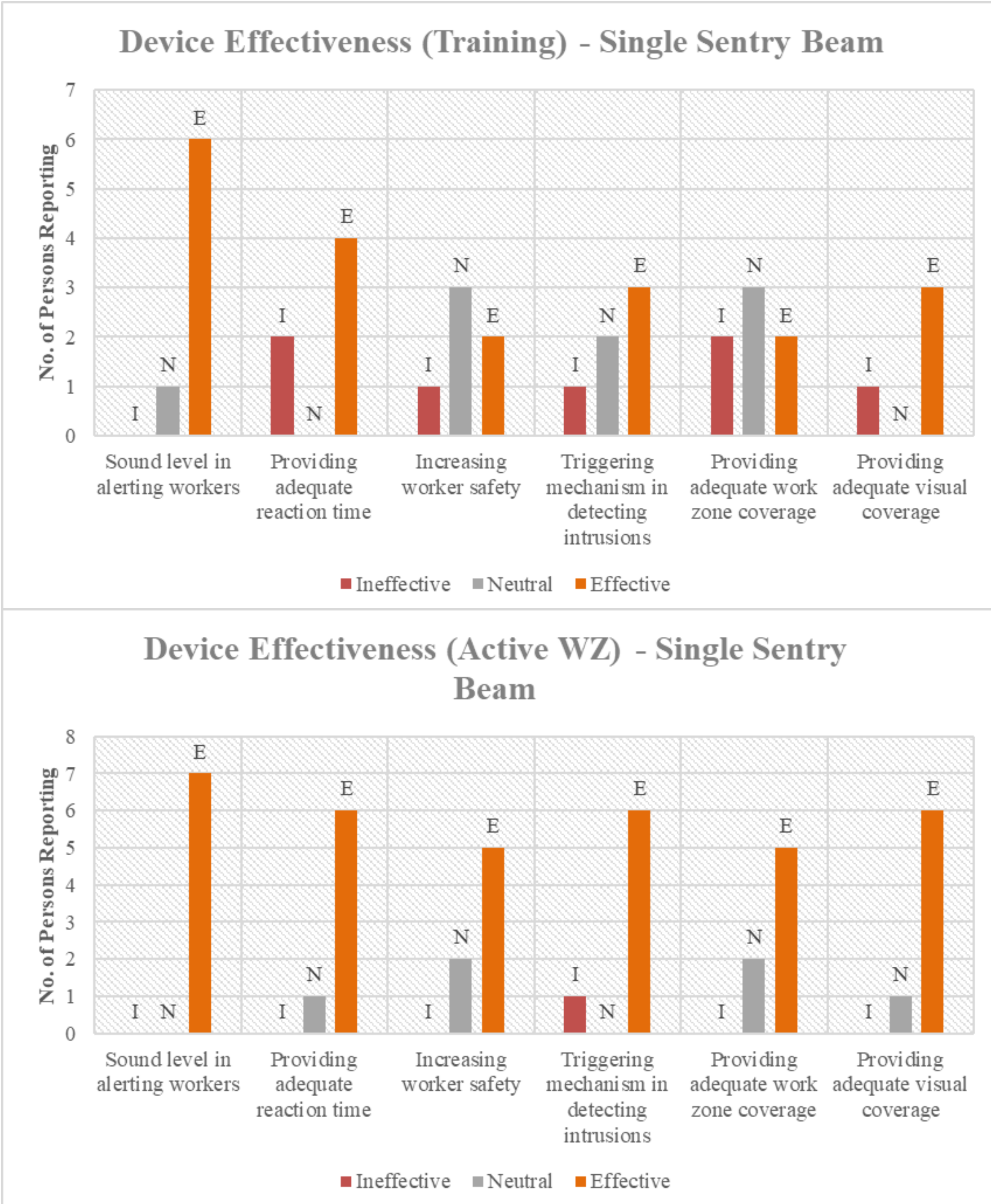


Figure 6.13 Comparison of Survey Results for Single Sentry Beam Device Effectiveness

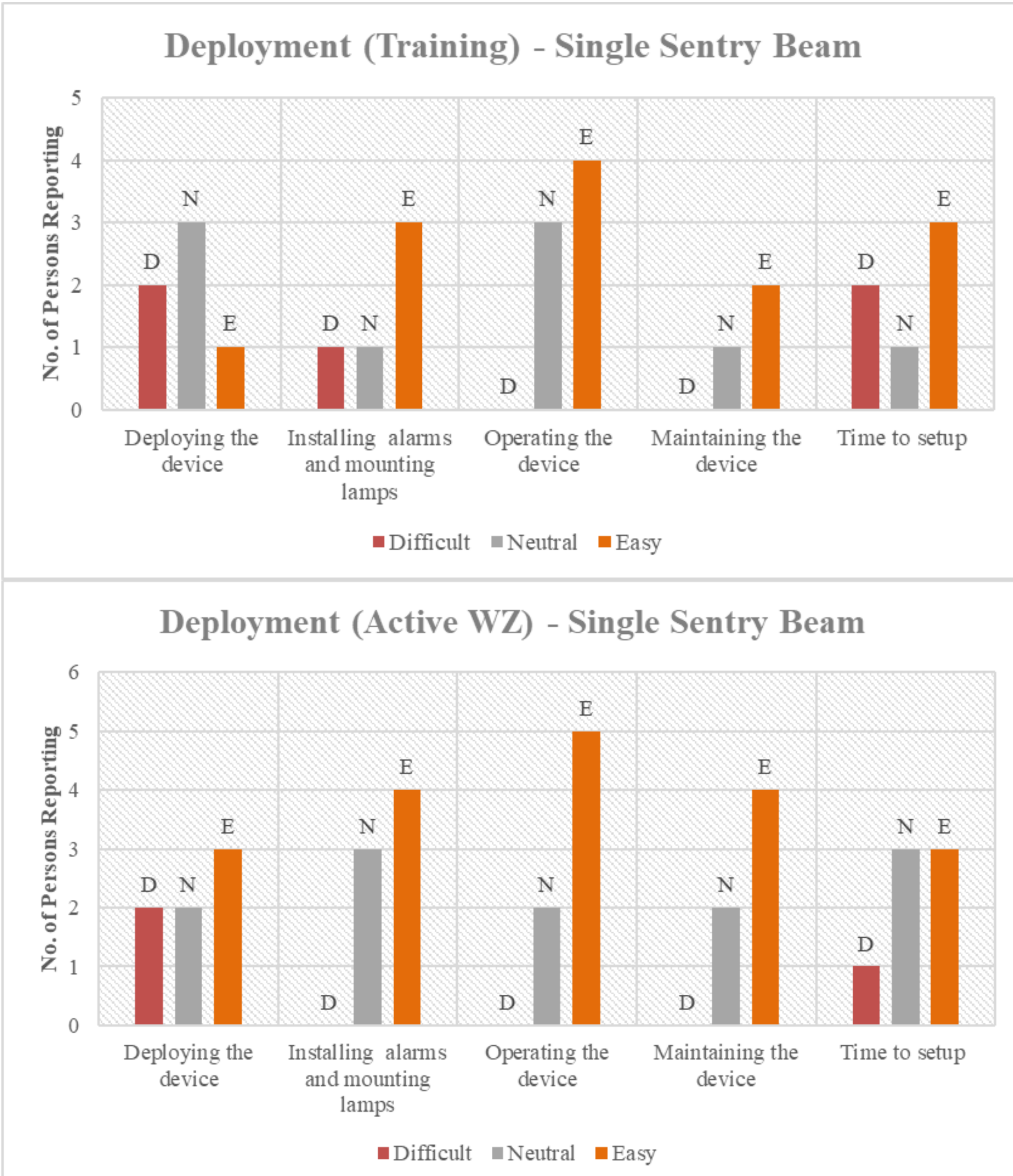


Figure 6.14 Comparison of Survey Results for Single Sentry Beam Deployment

6.4.3 Durability

Figure 6.15 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the durability of the Single Sentry Beam system. Similar to the Intellicone system survey results on this topic, while the responses were generally mixed, the results from both the surveys show that a majority of the maintenance workers did not provide a response to questions relating to the durability of the Single Sentry Beam system. Therefore, it is difficult ascertain anything definitively from the responses. However, there are a few more "Durable" responses in the active work zone survey.

Figure 6.15 Comparison of Survey Results for Single Sentry Beam Durability

Figure 6.15 Comparison of Survey Results for Single Sentry Beam Durability

6.4.4 Sound Distinctiveness

Figure 6.16 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the sound distinctiveness of the Single Sentry Beam system. The results from both the surveys clearly indicated that the maintenance workers considered the alarm sound to be distinctive and effective in alerting workers to possible intrusions. The results are not surprising, given the Single Sentry Beam system uses the Intellicone PSA, which has a three-tone alarm sound that is very effective.

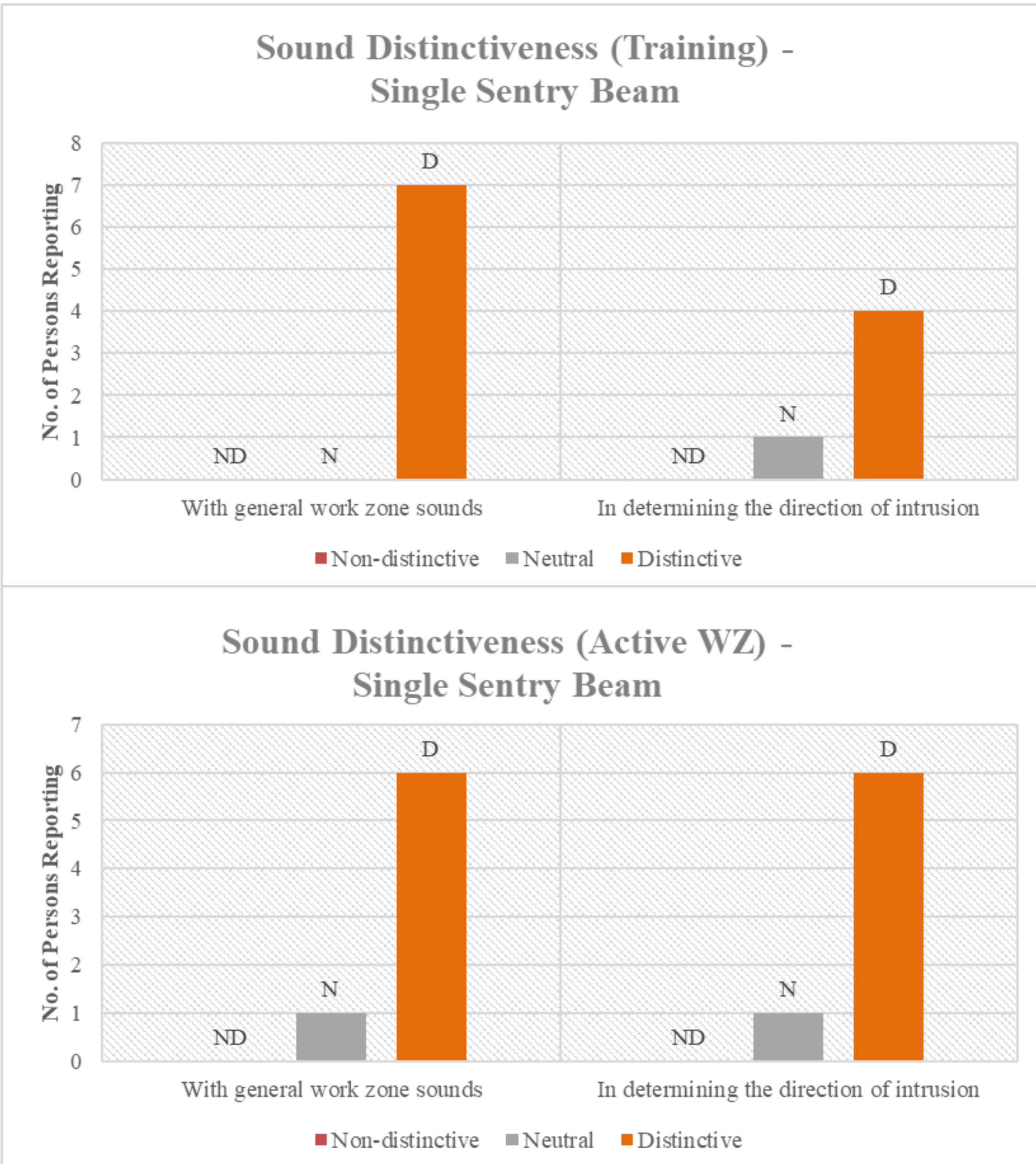


Figure 6.16 Comparison of Survey Results for Single Sentry Beam Sound Distinctiveness

6.5 SURVEY RESULTS – AWARE SENTRY

6.5.1 Device Effectiveness

Figure 6.17 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the effectiveness of the AWARE Sentry System. The results from the training session survey show the maintenance workers were uncertain about the visual coverage and the ability of the AWARE Sentry system to alert the workers with sound. These results could be attributed to the fact that the LED lights on the system face toward the drivers rather than the workers and the sound resembles a police siren, which may be ignored by the workers. The responses to other questions on device effectiveness were generally positive with a majority of "Effective" responses. The results of the survey responses in active work zone location showed predominantly "Effective" responses to all questions in this category. The results can be attributed to the large detection range offered by the system, which was clearly evident given the distances at which vehicles were detected in active work zone testing. Furthermore, the device was perceived to be "Effective" in providing adequate reaction time and activating the alarm when triggered. It is interesting to note that the survey respondents found the visual alert coverage to be effective as well, which was in contrast with the results during the training session survey. It is presumed that the respondents in the active work zone survey may be referring to the visual alerts given to the drivers being effective in gaining their attention towards the flagger. Another response to note relates to the effectiveness of the WorkTRAX PSD, which was found to be more effective in active work zone surveys vs training session surveys, possibly because the PSD was farther away from the base station in the active work zone and therefore, was the only major alert device for those workers.

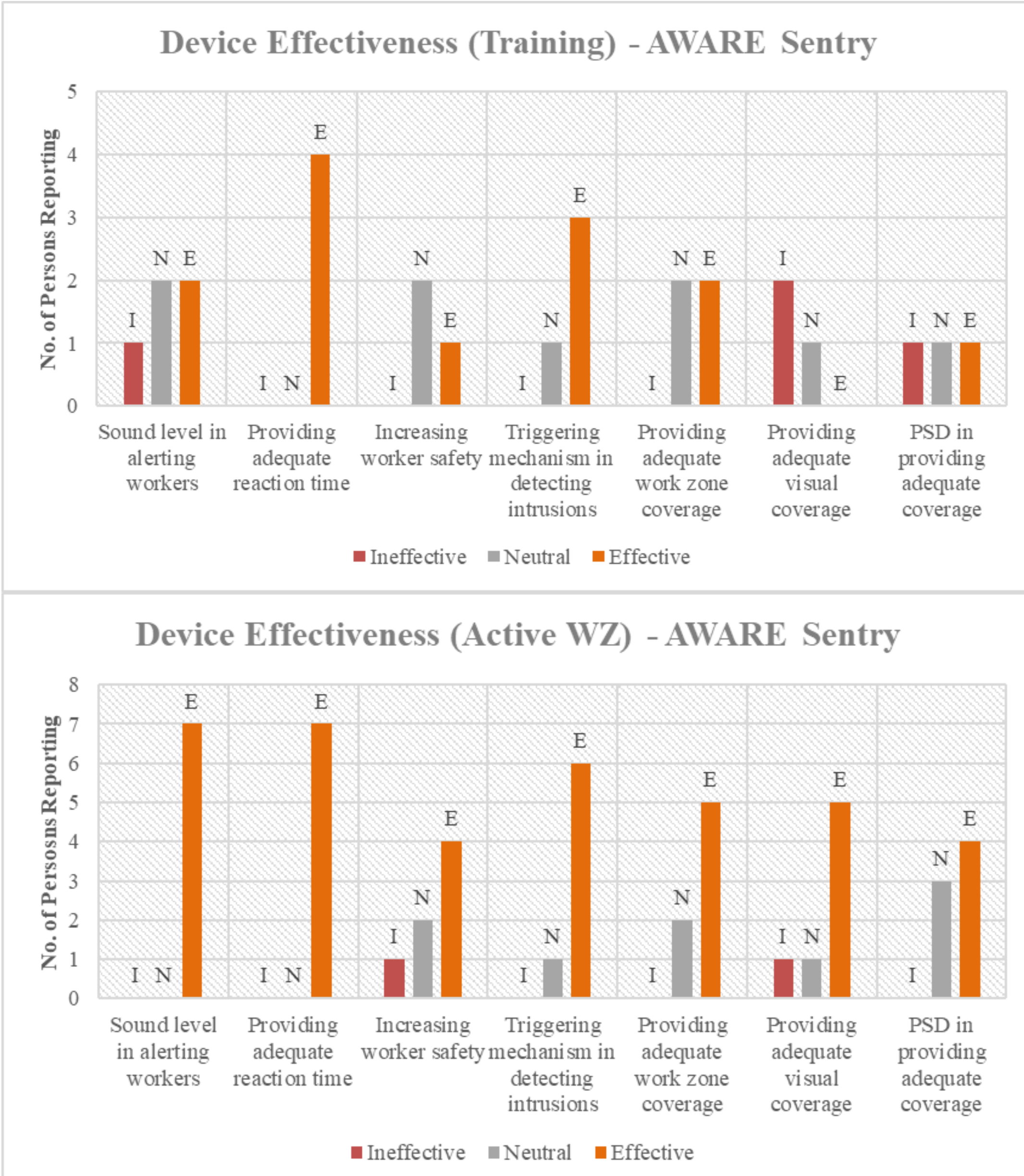


Figure 6.17 Comparison of Survey Results for AWARE Sentry Device Effectiveness

6.5.2 Deployment

Figure 6.18 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the deployment of the AWARE Sentry System. The results from the training session survey show a clear majority of "Easy" responses from the maintenance workers. This is because there are few steps involved in deploying the system, which is ready for use by turning on a single switch. On the other hand, the results of the active work zone survey show mixed results from the respondents, with a majority of "Difficult" responses for deployment and time to set up the device. It is unclear why the responses were mixed during active work zone testing. However, some of the written comments suggested difficulty in operating the device, given the tethered foot pedal and inability to set up speed threshold and other setting on the device itself (only available through smart phone application). It should be noted that one of the AWARE Sentry devices failed to function (for unknown reasons) during one of the active work zones testing days; this may have effected responses of some maintenance workers.

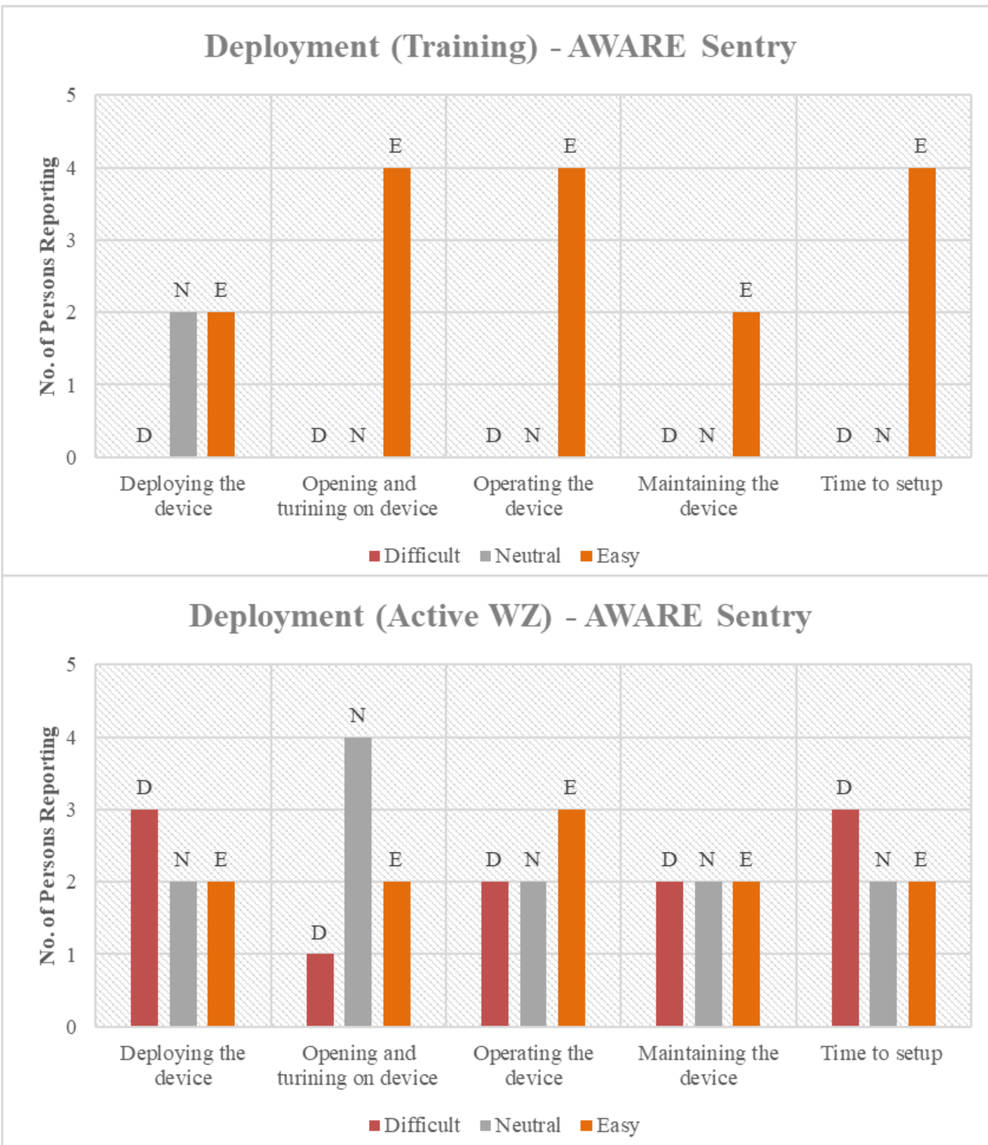


Figure 6.18 Comparison of Survey Results for AWARE Sentry Deployment

6.5.3 Durability

Figure 6.19 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the durability of the AWARE Sentry system. Similar to the Intellicone and Single Sentry Beam system survey results on this topic, the results from both the surveys show that a majority of the maintenance workers did not provide a response to questions relating to the durability of the AWARE Sentry system. Therefore, it is difficult ascertain anything definitively from the responses.

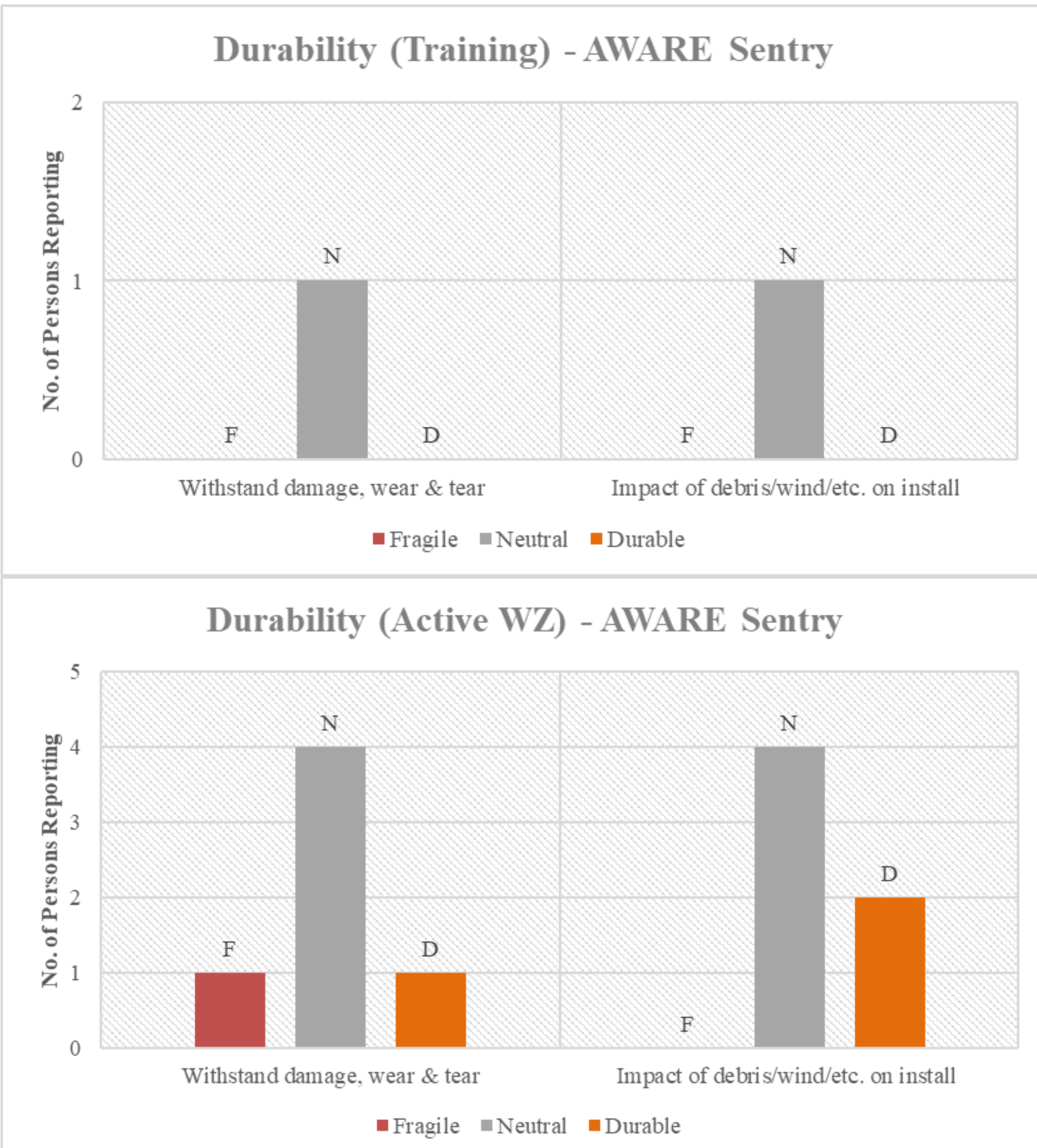


Figure 6.19 Comparison of Survey Results for AWARE Sentry Durability

6.5.4 Sound Distinctiveness

Figure 6.20 shows the survey responses, during the training sessions and active work zone testing, to questions regarding the sound distinctiveness of the AWARE Sentry system. The results from the training session survey were mostly "Neutral" on the sound distinctiveness of the AWARE Sentry system. The results of the active work zone survey clearly show that the workers perceived the system sound to be distinctive. The results could be explained by the fact that during the training session, the workers were in close proximity to the AWARE Sentry base station and could clearly hear the base station alarm sound, which is similar to a police siren. However, in the active work zone, the maintenance workers were farther away from the base station and the only alarm sound that could be clearly head was that from the WorkTRAX PSD, which is different from a police siren. The mixed responses to the question about the direction of the intrusion could be attributed to the fact that when the WorkTRAX alarm is triggered, it may not be clear which AWARE Sentry device has detected an intrusion especially if two devices are placed either side of a work zone in a flagging operation.

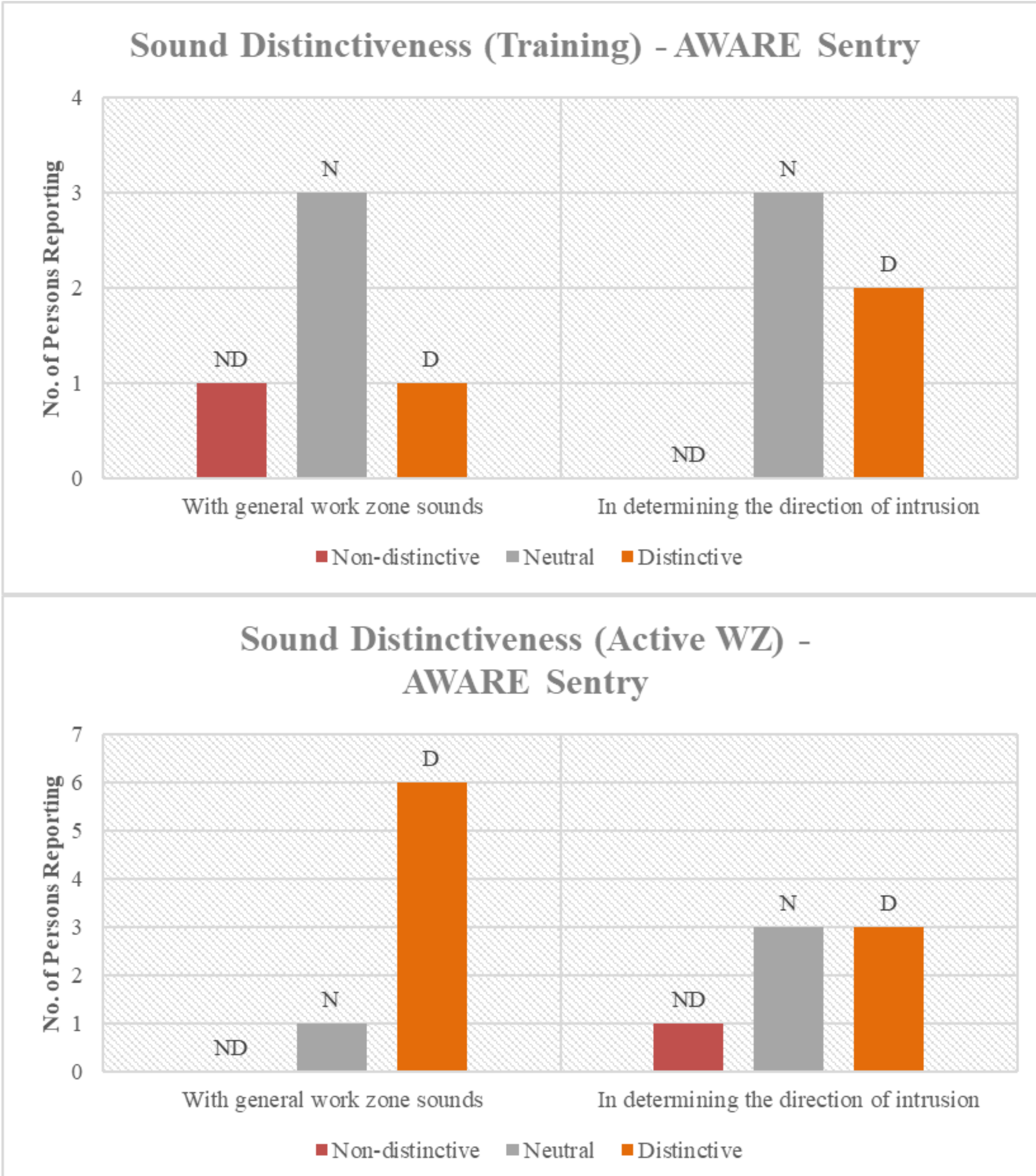


Figure 6.20 Comparison of Survey Results for AWARE Sentry Sound Distinctiveness

6.6 OVERALL SURVEY RESULTS

The survey included two questions that were intended to capture the overall impressions of the maintenance workers in determining the effectiveness of the selected WZIA systems. The first question related to the overall effectives of the WZIA systems relative to each other, in mitigating work zone crashes. The second question related to whether the selected WZIA systems will improve overall work zone safety. The results of responses to the two questions are discussed in detail in the next section.

6.6.1 Mitigating Work Zone Crashes

Figure 6.21 and Figure 6.22 shows the result of survey responses to the question intended to capture the overall perception of the maintenance workers regarding the effectiveness of the selected WZIA systems in mitigating work zone crashes. In Figure 6.21, the results of the training session survey shows that the WAS and Intellicone System had the most "Moderately Effective" responses, and the SonoBlaster and AWARE Sentry systems had the most responses for "Slightly Effective." The "Slightly Effective" responses may be attributed to the considerations required to set up and deploy the SonoBlaster device. The AWARE Sentry device's effectiveness may be impacted by the use of a foot pedal, since the workers felt the device would be more efficient if the foot pedal was replaced with a wireless remote controlled by the flagger. Figure 6.21 also shows the Intellicone Single Sentry Beam having equal responses between "Very Effective" and "Slightly Effective" The conflicting responses may be attributed to the workers having a positive response to the laser beam's ability to provide continuous detection coverage, but negative responses toward the weight and limited range of the system.

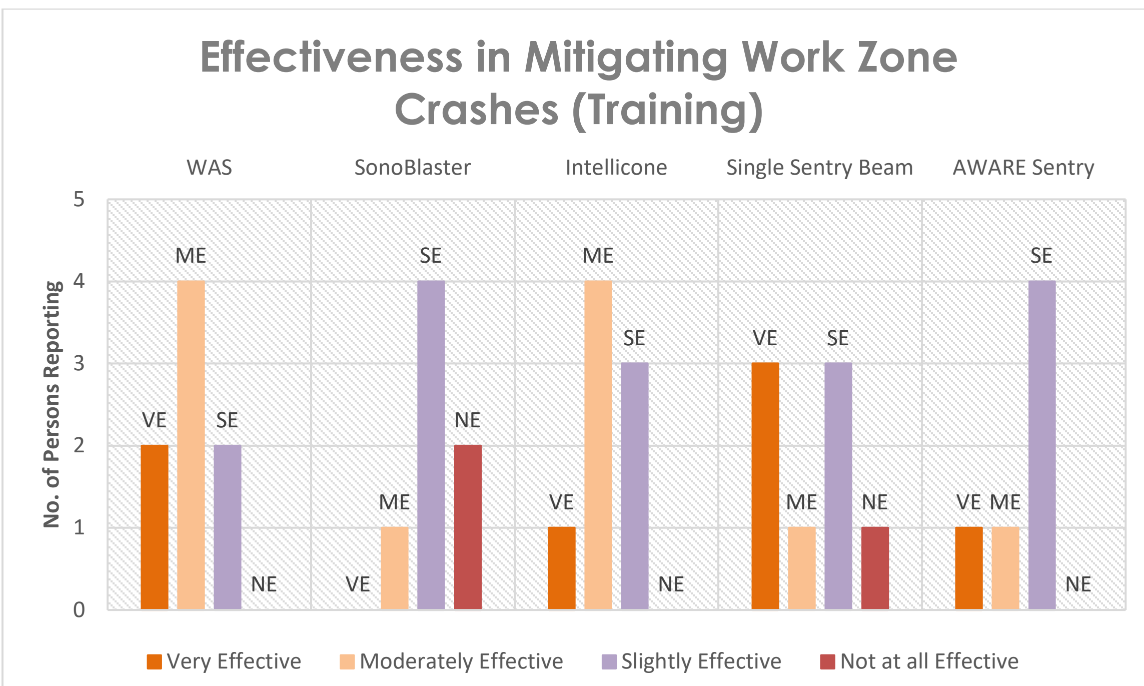


Figure 6.21 Training Session Survey Results for System Effectiveness in Mitigating Work Zone Crashes

In Figure 6.22, the results of the active work zone survey show improved perceptions of all the selected WZIA systems in mitigating work zone crashes with a predominance of "Very Effective" responses. The WAS and the Single Sentry Beam had the most responses as "Very Effective," while the Intellicone System, SonoBlaster, and AWARE Sentry systems had relatively mixed responses.

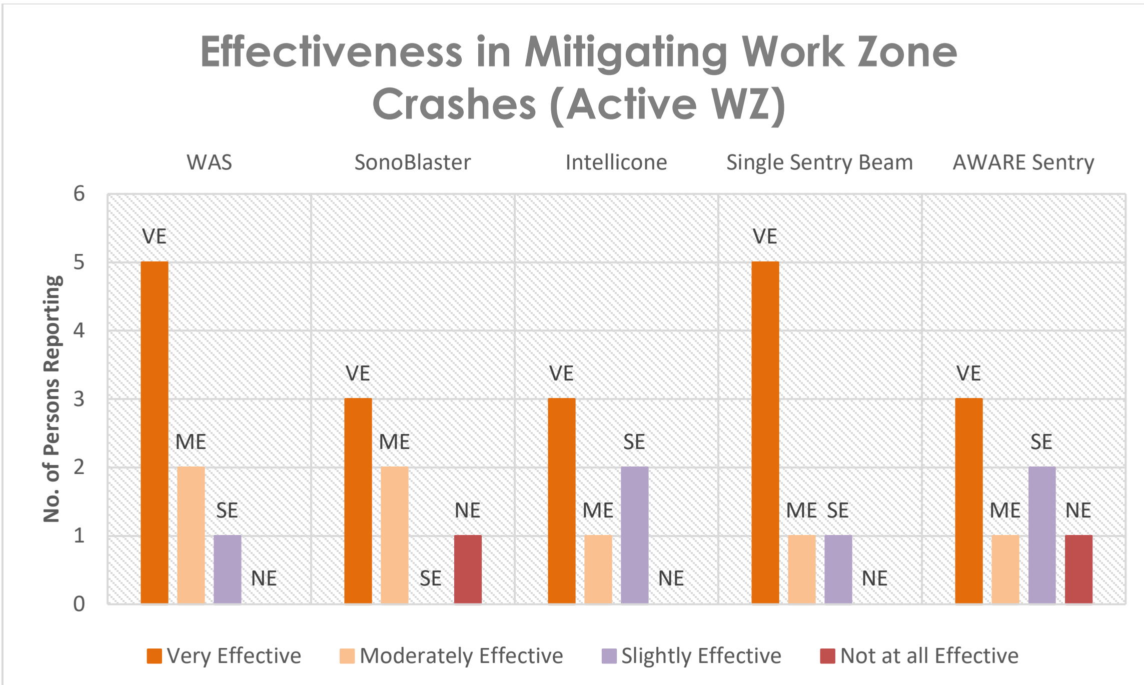


Figure 6.22 Active Work Zone Survey Results for System Effectiveness in Mitigating Work Zone Crashes

6.6.2 Improving Work Zone Safety

Figure 6.23 and Figure 6.24 show the results of survey responses to the question intended to capture the overall perception of the maintenance workers regarding the ability of the selected WZIA systems to improve work zone safety. Figure 6.23 shows that the WAS, Intellicone, and AWARE Sentry systems received the most "Slightly Likely" responses compared to the other systems, with the Single Sentry Beam receiving the second highest number of "Slightly Likely" responses. The SonoBlaster system received the most "Not at All Likely" responses, which may be due to (1) the workers' concern surrounding exposure to traffic during deployment of the SonoBlaster system in high-speed work zones and (2) the time and effort required to install individual devices on cones.

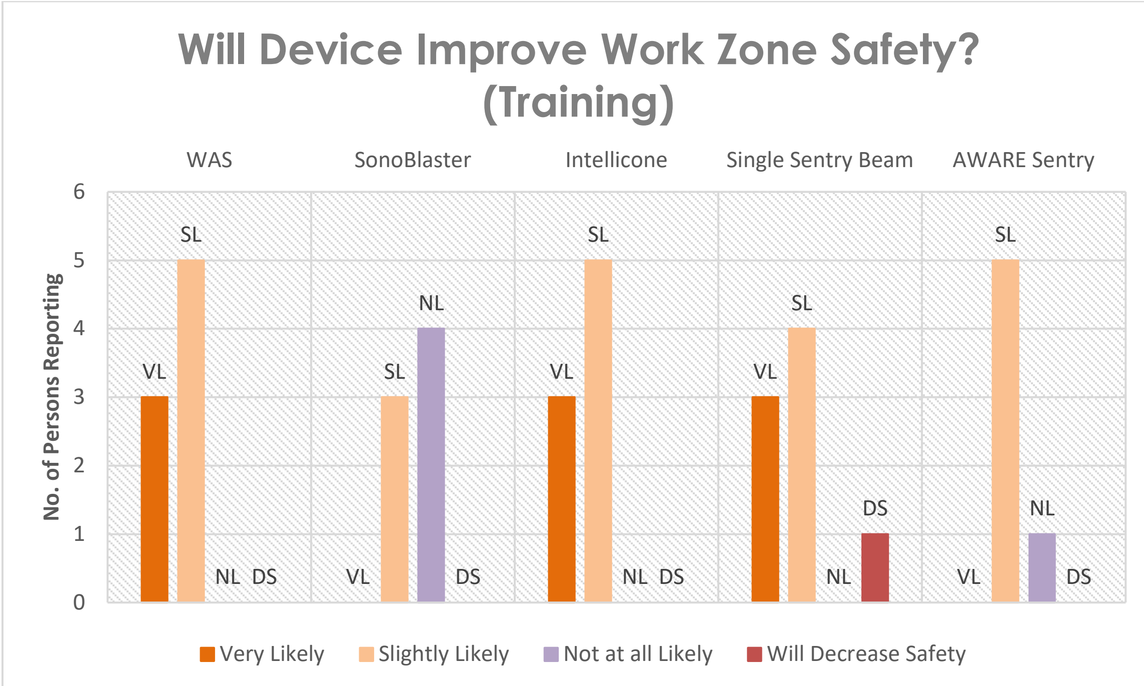


Figure 6.23 Training Session Survey Results on Systems' Ability to Improve Work Zone Safety

In Figure 6.24, the results of the active work zone survey show improved perceptions of all the selected WZIA systems in improving work zone safety with a predominance of "Very Likely" responses. The WAS received the most "Very Likely" responses compared to the other systems, with the Single Sentry Beam receiving the second highest number of "Very Likely" responses. The Intellicone System, SonoBlaster, and AWARE Sentry system had more mixed responses, although "Very Likely" was still the most prevalent response for these systems.

It is evident from Figure 6.21 through Figure 6.24 that once the maintenance workers tested and evaluated the selected WZIA systems in active work zone conditions, their overall perceptions of the systems improved considerably in terms of the effectiveness of the devices in mitigating work zone crashes, and of the systems' ability to improve overall work zone safety. This is also reflected in the written comments and discussions with the maintenance workers, indicating that while there may be specific issues and difficulties with certain systems, any system that can provide some level of warning to the workers about possible intrusions would be beneficial to improving the safety of the work zone. Figure 6.21 through Figure 6.24 show that each selected WZIA system has the potential to effectively mitigate work zone crashes and improve overall safety when used selectively in appropriate types of work zones under the right types of conditions, as discussed throughout this report.

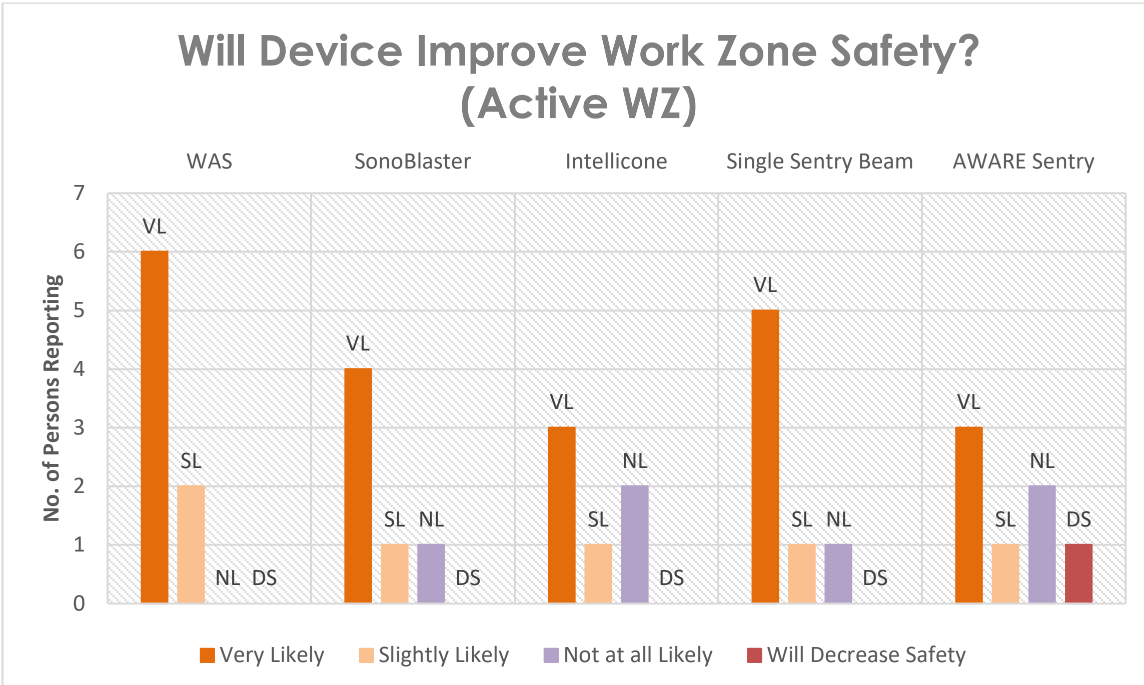


Figure 6.24 Active Work Zone Survey Results on Systems' Ability to Improve Work Zone Safety

7 ADDITIONAL TESTING AND EVALUATION

7.1 ADDITIONAL TESTING AND EVALUATION

The main focus of this research was the five WZIA systems selected in consultation with the Project Advisory Panel discussed in detail in the previous chapters. However, two new WZIA systems became available on the market at the later stages of the research, which were also procured as part of additional testing and evaluation tasks. The objective was to conduct limited testing on these systems to determine their capabilities, deployment, practicality, effectiveness, and reliability. The two new systems procured were the Guardian Cone system and the Alpha SafeNet Overwatch system.

7.1.1 Guardian Cone

The Guardian Cone is a radar-based device designed to alert workers to approaching vehicles exceeding a certain speed threshold. The Guardian Cone system consists of a cone sensor (Figure 2.12) deployed on a standard cone, which can detect the speeds of incoming vehicles. Based on the set threshold, the cone sensor can send a wireless signal to a wearable receiver (Figure 2.13). The device emits auditory and vibratory alerts based on incoming vehicle speeds exceeding a preset threshold. Details of the Guardian Cone system were presented in section 2.3.2 of this report.

To evaluate the capability and effectiveness of the Guardian Cone system, a limited series of tests was conducted on a two-lane road (College Town Drive) on the California State University Sacramento campus. The speed limit on the road was 25 mph and vehicles typically traverse a straight section of the roadway at between 25 and 35 mph. The system was tested with speed alert thresholds set to 15, 25, 30, and 35 mph.

The cone sensor was deployed on a standard cone and placed near the edge of the roadway (Figure 7.1). The wearable receiver was then tested at distances of 200, 330, and 380 feet from the cone sensor. At each distance range, the four different speed threshold settings were tested to assess the functionality of the system. The Guardian Cone system emits different sounding alerts depending on how much an approaching vehicle exceeds the set speed threshold.

Figure 7.1Guardian Cone Deployment on Two-Lane Road

The Guardian Cone system performed well at the various distances tested, detecting all approaching vehicle speeds, and emitting the different alarms according to the specifications. As per manufacturer specifications, the wearable device emitted a louder and more "urgent" alarm tone when vehicle speeds exceeded the set speed threshold by more than 15 mph. The Guardian Cone system is designed to send a vibratory alert to the wearable device, every time a vehicle is detected, regardless of the speed. The manufacturer specifications indicate that the system is designed to be deployed in areas of sporadic traffic where one or two workers must perform work and may not have additional help to keep a watch on traffic. Therefore, while this feature is effective in such conditions, roadways with more traffic may result in too many vibratory alerts, distracting the workers or forcing them to ignore some alerts.

The manufacturer instructions indicated that the presence of trees and metal objects may affect the performance of the system. Therefore, a second

Guardian Cone system was deployed and tested at the same distances and speed thresholds as previously noted, on the other side of the roadway where several trees were present. The goal was to test the operation of the system without a clear line of sight, as shown in Figure 7.2.

Figure 7.2 Guardian Cone Testing Without Clear Line of Sight

Despite the proximity of the metal fence, as shown in in Figure 7.1, the signal was not affected, and the system performed optimally throughout all the tests. While testing the system without a clear line of sight due to presence of trees, there were some instances of lost signal between the cone sensor and the wearable receiver and there were two false positive alerts. The reason for the lost signal and false positive alerts was unclear.

Overall, the Guardian Cone system performed well during the limited testing according to manufacturer specifications. The system is designed for use in sporadic traffic conditions and by limited workers working on or near the side of the roadway. Deployment of the system is easy, and the alerts allow for workers to pay attention based on the speeds of approaching vehicles. As such, this system would be useful for deployment in rural areas and other similar low traffic conditions.

7.1.2 Alpha SafeNet Overwatch System

The Alpha SafeNet Overwatch system device (Figure 2.14) utilizes LiDAR laser technology to create an invisible barrier between the work zone and traffic. When a vehicle or person crosses the path of the laser, the system emits an auditory siren with flashing LED lights. In terms of capabilities, the Overwatch system is very similar to the Single Sentry Beam in providing a continuous barrier and coverage in a work zone. The Overwatch system also includes an Auxiliary Horn Unit (AHU) that acts as a portable speaker placed near the workers as an additional warning device. The Overwatch system laser can be set to terminate at a fixed distance or to its maximum range of 700 feet. Details of the Overwatch system are presented in section 2.3.3 of this report.

In an effort to evaluate the capabilities and effectiveness of the Overwatch system, a limited series of tests (two trials) were conducted on the same two-lane road (College Town Drive) on the California State University Sacramento campus as described in the previous section. There was no work zone set up on the roadway to detect vehicle intrusions. Instead, the Overwatch system was used to detect any incoming vehicle on the road and verify whether the system was able to detect vehicles at specified distance ranges and under the given conditions.

For the first trial, the target cone was placed 312 feet upstream from the system unit to set up the laser to detect vehicles at that distance (Figure 7.3). The Overwatch device was located on one edge of the roadway and the target cone was placed on the opposite side of the road to detect all passing vehicles. The 135 dB alarm was not turned on because there was concern that the alarm may cause too much stress on drivers. During the first trial, the lights on the device unit activated for every oncoming vehicle passing through the LiDAR beam for a duration of approximately 3 seconds given the placement of the system and vehicle speeds. It was noted that lightly tapping or bumping the device will also activate the lights.

Figure 7.3 Overwatch Trial 1 Setup on Two-Lane Roadway

The portable horn unit (AHU) was turned on temporarily during the first trial. The AHU was placed with no clear line of site about 332 feet downstream from the system unit, as shown in Figure 7.4. The AHU remained fully operational at this distance, sounding the alarm for every detected incoming vehicle. When the AHU was activated, the alarm sounded for about 2 to 3 sec before deactivating once the vehicle had gone outside the laser detection beam. It was noted that the incoming vehicle noticeably lowered their traveling speed despite already traveling at or near the speed limit. The AHU was turned on and off after the system was already armed and in use during the first trial and showed no issues.

Figure 7.4 Overwatch Auxiliary Horn Unit Placement Trial 1

For the second trial, the Overwatch system unit was turned 180 degrees to face traffic in the opposite direction of trial 1 and a target cone was placed 321 feet upstream of the system unit (Figure 7.5 and Figure 7.6). Once the target was set and the system was armed, it was observed that the lights on the device were activating sporadically. Although the system was detecting incoming vehicles activating the lights for about 2 to 3 seconds, the lights were also activating very quickly and erratically when no vehicles were present. It was determined that the overgrown grass behind the target cone was the cause. The movement of the grass in the wind was possibly interfering with the laser signal and triggering the alarm. Therefore, the target cone was moved to about 267 feet upstream of the system unit. At this new placement there were no further erratic activations, and all incoming traffic was detected.

The results of the two trials of the Overwatch system showed that the system is successful in triggering an alarm whenever the LiDAR laser beam is disrupted by a vehicle. The sound of the alarm unit and AHU was very loud and resembles the sound of a fire engine siren. Despite having the system alarm inactive during the trials, most vehicles reduced their speeds once the lights on the system unit were activated. The added ability to deploy the AHU which connects wirelessly to the main unit at 300+ foot range allows for greater flexibility in deploying the system in a work zone at various locations to warn workers of intrusions.

It should be noted that while the LiDAR laser on the Overwatch system offers considerable range, setting up the laser in the correct direction can be challenging. The LiDAR device attaches to the top of the base unit and must be set up pointing at the target cone through a detachable video screen. Once set up, even a slight movement of the base unit or the LiDAR atop the box may result in a large shift in the direction of the laser beam at longer distances. Additionally, the alarm on the Overwatch system operates like an on/off switch, i.e., the alarm will sound only for the duration during which the laser beam is disrupted and will switch off as soon as the disruption goes away. Therefore, there is no consistency in the duration of the alarm and it was observed that slower moving vehicles produced an alarm of longer duration and, vice versa.

Figure 7.5 Overwatch Trial 2 Setup on Two-Lane Roadway

Figure 7.6 Overwatch Trial 2 Cone Placement

8 SUMMARY, DISCUSSIONS, AND RECOMMENDATIONS

The main goal for this research was to evaluate the effectiveness and practicality of deploying and operating selected WZIA systems in California work zones. The objective was to provide recommendations and guidance to Caltrans on the effectiveness and practicality of implementing such systems in active work zones through field observations and feedback provided by Caltrans maintenance staff. Selected WZIA systems were procured and tested in active work zone conditions after two crews of Caltrans maintenance workers were provided an opportunity to train with the systems. Worker feedback on the performance and effectiveness of the systems was collected before and after testing in active work zone conditions. The selected WZIA systems were tested in a variety of active work zone conditions to ascertain their capabilities related to deployment, operation, effectiveness, retrieval, and potential to improve work zone safety. A summary of the observations, evaluation, recommendations, and conclusions is presented in this chapter. Additionally, a number of general recommendations, based on overall observations and experiences in this research, are presented to outline best practices for use of WZIA systems.

8.1 WORKER ALERT SYSTEM

8.1.1 Summary

This section presents a summary of the evaluation of WAS through observations during the training sessions and active work zone testing, and from results of the maintenance worker surveys.

- WAS utilizes pneumatic hoses to provide continuous coverage to detect potential vehicle intrusions into a work zone.
- Multiple pneumatic hoses can be utilized within the same work zone to provide additional detection coverage and wirelessly connect with multiple alarm units.
- WAS is one of the few systems to offer a PSD to alert individual workers of vehicle intrusions.
- The system provides both visual and audio alerts through the alarm unit and additional haptic alert through the PSD; although the visual alert is limited, given the placement of a small light source only on one side of the alarm unit.
- The WAS alarm unit consists of a magnet allowing it to be attached to a vehicle or any other metal surface in a work zone.

- The system requires pre-deployment steps (charging of alarm unit battery and replacements of AA and AAA batteries in the hand-held remote, PSD, and pneumatic hose pressure sensor).
- A single crew member typically requires 5 to 10 minutes to deploy, and similar time to retrieve, a set of three pneumatic hoses and six alarm units in a typical shoulder/lane closure work zone. Deployment and retrieval times may be reduced for ramp closures.
- The maximum range stated by the manufacturer of 1,000 feet could not be achieved, and systematic trials concluded that the maximum range to deliver consistently 100 percent success in alarm activation was (Khan et al, 2019):
  - 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.
- The WAS performs consistently when the alarm unit is placed at least 4 feet above the ground; easily achieved by attaching the alarm unit to a vehicle in a work zone using the magnet on the unit.
- Moving the pneumatic hoses or the alarm units after deployment is possible without triggering the alarm if the activity area shifts or moves within a closure.
- The alarm unit sound is more effective when multiple alarm units are used close to the activity area. The alarm duration was 5 seconds.
- Deploying the WAS pneumatic hoses inside the taper and closure perpendicular or diagonal to the movement of traffic is the safest option to reduce worker exposure to traffic during deployment, but this increases the potential for false alarms due to equipment movement inside the closure.
- Deploying the WAS pneumatic hoses parallel to traffic edge of closure provides additional coverage in detecting vehicle intrusions, but increases the potential for damage to the hose sensor and exposure to workers while deploying the hoses.
- Deployment on ramp closure is simple with less potential for worker exposure to traffic given the presence of a shadow vehicle at the point of closure.
- Caltrans maintenance workers liked the simplicity and flexibility of the system in deployment, operation, and overall improvement of work zone safety.
- Caltrans maintenance workers found the alarm unit sound (multiple alarm units used together) and PSD alarm and haptic alert to be effective.
- A few false alarms were observed during active work zone testing due to the nature of the manual activation buttons on the PSDs, which slightly

protrude from the body of the PSD. The manual activation button on PSDs inside the pockets of the maintenance workers' clothing would be accidentally pressed against equipment or clothing as the maintenance crews were working, resulting in accidental false alarms.

- Retrieval is easy and quick with minimum exposure. Workers need to remember to turn off the sensor to preserve batteries.
- The cost of the system is moderate in comparison with other systems procured during this research.

8.1.2 Discussion and Recommendations

Based on the evaluation of WAS through observations during active work zone testing and worker training sessions, and from results of maintenance worker surveys, the following general recommendations are provided for use of WAS in the field.

The WAS performed effectively in both shoulder/lane closure and ramp closure work zones with certain limitations and considerations. The system can be deployed in both high-speed (freeways) and low-speed work zones. It is important to note that the effectiveness of a timely warning to workers in a work zone is highly dependent on the exact point of vehicle intrusion in a work zone and the coverage provided by WZIA system. If a vehicle enters the work zone very close to or within the activity area, no system would be effective in providing a timely alert to workers. However, a vehicle travelling at 65 mph entering a work zone at the earliest point of detection (pneumatic hose) will take approximately 2.36 seconds before reaching the closest WAS alarm unit, providing the workers at least that much reaction time to take evasive actions. Video observations of WAS during active work zone testing revealed that most workers reacted to alarm trigger within one second. Therefore, a potential 2 to 3 second warning/reaction time could be useful in alerting workers in a work zone. With deployment of WAS in lower speed work zones, or given lower vehicle entering speeds, the reaction time available to workers to take evasive actions would potentially be greater, depending on the earliest point of vehicle detection/intrusion. Therefore, there are potential safety benefits to be gained from the deployment of WAS in both high-speed and low-speed work zones.

While the WAS pneumatic hoses allow for some flexibility in the deployment configuration of the system in a work zone, two deployment configurations are recommended based on the outcomes of this research, as illustrated in Appendix E.

In the first configuration, the WAS pneumatic hoses may be deployed diagonally inside the closure, resulting in less exposure to workers because they are away from the traffic lane during deployment. However, this configuration may increase the potential for false alarms due to equipment movement inside the closure. Therefore, it is recommended that the deployment of pneumatic hoses diagonally or perpendicular to the movement of traffic be considered for work zones with high-speed traffic or low levels of activity.

In the second configuration, the WAS pneumatic hoses may be deployed parallel to the traffic edge of the closure. This deployment configuration has the benefit of being closest to the point of vehicle intrusion in to a work zone and may provide additional coverage length depending on the number pneumatic hoses used. However, such a deployment may increase worker exposure to moving traffic and potential damage to the pneumatic sensor because they are closer to the moving traffic lane.

Therefore, it is recommended that the deployment of pneumatic hoses parallel to the traffic edge of the closure be considered for work zones with low-speed traffic or high levels of activity within the work zone. It should be noted that observations during the training sessions, active work zone testing, and maintenance worker surveys revealed that the maintenance workers preferred the parallel deployment configuration of the WAS pneumatic hoses, possibly due to the increased coverage provided by the length of multiple pneumatic hoses deployed end-to-end. Nevertheless, the final decision on deployment configuration should be taken by the maintenance crew supervisor in general view of the traffic speed conditions, type of closure, amount of expected activity within the work zone, and potential for worker exposure during deployment.

Additional factors that may also affect the deployment configuration are the size of the work zone closure and the availability of the number of WAS pneumatic hoses and alarm units. When pneumatic hoses are deployed parallel to moving traffic, as was the case during active work zone testing of WAS in a shoulder closure, the three 33-foot pneumatic hoses provide a combined coverage length of approximately 100 feet deployed end-to-end. Given the effective range of 225 feet between the closest pneumatic hose and alarm unit, the total work zone coverage area thus available was approximately 325 feet. When pneumatic hoses are placed diagonally to the moving traffic some distance apart from each other (75 feet max.) as illustrated in Appendix E, the total work zone coverage area can be extended to approximately 375 feet; with some gaps given the diagonal deployment configuration. These reference coverage lengths can be used to determine the need for number of pneumatic hoses for work zones of various sizes and lengths in the field. It should be noted that the manufacturer has discontinued the sale of 33-foot pneumatic hoses and only12-foot length hoses are now available; therefore, an end-to-end coverage length of 100 feet would require eight to nine pneumatic hoses if 12-foot hoses are used.

The use of WAS in ramp closures was effective, as the pneumatic hose can be placed at the entry point of the ramp to provide sufficient coverage to detect any intruding vehicles. During typical Caltrans ramp closure, the entry point of a ramp is protected by a shadow truck blocking any vehicle entry. In such cases, the WAS pneumatic hoses can be deployed alongside or around the shadow truck to cover potential gaps where vehicles may possibly intrude. The curvature of a ramp may also reduce or eliminate the chance of the alarm unit being out of range of the pneumatic hose; however, this is dependent on the size and length of the ramp. The WAS on a ramp closure may also be used on a sidewalk to detect potential bicycle or pedestrian intrusions.

The number of alarm units required to provide a sufficiently loud warning to work zone workers depends on the traffic and general noise levels in a typical work zone. Each WAS alarm unit is capable of an approximately 60 dBA alarm. Based on the observations during the training sessions and active work zone testing in this research, the use of four alarm units was sufficient in alerting workers during shoulder closure on a freeway with moderate traffic levels and equipment noise such as a generator truck, etc. However, it is recommended that at least five WAS alarm units be deployed in all types of work zones to cover higher noise levels due to additional equipment, increased traffic levels, considering spacing between alarm units deployed near the activity area.

Based on the outcomes of this research, additional general recommendations are summarized as follows:

- Even though the batteries used in the WAS system (AA, AAA, and rechargeable alarm unit battery) can last for multiple days, it is recommended that fresh disposable batteries be installed before each deployment. One reason for this recommendation is that workers often forgot to turn off the pneumatic sensor hoses or the PSD resulting in battery drainage. The alarm unit battery should be recharged overnight before deployment in an active work zone.

- The maintenance worker deploying the pneumatic hoses should always remember to turn on the hose sensor before placing the hose on the pavement.
- For optimal and consistent operation, special attention should be paid to ensure that the maximum distance range between the closest pneumatic hose and alarm unit, between two alarm units, and between a PSD and alarm unit, does not exceed 225 feet, 175 feet, and 75 feet, respectively.
- Given the need to place the alarm unit or the pneumatic sensor hose at least 4 feet above the ground for consistent operation, it is recommended to the manufacturer to offer a zip or Velcro strap that will allow users to place the hose sensor above ground.
- To avoid false alarms due to the activation button on the PSD, it is recommended that the manufacturer remove or disable the manual activation button.
- Providing Velcro straps is recommended to help keep hoses organized after retrieval and for easier transport.
- Providing a weight is recommended to be placed at the end of the hoses to be more stable and stationary.

8.2 SONOBLASTER

8.2.1 Summary

This section presents a summary of the evaluation of SonoBlaster, through observations during training sessions and active work zone testing and from results of maintenance worker surveys.

- The SonoBlaster is a mechanical system consisting of an alarm trigger that activates a pressure horn powered by high pressure gas released from a CO_2 cartridge. The SonoBlaster can be installed on individual cones or drums in a work zone.
- The system provides an audible alarm, only when a cone with an attached SonoBlaster unit is impacted by a vehicle. The SonoBlaster was one of the loudest systems tested, with the alarm sound level at 125 dBA that consistently lasted for 15 to 90 seconds.
- The SonoBlaster system is the only unit that does not require batteries; instead, it utilizes a CO_2 cartridge to power a pressure horn which is triggered when the cone is tilted by more than 70 degrees.
- The system requires pre-deployment steps involving (1) installation of a mounting bracket on a cone or drum to which the SonoBlaster unit is attached, and (2) installation of a CO_2 cartridge.

- Installation of the mounting bracket and the CO_2 cartridge is a one-time operation, unless the SonoBlaster is impacted by an intruding vehicle.
- The average installation time for a SonoBlaster unit was found to be approximately 12 minutes for an experienced user.
- Installing the mounting bracket under the cone base, as per manufacturer instructions, is not possible due to the base thickness.
- One issue observed during testing was that the CO_2 cartridge could not be properly installed in some cases, without any indication of an improper install. This may result in non-activation of the alarm when the cone is hit by an intruding vehicle.
- Multiple cones, with SonoBlaster units installed, can stack on top of one another. However, it was observed during testing that a typical Caltrans cone body truck cannot accommodate two rows of stacked cones laying on their side with SonoBlaster units installed, reducing the capacity of the cone body truck.
- The deployment of a SonoBlaster installed cone requires a series of steps involving picking up of the cone, unlocking the unit, and placing it on the pavement without tilting the cone by more than 70 degrees. This may result in accidental activation of the alarm during cone deployment from a standard Caltrans cone body truck.
- Caltrans maintenance workers preferred to deploy to the SonoBlaster installed cones from the front of the shadow truck.
- The greater the number of cones and drums with SonoBlaster deployed, the greater the coverage in a work zone. However, the SonoBlaster system does not provide continuous coverage like the WAS, due to gaps between cones or drums in a work zone.
- A benefit of the SonoBlaster system is that users do not have to worry about range considerations during deployment (whether units are within a certain range or not).
- Moving a SonoBlaster installed cone or drum is not recommended after deployment, as a tilt of more than 70 degrees may result in accidental trigger of the alarm.
- There were potential durability issues after a few activations, so the device should be discarded after alarm activation.
- During the training sessions, the Caltrans maintenance workers expressed concern because of the time and effort required for installation and possible increased worker exposure during deployment.
- During active work zone testing, the Caltrans maintenance workers were less concerned about installation effort, since the cones delivered to them were pre-installed with SonoBlaster units. However, exposure concerns persisted, especially in high-speed work zones.

- Retrieval of the SonoBlaster installed cones was relatively easy and without any issues, as long as the workers remember to lock the unit before picking up the cones to prevent accidental alarm activation.
- Although the cost of the SonoBlaster unit is low, the need for multiple units to be installed on individual cones to provide adequate work zone coverage may result in increased costs.

8.2.2 Discussion and Recommendations

Based on the evaluation of the SonoBlaster through observations during active work zone testing and training sessions, and from maintenance worker survey results, the following general recommendations are provided for use of SonoBlaster in the field.

The SonoBlaster system received higher evaluations for low-speed vs. high-speed conditions, primarily due to worker exposure concerns. The steps involved in the deployment of the SonoBlaster installed cones make it difficult to avoid getting close to moving traffic. Even if cones are deployed from a moving vehicle, the process of unlocking the SonoBlaster unit either slows down the process of cone deployment or requires a separate worker to visit each cone and unlock the unit after being placed on the pavement, resulting in extra time close to moving traffic, increasing exposure. This issue was observed first-hand during active work zone testing in this research when the SonoBlaster system was partially deployed on a lane closure on a freeway. It is for this reason that the SonoBlaster system is not recommended for use in high-speed work zones and should only be used in low-speed traffic conditions. The use of the SonoBlaster system is generally more effective in ramp closures because of lower traffic speeds (reducing worker exposure to traffic) and the ability to deploy cones with SonoBlaster units installed as a barrier at the entry point of the ramp.

The effectiveness of the SonoBlaster system is highly dependent on where exactly a vehicle intrusion occurs in a work zone. The greater the distance between a vehicle intrusion hitting a SonoBlaster installed cone, the greater the reaction time will be available for workers to take evasive actions. Furthermore, the greater number of cones installed with SonoBlaster units, the greater the potential to detect a vehicle intrusion. One of the limitations of the SonoBlaster system is that it is unable to provide continuous coverage in a work zone due to gaps between the deployed cones. Maintenance workers may deploy additional cones with shorter gaps than recommended by the Caltrans Standard Traffic Control Plans. However, this may result in some additional exposure to workers, given the increased time required to deploy a larger number of cones. Therefore, it is recommended that careful consideration be given to the traffic and work zone conditions while deploying the SonoBlaster system.

Given the observations in this research surrounding the effort required to install SonoBlaster units to cones and drums, it is recommended that maintenance crews set aside a group of cones in the maintenance yard and pre-install the SonoBlaster units to those cones or drums well ahead of time. This installation is a one-time effort and the cones can be used repeatedly in multiple work zones. As was evident by the feedback from the maintenance workers during active work zone testing, there were fewer concerns about pre-installation effort required when the workers were provided with pre-installed SonoBlaster cones. Maintenance supervisors can emphasize the benefits of the SonoBlaster system not requiring battery replacements for each deployment and other charging requirements. Care should be taken during the installation of the CO_2 cartridge, which can sometimes be 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. Given the issues surrounding the durability of the SonoBlaster unit if hit by a vehicle, it is recommended that such a unit be discarded and not used again.

As was observed in this research, the deployment of the SonoBlaster system is possible from the standard Caltrans cone body truck. However, it requires careful handling of the cones, from picking the cone from a side position to unlocking the alarm unit and placing the cone on the pavement, resulting in a possibility of accidental activation of the alarm. Furthermore, fitting two rows of SonoBlaster installed cones in a standard Caltrans cone body truck is not possible. Therefore, the preferred deployment method recommended by this research is to deploy the SonoBlaster installed cones from the front of the shadow truck with cone carrying capability.

Based on the recommendations provided by the maintenance workers and outcomes of this research, a few other general recommendations are summarized as follows:

- Manufacturer should provide self-tapping screws when attaching the bracket to the cone.
- Manufacturer should consider the use of clips instead of a bracket that can attach to the protruding parts of the cone base, reducing installation time and improving ease of removal if needed.

- Manufacturer should provide an assembly for the SonoBlaster unit to be "dropped" on top of the cone to allow for quick and easy installation and deployment.
- If possible, link the cones together using a chain or tie to activate multiple units if a vehicle intrudes between cones or hits a single cone. Note that this may create a barrier preventing the entry of authorized vehicles in a work zone.

8.3 INTELLICONE SYSTEM

8.3.1 Summary

This section presents summary of the evaluation of the Intellicone system through observations during the training sessions and active work zone testing, and from results of maintenance worker surveys.

- The Intellicone system consists of an alarm unit (PSA) that is triggered when a special lamp deployed on a cone (with a sensor, that wirelessly connects to the alarm unit) is hit by an intruding vehicle.
- The PSA provides both visual and audible alerts using a three-tone alarm that is specially designed to be highly effective in alerting workers.
- The audible alarm duration is approximately 30 seconds with an average sound level of approximately 60 dBA.
- The visual alarm has rotating lights with two different colors.
    - A red alert is for automatic detection of vehicle intrusion impacting a traffic cone with a special lamp installed.
    - A blue alert is for manual activation to warn of an expected delivery and other authorized vehicles.
- The visual alarm component is not very effective in daylight but is highly effective at night.
- The maximum transmission range observed was 100 feet between two lamps and between a single PSA and the closet lamp, as stated by the manufacturer.
- The PSA unit has additional cellular network connection capability that allows two PSA units to transmit alarms over an unlimited range without intermediate lamps (not required for connection within 100 feet between two PSA units).
- Multiple cone lamps can tether with others to transmit the signal to the PSA, theoretically with an unlimited range according to the manufacturer.
- The Intellicone system requires pre-deployment steps such as charging the PSA battery overnight and checking the batteries in the cone lamps.

- The Intellicone system also consists of an online dashboard that can be used to optionally geofence the operational range of PSA. This allows for multiple Intellicone setups to operate separately when deployed within close proximity of each other.
- A single worker can easily carry up to three PSA units and up to eight cone lamps when deploying in a work zone on foot. However, this does result in worker exposure issues, especially in high-speed work zones.
- Deployment of the cone lamps from a Caltrans cone body truck is also possible, as was tested in this research, and preferred by the maintenance workers resulting in reduced exposure to traffic when deploying the lamps on foot.
- Deployment on ramp closure is simple with less potential for worker exposure to traffic, given the presence of a shadow vehicle at the point of closure.
- The PSA can be deployed on a cone and placed close to the activity area. The PSA requires 3 to 5 minutes to connect and be ready to operate.
- The greater the number of cone lamps deployed, the greater the coverage in a work zone. However, the Intellicone system does not provide continuous coverage like the WAS due to gaps between cones deployed in a work zone.
- Moving the cones with a cone lamp deployed is not possible without triggering the alarm.
- The alarm sound is more effective when multiple PSA units are used close to the activity area.
- Caltrans maintenance workers preferred having the PSA units close to the activity area to warn the workers of possible vehicle intrusions.
- Caltrans maintenance workers like the rotating visual alarm which would be useful during nighttime operation.
- Caltrans maintenance workers shared some concerns about wind or high-speed passing traffic disturbing the cones, resulting in alarm activation. However, no such issues were observed during active work zone testing close to high-speed traffic conditions.
- Even though the maintenance workers liked the ease of cone lamp deployment, concerned were shared about possible exposure to traffic when deploying and retrieving the cone lamps on foot.
- Caltrans maintenance workers liked the simplicity of the system in deployment and operation.
- Retrieval of the Intellicone system was easy; however, some issues related to exposure of workers to traffic were observed while retrieving the cone lamps.

8.3.2 Discussion and Recommendations

Based on the evaluation of the Intellicone system through observations during active work zone testing and worker training sessions, and from the results of maintenance worker surveys, the following general recommendations are provided for use of the Intellicone system in the field.

The overall performance of the Intellicone system was similar in low-speed and high-speed conditions. However, the main issue observed in this research in high-speed work zone conditions was worker exposure concerns when deploying the cone lamps on foot. These concerns were also shared by the maintenance workers during the training sessions, and they preferred to deploy the cones from the Caltrans standard cone body truck. However, during active work zone testing on a freeway shoulder closure, there was insufficient space for the cone body truck to operate within the closure to deploy the lamps, and operating the cone body truck in the traffic lane was infeasible. The cone lamps had to be deployed by a worker on foot over a distance of almost 600 feet, resulting in exposure to high-speed traffic. Therefore, it is recommended that the Intellicone system be primarily used in low-speed traffic conditions and may be deployed in a high-speed work zone if there is sufficient space available to operate a cone body truck within the closure. The use of the Intellicone system is more effective in ramp closures due to lower speeds and the ability to deploy cone lamps as a barrier at the entry point of the ramp.

Similar to the SonoBlaster system, the effectiveness of the Intellicone system is highly dependent on where a vehicle intrusion occurs in a work zone. The greater the distance between a vehicle intrusion hitting an Intellicone cone lamp and the workers, the greater time will be available for workers to take evasive actions. Furthermore, the greater number of cone lamps installed, the greater the potential to detect a vehicle intrusion. Similar to the SonoBlaster system, one of the limitations of the Intellicone system is that it cannot provide continuous coverage in a work zone due to gaps between the deployed cones. Maintenance workers may, however, deploy additional cone lamps on cones with shorter gaps than recommended by the Caltrans Standard Traffic Control Plans. However, this may result in some additional exposure to workers, especially if the cone lamps are being deployed on foot in high-speed conditions. Therefore, the deployment configuration for the Intellicone system recommended by this research involves placement of the cone lamps on as many cones as possible in work zone. Additionally, it is recommended to deploy a transverse set of cones with lamps within the closure in addition to installation on typical cone placements in the taper and the tangent sections, as illustrated in Appendix E.

The number of Intellicone PSA units required to provide a sufficiently loud warning to workers depends on the traffic and general noise levels in a typical work zone. Each PSA unit is capable of producing a three-tone alarm sound at approximately 60 dBA. Based on the observations during the training sessions and active work zone testing in this research with a 100-foot activity area, the use of two alarm units was sufficient in alerting workers during shoulder closure on a freeway with moderate traffic levels and equipment noise such as a generator truck. It is therefore recommended that at least two PSA units be deployed in all types of work zones. If the activity area is greater than 100 feet in length, additional alarm units are recommended to be deployed.

The Intellicone PSA has a rechargeable battery that can last for approximately 37 hours of continuous use. The PSA unit has a battery indicator and on/off button. It is recommended that the PSA be recharged overnight before each deployment in a short-term work zone.

Intellicone lamps require a lantern type disposable battery that can last for multiple months. There is no battery indicator on the cone lamps and no on/off button. The lamps turn on or off automatically when deployed or removed from a cone. Therefore, it is recommended that the batteries in all the cone lamps be replaced periodically at the same time and a quick battery check be performed at the maintenance yard by installing one of the cone lamps on a cone to check if the light turns on.

Based on the recommendations provided by the maintenance workers and outcomes of this research, two additional general recommendations are summarized as follows:

- Special attention should be paid to ensure that the maximum distance between the Intellicone lamps and the lamp and PSA unit does not exceed 100 feet to ensure optimal connection and consistent operation.
- Intellicone lamp spacing can be 100 feet but closer lamps may offer greater coverage.

8.4 SINGLE SENTRY BEAM

8.4.1 Summary

This section presents a summary of the evaluation of the Intellicone Single Sentry Beam system through observations during the training sessions and active work zone testing, and from the outcomes of maintenance worker surveys.

- The Single Sentry Beam system utilizes a portable laser beam to detect potential vehicle or pedestrian intrusions in a work zone.
- The system utilizes the same alarm unit as the Intellicone system (PSA) and can communicate wirelessly with a PSA at a maximum distance of 175 feet as observed in this research. The manufacturer stated 246-foot range distance could not be achieved during testing.
- The laser beam can be configured to detect intrusions at a user desired detection setting from 30 feet up to 115 feet. It takes approximately 10 seconds to complete the setup.
- The laser unit can operate continuously for up to 120 hours, requires overnight charging, and weighs approximately 45 lbs. with the battery installed.
- Deployment of the Single Sentry Beam laser unit is fairly simple. Once the device is turned on, it emits a beeping sound for 10 seconds indicating the laser is ready to be configured for a user desired distance range.
- The detection range can be set by pointing the laser at an object, such as a worker or vehicle, at the desired distance. The detection range resets after restarting the device.
- Once the laser unit is turned on and configured, it can be moved around to point the laser in any direction where detection is desired.
- The flexibility of the laser unit to be configured at a desired detection range was useful during testing in different types of active work zone conditions.
- An object is detected when the laser beam is interrupted, triggering the alarm on all nearby PSAs connected to the system.
- Although the manufacturer is the same for the Intellicone and the Single Sentry Beam system, the laser unit can only communicate with PSAs and does not tether to another laser unit or Intellicone cone lamps to extend the observed 175-foot maximum range.
- Multiple laser units can be deployed in a work zone to provide additional coverage; however, the lack of tethering capability limits the range distance between the laser unit and PSA.
- Worker exposure concerns were low during deployment and operation of the Single Sentry Beam system, given the deployment location and ability to point the laser in a desired direction.
- The features, deployment, and operation details and requirements of the PSA are the same as those described in the Intellicone section.
- Maintenance workers liked the flexibility in setting the laser detection range at multiple desired distance for specific work zone conditions.

- Maintenance workers agreed that multiple laser units would be required to provide adequate coverage in larger work zones, given the 175-foot range distance.

8.4.2 Discussion and Recommendations

Based on the evaluation of the Single Sentry Beam system through observations during active work zone testing, worker training sessions, and results of maintenance worker surveys, the following general recommendations are provided for use of the system in the field.

The Single Sentry Beam system performed effectively in both shoulder/lane closure and ramp closure work zones with certain limitations. While the system can be deployed in both high-speed (freeways) and low-speed work zones, the 175-foot range between the laser unit and PSA, plus the inability to tether with additional units to extend the range, limits the usefulness of the system in providing adequate warning to workers high-speed traffic conditions. Therefore, it is recommended that the Single Sentry Beam system be deployed in smaller and low-speed work zones. With deployment of the Single Sentry Beam system in a lower speed work zone, or given lower vehicle entering speeds, worker reaction time would potentially be greater, depending on the earliest point of vehicle detection/intrusion.

The use of the Single Sentry Beam system was effective in ramp closures as the laser beam could be placed at the entry point of the ramp to provide sufficient coverage to detect intruding vehicles. During typical Caltrans ramp closure, the entry point of a ramp is also protected by a shadow truck blocking any vehicle entry. In such cases, the Single Sentry Beam may be deployed ahead of the shadow truck to detect possible vehicle intrusion to provide warning to workers close to the entry point of the ramp. The laser unit can also be useful in detecting pedestrians or bicyclists potentially entering a closure.

The continuous coverage of the laser beam is useful in providing additional coverage in a work zone compared with systems that only deploy on cones. Furthermore, the continuous coverage allows for flexibility in deployment configuration depending on the conditions in a work zone and location of greatest threat of potential intrusions. During active work zone testing and training sessions, the maintenance workers instinctively placed the Single Sentry Beam laser unit near the traffic edge with the laser beam pointed in a direction parallel to the moving traffic. However, this deployment configuration was considered not to be safe given the weight of the laser unit and potential damage due to being struck by a vehicle. Therefore, the deployment configuration recommended in this research involves placing the Single Sentry Beam laser unit on the shoulder with the laser beam pointing in a direction perpendicular to the flow of traffic terminating near the traffic edge of the work zone. Multiple laser units can be deployed in this configuration to provide additional coverage within the closure, as illustrated in Appendix E. This configuration also reduces potential worker exposure when deploying the system. However, this configuration may increase the potential for false alarms due to equipment movement inside the closure. Therefore, it is recommended that the deployment of the Single Sentry Beam system be considered for work zones with low levels of activity. The final decision on deployment configuration should be taken by the maintenance crew supervisor considering traffic speed conditions, type of closure, amount of expected activity within the work zone, and potential for worker exposure during deployment.

The number of alarm units required to provide a sufficiently loud warning to work zone workers and associated recommendations are similar to the ones presented in the Intellicone section of this report.

Based on outcomes of this research, two other general recommendations are summarized as follows:

- The Single Sentry Beam laser is invisible, unlike the functionally similar visible pneumatic hose of the WAS, resulting in a few instances of workers inadvertently triggering the alarm. Therefore, the laser unit is not recommended for deployment close an area of high worker activity.
- The ability and use of the system to detect pedestrian and bicyclist intrusions is a novel application and may be quite useful in certain work zone conditions in urban areas.

8.5 AWARE SENTRY

8.5.1 Summary

This section presents a summary of the evaluation of the AWARE Sentry through observations during the training sessions and active work zone testing, and from results of maintenance worker surveys.

- The AWARE Sentry system is primarily designed to be used in flagging operations. The system is not recommended for use on highways and freeways.
- The system utilizes a radar sensor to continuously monitor traffic and detect vehicles that have a possibility of intruding into the work zone.

- The system detects vehicles that exceed a certain user defined speed threshold to sound an alarm warning both the driver and workers. This is the only system that warns drivers as well.
- Speed threshold (min. 5 mph to max. 45 mph) and other settings can be changed in the field using a mobile application and Bluetooth connection.
- The radar can monitor and detect vehicles at a distance of up to 600 feet.
- When activated, the sentry unit will sound an audible alarm through the alarm speaker on the base station and visual flashing white and amber LED lights warning drivers and adjacent workers.
- Haptic and auditory alerts can also be produced by the WorkTRAX devices worn by the workers.
- The alarm duration increases depending on how much the detected vehicle is exceeding the set speed threshold.
- The system uses a foot pedal that is connected to the base station through a wired connection to stop and allow traffic to proceed, mimicking a flagging operation.
- The AWARE Sentry system is the only system capable of warning workers of a potential intrusion before it occurs.
- The system is one of the few with a PSD (WorkTRAX) also available to warn individual workers.
- The AWARE Sentry base unit will record unsafe events including a short video of detected vehicles, which can be reviewed later using the online dashboard.
- The system has a battery life of 15 hours and requires overnight charging before use.
- The system is packaged in a box with retractable mast arms with LED lights and wheels for easy transport.
- Deployment of the system is easy with a single on/off toggle switch to start the base unit and single button on the WorkTRAX unit.
- Because the system will sound an alarm for every detected vehicle, the main challenge observed in this research was setting an appropriate speed threshold (discussed in detail in the next section).
- Caltrans maintenance workers liked the ability of the system to alert drivers in addition to workers.
- Some workers were concerned about the wired foot pedal connection and the need to continuously press the foot pedal to allow traffic to proceed, restricting the flagger’s movement in a work zone. This limitation was also observed during active work zone testing.

- Maintenance workers liked the system's ability to stop the alarm once the drivers reduced their speeds below the set threshold.
- Maintenance workers were particularly impressed with the 600-foot range of the system in detecting vehicles and the ability to detect vehicles even when visually obscured by vehicles in the queue.

8.5.2 Discussion and Recommendations

Based on the evaluation of the AWARE Sentry system through observations during active work zone testing and worker training sessions, and from results of maintenance worker surveys, the following general recommendations are provided for use of AWARE Sentry in the field.

The AWARE Sentry system is primarily designed to be used in a flagging operation with lane closure on a two-lane roadway. Therefore, the use and deployment of the system is limited to such types of work zones and is illustrated in Appendix E. The setup and deployment procedures are straightforward and were easily accomplished during active work zone testing and training sessions without any issues. A mobile application associated with the AWARE Sentry system can be used to configure and control all the functions of the system including setting of the speed threshold between a minimum of 5 mph to a maximum of 45 mph. The most important element of AWARE Sentry operation is the setting of an appropriate speed threshold to detect vehicles in a work zone. If a speed threshold is set too low, an excessive number of detections and warnings may potentially lead the workers to ignore the warnings. Setting the speed threshold too high may result in not detecting potential intrusion threats.

During active work zone testing on a 55-mph two-lane roadway, the speed limit approaching the lane closure flagging operation was 35 mph. Hence, the speed threshold on the AWARE Sentry unit was set at 35 mph. Although upstream signs warning drivers to reduce speeds to 35 mph were placed well beyond the 600-foot detection range of the AWARE Sentry system, it was immediately observed that most of drivers were not slowing down below 35 mph before the detection range of the AWARE Sentry system, resulting in an excessive number of warnings generated. Therefore, the speed threshold was raised to 45 mph to detect only the most serious potential threats. This observation and experience during active work zone testing emphasizes the importance of having prior knowledge of typical speeds near the flagging operation, which would be helpful in setting the most appropriate speed thresholds to avoid false alarms and worker apathy due to excessive alerts. It is recommended that after the deployment of AWARE Sentry unit and before distributing the WorkTRAX PSD to workers, the maintenance supervisor should mute the audio alarm and observe the approaching vehicular speeds detected by the system for a certain period of time before setting the most appropriate threshold limit.

As observed during active work zone testing in this research, the AWARE Sentry system encountered some unexpected issues due to the presence of horizontal curve and diverging roadway. Therefore, it is recommended that the AWARE Sentry system be deployed in work zones with straight roadways and no nearby intersections. If such conditions are unavoidable, care should be taken to avoid false alarms as much as possible by calibrating the system settings in the field.

The results of this research also indicated that the WorkTRAX PSD offers effective audio and haptic alerts to workers at approximately 500-foot distance. Workers are recommended to place the WorkTRAX device in their pockets close to the body to be able to feel the haptic alert, even though the audio alert was considered sufficient by most workers. One of the limitations of the AWARE Sentry system is that each base unit includes only four WorkTRAX PSDs.

Based on the outcomes of this research, two other general recommendations are summarized as follows:

- It is recommended to the manufacturer to:
    - provide setting configuration option on the device in addition to the mobile application,
    - provide an option to dim the lights on the Sentry base unit, and
    - provide an option of a wireless connection between the base unit and foot pedal or wireless remote for the flagger to control the base unit.
- Although not designed for use outside of flagging operation, one maintenance supervisor recommended using the AWARE Sentry system as an early warning system for drivers when placed well ahead of the flagger. The use of the system as an early warning device could have interesting and useful implications in providing proactive warnings and reducing the change of an intrusion in a work zone.

8.6 OTHER SYSTEMS

Towards the end of the research project, two new WZIA systems became available on the market, the Guardian Cone and Alpha SafeNet Overwatch systems. These systems were procured by the research team in an effort to conduct limited testing and to document the systems in this report for posterity.

The authors are unable to provide detailed guidance and recommendations for these systems due to limited experience. However, specifics of the limited testing and outcomes are presented in Chapter 7 of this report.

8.7 GENERAL CONCLUSIONS AND RECOMMENDATIONS

While this research primarily focused on evaluating the selected WZIA systems, there were numerous observations and lessons learned that can be summarized as general recommendations and can help highlight and ensure best practices in the future for use of any WZIA systems in California work zones.

- The main factors that distinguished the features and use of selected WZIA systems relate to the effectiveness of WZIA systems in high-speed vs. low-speed conditions, extent of coverage provided in a work zone, issues related to deployment and retrieval, and issues surrounding worker exposure during deployment and retrieval; besides numerous other characteristics specific to each system. Therefore, any new or future systems should also be evaluated and considered in view of these critical factors to ensure effective implementation.
- Buy in from maintenance workers is the key to the successful and effective use of WZIA systems in improving work zone safety. Therefore, it is recommended that Caltrans adopt concerted measures to provide widespread training to maintenance crews in the use of WZIA systems, enabling them to become familiarized with their features and benefits.
- The crew supervisors should be designated and encouraged to make it a practice to use WZIA systems in work zones.
- The crew supervisors should assign one or two crew members the responsibility to set up, deploy, operate, and retrieve of WZIA systems in work zones under their direction, which would ensure efficiency and effectiveness, and reduce the number issues encountered. Tasking a maintenance worker to deploy a WZIA system generally did not yield the desired results, as observed in this research.
- Discussions between supervisor and crew on best device selection and best deployment strategy is critical and highly recommended because no two work zone conditions are the same.
- Proper application of the most suitable WZIA system in appropriate work zone conditions will result in clear safety benefits, which is critical for adoption and buy-in from the maintenance workers.
- It was evident from the comparison of results of maintenance worker surveys during training sessions and active work zone conditions that their overall perceptions improved considerably in terms of the safety benefits

of the WZIA systems after testing and evaluating the systems in an actual work zone. This signifies the importance of familiarizing the workers and selective application in appropriate types of work zones under the right types of conditions, as discussed throughout this report.

- To ensure widespread use and adoption, Caltrans should implement measures to require contractors to use WZIA systems in California work zones.
- In view of the outcomes of this research and based on the summary, discussions, and recommendations provided in this chapter, training instructions for maintenance workers showing setup, deployment, operation, and issues to consider for each selected WZIA system are presented in Appendix E.
- Appendix E also shows the deployment plans for selected WZIA systems based on Caltrans Standard Traffic Control Plans for work zones.

Table 8.1 presents a summary of key highlights, observations, and recommendations related to each selected WZIA system based on the outcomes of this research.

Table 8.1 Summary Table of Key Highlights, Observations, and Research Recommendations

WZIA Systems	WAS	SonoBlaster	Intellicone	Single Sentry Beam	AWARE Sentry
High/Low Speed Application*	Both	Low Speed Only	Both	Low Speed Only	Both
Recommended Application (work zone type)	Lane /Shoulder /Ramp closure	Lane / Ramp closure	Lane / Ramp Closure	Lane / Ramp closure	Flagging Operation
Work Zone Coverage	Continuous (dependent on number of pneumatic hoses used)	Intermittent (dependent on number of SonoBlaster cones/drums deployed)	Intermittent (dependent on number of Intellicone Lamps deployed on cones)	Continuous (dependent on max. range of single laser beam; 115 feet)	Continuous (covers up to 600 feet upstream of work zone)
Range Considerations**	225 feet between hose and alarm, 175 feet between two alarms, 75 feet between a PSD and alarm unit	None	100 feet between two cone lamps and cone lamp and PSA	175 feet between device and PSA	600 feet traffic detection radar range; 500 feet between base unit and PSD
Power Source (Batteries)	Rechargeable /AA/AAA	None	Rechargeable /Lantern Type	Rechargeable	Rechargeable
Deployment Effort Required	Low	High	Moderate	Low	Moderate
Recommended Number of Alarm Units to Use***	5	As many as possible	2	2	NA
Potential Exposure to Workers During Recommended Deployment/Use	Low (depends on hose placement)	High (depends on cone placement)	High (depends on cone lamp placement)	Low	Low

**High speed may be considered >55 mph speed limit; low-speed may be considered < 35 mph speed limit conditions.*
***Data based on observations in this research, not manufacturer specifications.*
****Recommendation based on a typical 100-foot length work area; longer areas may require additional alarm units.*

8.8 FUTURE RESEARCH

The results of this research were based on active work zone testing conducted over a few days; each device being tested at two separate locations. Additional active work zone testing is necessary over a longer period of time with repeated use, to evaluate the long-term performance, durability, and reliability of the selected 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 at higher risk.

Most of the recommendations and guidance provided to Caltrans regarding the deployment and implementation of the selected WZIA systems focused on testing in lane/shoulder and ramp closures. It is recommended that additional testing in other types of active work zones be performed to assess the performance of each selected WZIA under different types of conditions. It would also be useful to conduct comprehensive and detailed impact tests 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. Additionally, advances in the system designs warrant a periodic review by Caltrans to determine if updated or new systems are suitable for use in different types of work zones.

The Guardian Cone and Alpha SafeNet Overwatch systems were two new devices that entered the market at the end of the research period and were briefly studies in this research. It is recommended that additional testing of the two systems in active work zones be performed to better asses both systems' capabilities in real world conditions.

The literature review revealed a lack of 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. One of the suggestions from a meeting of the Strategic Highway Safety Plan action leads was to explore the option of integrating low-cost data collection devices (e.g., Bluetooth sensors, radar speed detectors, etc.) with existing Caltrans work zone vehicles and equipment to collect work zone data during routine Caltrans maintenance operations. Such data would be extremely useful for Caltrans and researchers to study typical work zone conditions and threats that maintenance workers encounter in active work zones. Furthermore, there are other types of systems and devices that can integrate and communicate with driver aids, vehicle navigation systems, and other work zone management systems to offer drivers and workers warning about work zones. These systems should be explored and also evaluated as part of a concerted broader effort to improve work zone safety benefiting Caltrans and other agencies in the United States.

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APPENDIX A

LITERATURE REVIEW DETAILS

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., 2021)

New and Emerging Work Zone Safety Technology

The following presents details of new and emerging technologies that are currently being pilot tested and studied as part of work zone safety improvement technologies.

Wireless Sensor Network

The Wireless Sensor Network (WSN) system is composed of a sensor node that utilizes an ultrasonic beam to detect intruding vehicles and individual warning devices worn by the workers (Figure 2.17 and Figure 2.18). Martin conducted a study in a closed track environment for a short-term work zone scenario to evaluate the potential for a WSN based intrusion alarm system.

Figure A.1 Wireless Network System Sensor Node
(Source: Martin et al., 2016)

Figure A.2 Wireless Network System Wearable Device
(Source: Martin et al., 2016)

The results of the study showed that the sensor node successfully alarms the individual warning devices and detects for vehicle speeds between 30 and 90 km/h, with no missed detections out of the 10 trials. The Sensor node also successfully alarms and detects vehicles with a vehicle speed of 60km/h and a node line of sight angle between -60 and +60 degrees, with no missed detections out of the 10 trials for each angle (Martin et al., 2016). Both tests were conducted with the sensor node 3 meters away from the road as shown in Figure 2.19. Based on the results, it was concluded that the sensor node line of sight angle and vehicle speeds do not significantly impact vehicle detection.

Figure A.3 Photo of WSN Sensor Node During Closed Track Testing
(Source: Martin et al., 2016)

A third test was conducted for vehicle detection accuracy based on the sensor node's distance to the road. From distances between 1 and 7 meters away from the road and out of 10 trials at each distance, there were only two missed detections at the distance of 7 meters. The results concluded that there is no significant change in average latency with sensor node distances between 1 and 52 meters. The overall conclusion of Martin's evaluation is that WSN proves to be an effective and useful tool for work zone safety, with an easy deployment and quick set up.

The SmartCone

The Ottawa-based SmartCone Safety Solution combines IoT technology with any 3rd party sensor available on the market to promote efficiency and worker safety on roadways and construction sites (TheSmartCone, 2021). The SmartCone Modular Platform (Figure 2.20) utilizes motion detection to send visual, and audio alarms to interact with other applicable devices. Devices interacting with the SmartCone may include a small wearable device that may be body worn or placed on the workers safety helmet (Figure 2.21), and SmartTorches (Figure 2.22). The warning alerts for both devices can be audio and or visual, with a multiple color option for the SmartTorches.

Figure A.4 SmartCone System Components
(Source: TheSmartCone, 2021)

Figure A.5 SmartCone System Wearable Device
(Source: TheSmartCone, 2021)

Figure A.6 SmartTorch
(Source: TheSmartCone, 2021)

Smart Vest

The Smart Vest was developed and tested by Virginia Tech Transportation Institute to accurately localize, monitor, and predict potential collisions between workers and errant vehicles, shown in Figure 2.23. The Smart Vest technology uses the workers movements and activities to communicate potential collisions to workers, passing drivers, and connected/automated vehicles (Roofigari-Esfahan et al., 2021). A study evaluating the effectiveness of the Smart Vest concluded that for successful implementation, the Threat Detection Algorithm utilized by the Smart Vest needs to be modified to include activity recognition since the current algorithm lacks accuracy and requires extensive computational modeling.

Figure A.7 Smart Vest
(Source: Roofigari-Esfahan et al., 2021)

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 (feet):	
Spacing (feet):	
Activity Area	
Length (feet):	
Spacing (feet):	
Activity Type:	
Other Information	
Length of work zone (feet):	
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:	

Device Information	
Stopping Sight Distance (feet):	

Functional Characteristics - Deployment

Set up time of the device (min):	
Ease of set up (comment):	
Deployment time (after set up, 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 ____feet (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 (feet):	
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 (feet) (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/ set up/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. Years of industry experience: ____________________

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

____
____

4. 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

5. Will the WZIA System tested today will improve work zone safety?

☐ Very likely
☐ Slightly likely
☐ Not at all likely
☐ Will decrease work zone safety

6. Do you feel safe in deploying and using this system in a work zone?

☐ Yes
☐ No
☐ Not Sure

7. 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, PSD in providing adequate coverage.	☐	☐	☐	☐	☐

Comments/Additional Thoughts

8. 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

9. 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

10. 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.	☐	☐	☐	☐	☐

11. 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

MAINTENANCE STAFF TRAINING SCHEDULE AND PLAN

Appendix D: Maintenance Staff Training Schedule and Plan

Training Schedule

Two training days have been scheduled initially on March 29, 2022, and April 4, 2022, details of which are presented in the table below. Any additional training sessions will be scheduled based on needs and any new crews identified.

Day	Date	Time	WZIA System
1	March 29, 2022	7 AM – 5 PM*	Worker Alert System, Intellicone System, Single Sentry beam, and SonoBlaster
2	April 4, 2022	7 PM – 3 PM*	AWARE Sentry

*Possible lunch break or other breaks depending on training progress

<u>Contact</u>:

Larry Schwartz Safety and Training Liaison MAZEEP Contract Manager California Department of Transportation Division of Maintenance 916-997-0067	Ghazan Khan Sacramento State University Research Team PI 732-698-8519 khan@csus.edu

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

1. Safety Meeting
    a. Safety gear
    b. Conduct during live demonstration with vehicle if required
    c. Hydration
    d. Skin protection
2. Review mock closure set-up by Larry Schwartz at META.
3. Set up workstation/work area for equipment and demonstration.
4. Introduction with crew and review objectives for the day.
    a. Main Objectives: To get the crew familiarized and comfortable in the deployment, use, and retrieval of each system so they can independently use the systems in Active Work Zone locations.
5. Present an overview of each system.
    a. How each system works, proposed deployment plans, and things to watch out for.
6. Live Demonstration by Research Team for each system.

    a. Deployment, operation/alarm trigger, and retrieval of each system.
7. Allow maintenance crew to deploy, operate, and retrieve each system at a time.
    a. Interactive discussions during this phase on various aspects of deployment, operation, and retrieval of each system to help crew become familiarized with each system.
8. WZIA system retrieval and wind-up.
9. Distribute survey to participants.
10. Wrap-up for the day.

APPENDIX E

WZIA SYSTEMS – DETAILED SETUP AND DEPLOYMENT INSTRUCTIONS

Appendix E: WZIA Systems - Detailed Setup and Deployment Instructions

Worker Alert System

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 E.1 Turning on Horn/Light Alarm

Hose/Sensor Assembly

Figure E.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 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 E.3 Turning on Personal Safety Device

Worker Alert System – Proposed Deployment Plan

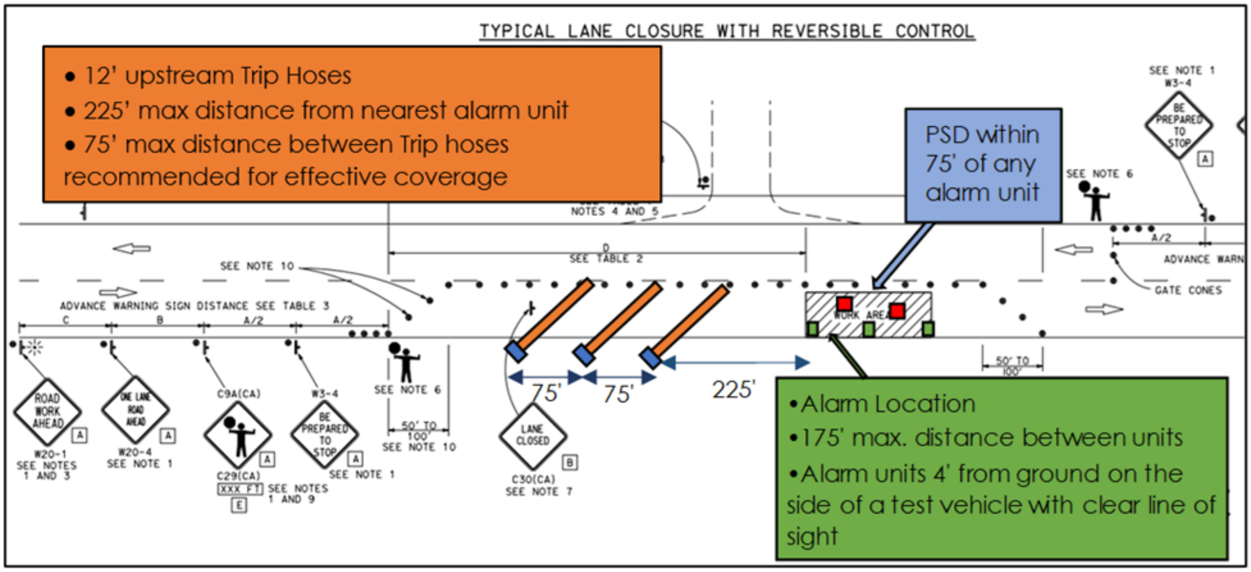


Figure E.4 Recommended Deployment Plan for Worker Alert System on a Standard T-13 Closure

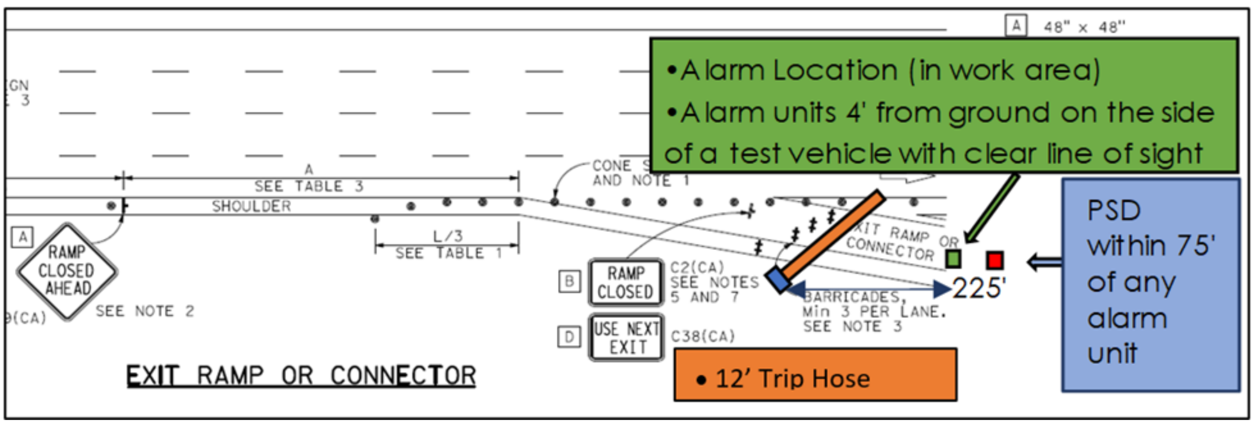


Figure E.5 Recommended Deployment Plan for Worker Alert System on a Standard T-14 Ramp Closure

Worker Alert System – Things to Watch out For

1. Always check/replace batteries in pneumatic sensor hose and PSD, and charge alarm unit before use.
2. Ideally, the alarm unit should be deployed at least 4 feet. above ground (e.g., attach to a vehicle using magnet).
3. Pay close attention to the maximum range distances for each system component as presented in the recommended deployment plan.
4. If the alarm unit does not trigger when hose is activated, check the following:
   a. Check battery power indicator light is green indicating the unit has ample power.
   b. The alarm unit may need linking with hose sensor.

c. Activate the hose/sensor by stepping on it while simultaneously powering on the horn/light alarm.
d. 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.

5. Always test the complete system before using in the field.

SonoBlaster

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 E.6 SonoBlaster Bracket Assembly

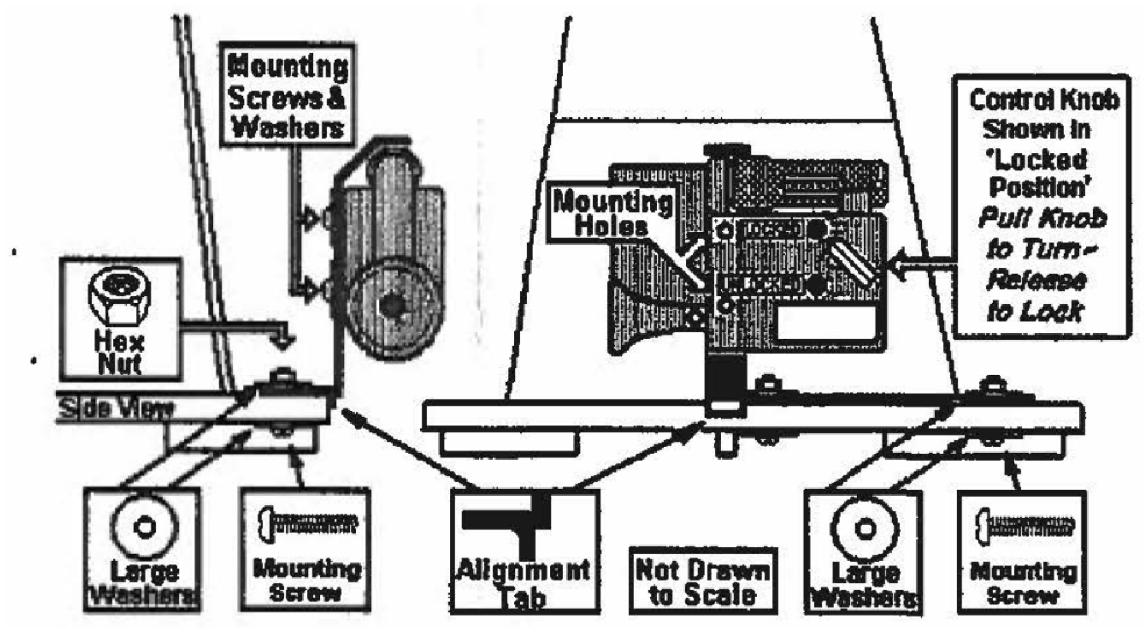


Figure E.7 SonoBlaster Bracket Assembly

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.

SonoBlaster – Proposed Deployment Plan

Figure E.8 Recommended Deployment Plan for SonoBlaster Cones

SonoBlaster – Things to Watch out For

1. Installation instructions recommend installing the bracket at the base of the cone (for cones with feet). However, depending on the type of the cone, the bracket may be installed on top of the base as well. However, this may reduce stacking capacity of the cones.
2. Insert the CO_2 cartridge carefully as improper installation may result in nonactivation of alarm.
3. Ensure the SonoBlaster unit is in locked position during handling and transportation to avoid accidental activation.

Intellicone System

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 (Subscriber Identity Module [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. **(NOTE: GPS/SIM connection not required for operation of the system)**
4. The Sound button on the Portable Site Alarm control panel can be used to mute/unmute the alarm sound.
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 after alarm activation.
8. Press the power button to turn off the Portable Site Alarm.

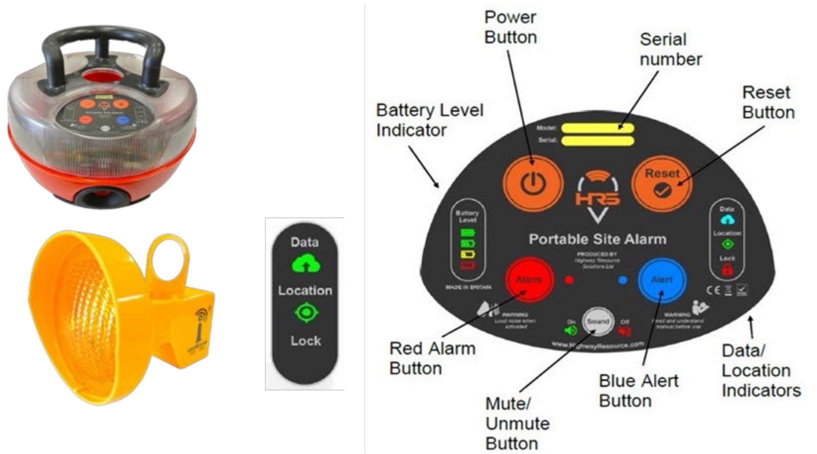


Figure E.9 Intellicone System PSA Detail

<u>Intellicone Static Cone Lamp</u>

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. After 1 Minute, the lamp is ready for optimal transmission range.
4. 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)

Intellicone System – Proposed Deployment Plan

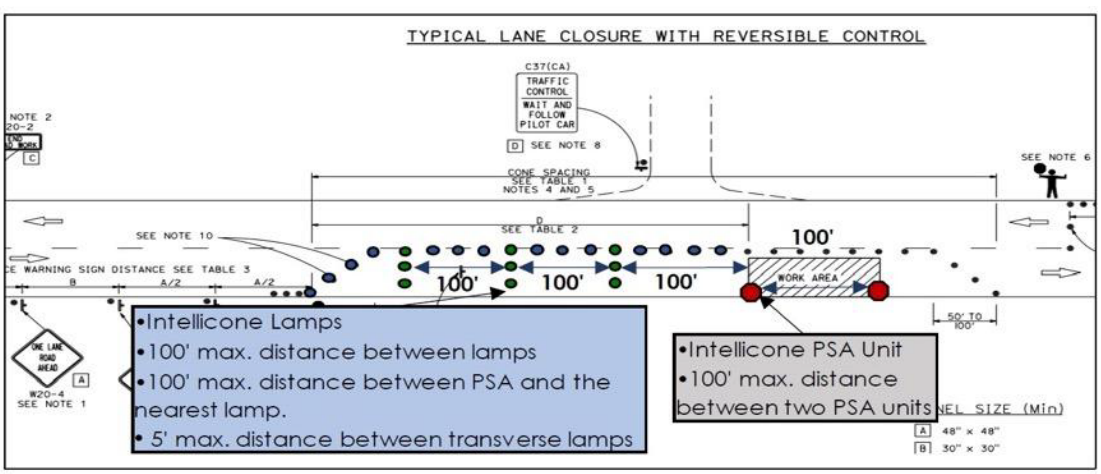


Figure E.10 Recommended Deployment Plan for Intellicone System on a Standard T-13 Closure

Intellicone System – Things to Watch out For

1. Always check the Portable Site Alarm unit is fully charged for 24 hours before use. The cone batteries should be replaced also.
2. The Portable Site Alarm must be placed outside in a location which is fully visible to the sky. DO NOT place the device underneath a bridge or other object, which would impede its ability to acquire a GPS location via satellites.
3. 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.

Intellicone Single Sentry Beam

Intellicone Single Sentry Beam – Setup and Deployment Instructions

Intellicone Single Sentry Beam – Set up

1. Use the provided connector cables to connect the battery box to the Intellicone Single Sentry Beam device.
2. Press the power on button on the battery box to turn on the device. The device should start beeping, ready to set up the detection range.
3. After the device is turned on, point the laser at an object placed at the desired detection range distance (see Figure 7).
4. Once the detection range is set, the device should stop beeping after about 10 seconds. Any vehicle or person crossing the laser beam within the set up detection range will trigger the Intellicone Portable Site Alarm unit.

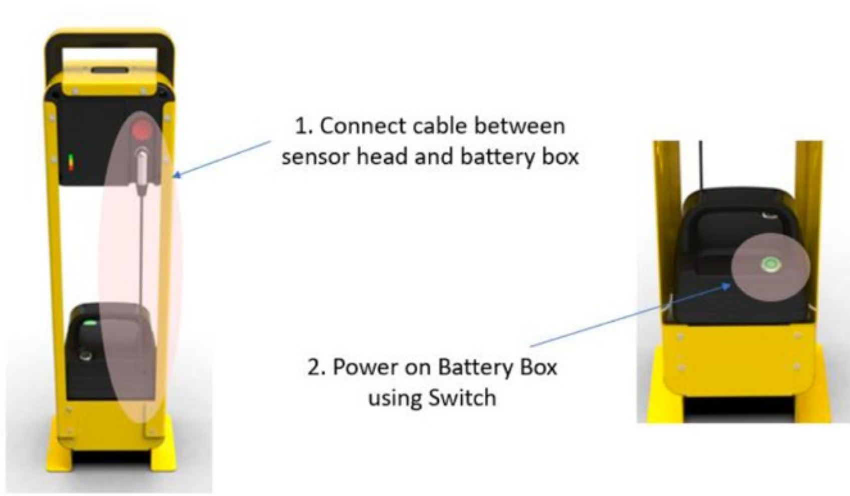


Figure E.11 Intellicone Single Sentry Beam Assembly

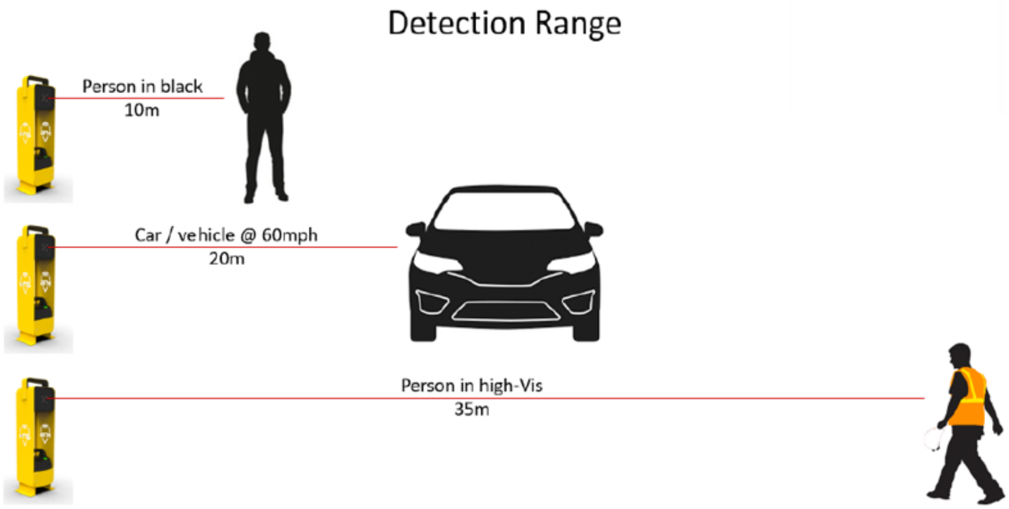


Figure E.12 Detection Range Capabilities of Single Sentry Beam

Intellicone Single Sentry Beam – Proposed Deployment Plan

Deployment may vary depending on the desired need and critical location of vehicle intrusion as determined by the work zone supervisor. Unlimited distances only possible if GPS/SIM connection is available.

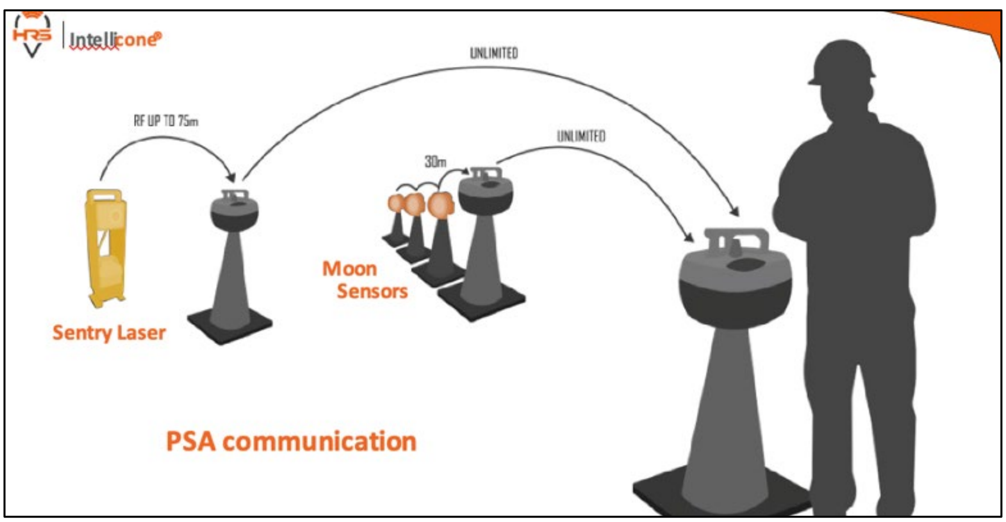


Figure E.13 Intellicone Single Sentry Beam Deployment Options

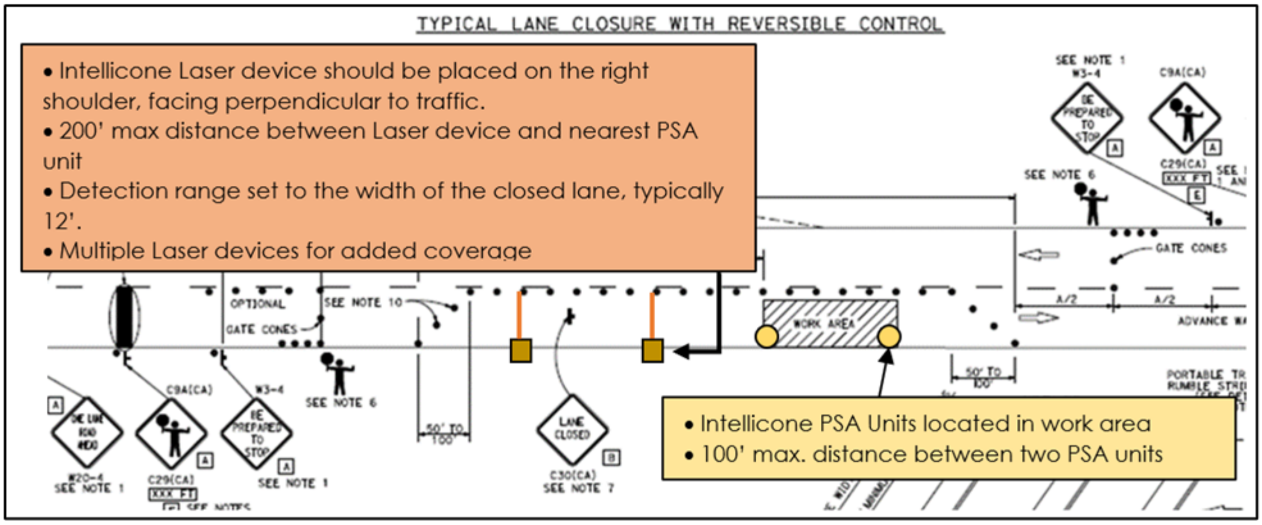


Figure E.13 Recommended Deployment Plan for Intellicone Single Sentry Beam on a Standard T-13 Closure

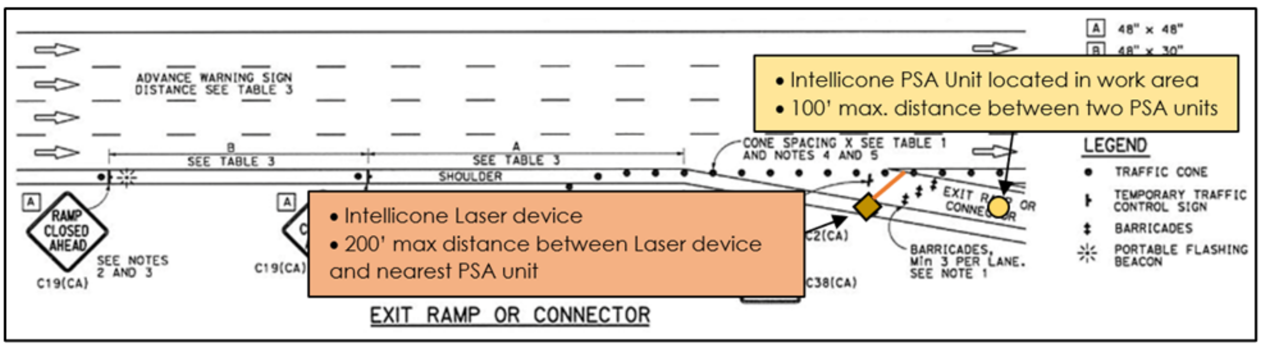


Figure E.14 Recommended Deployment Plan for Intellicone Single Sentry Beam on a Standard T-14 Ramp Closure

Intellicone Single Sentry Beam – Things to Watch out For

1. Always check the Intellicone Laser battery pack is fully charged before operation.
2. Once turned off, the Intellicone Single Sentry Beam desired detection range must be set up after restarting the device.
3. The Intellicone Single Sentry Beam device must be placed at most 75 meters from the Portable Site Alarm with a clear line of site.

AWARE Sentry System

AWARE Sentry – Set up and Deployment Instructions

1. Roll the Sentry device in front of the flagger near the edge of the roadway on level ground facing traffic, down the lane of travel parallel to the edge of the roadway.

2. Open the case, then lift the light bar in an upright position. Make sure the light bar locks into position by gently pushing it forward.
3. Press the T-bar Knobs and unfold both warning light arms. Make sure the light arms click into place.
4. Unfasten the toggle and raise the light bar. Once raised fasten the toggle tightly.
5. Turn the Sentry unit on by pressing the Power On button.
6. Arm the system by pressing the Arm switch.
7. Remove the foot pedal from the case and unroll the chord. Place the foot pedal behind the Sentry unit case, in front of the Flagger's feet.

Figure E.15 AWARE Sentry System Components

<u>WorkTRAX Device Assembly</u>

1. Remove the WorkTRAX (Personal Safety Device) devices from the case and press the power button to switch on. The device will beep and vibrate indicating it is on.
2. Press the power button again to turn off the WorkTRAX device. The device will beep and vibrate indicating it has turned off.
3. Place the WorkTRAX device on an armband or in the pocket of the safety vest.

Figure E.16 AWARE WorkTRAX Device

<u>Starting and Stopping Traffic (Flagging Operations)</u>

1. After removing the foot pedal from the case, the default condition of AWARE is "STOP."
2. Step and keep pressure on the foot pedal to release traffic. The light behind the light bar should switch from stop to slow.
3. Release the foot pedal to stop traffic. The light should switch from slow to stop.

Figure E.17 Back View of AWARE Sentry Device When Pedal is Released

Figure E.18 Back View of AWARE Sentry Device When Pedal is Pressed

AWARE Sentry – Proposed Deployment Plan

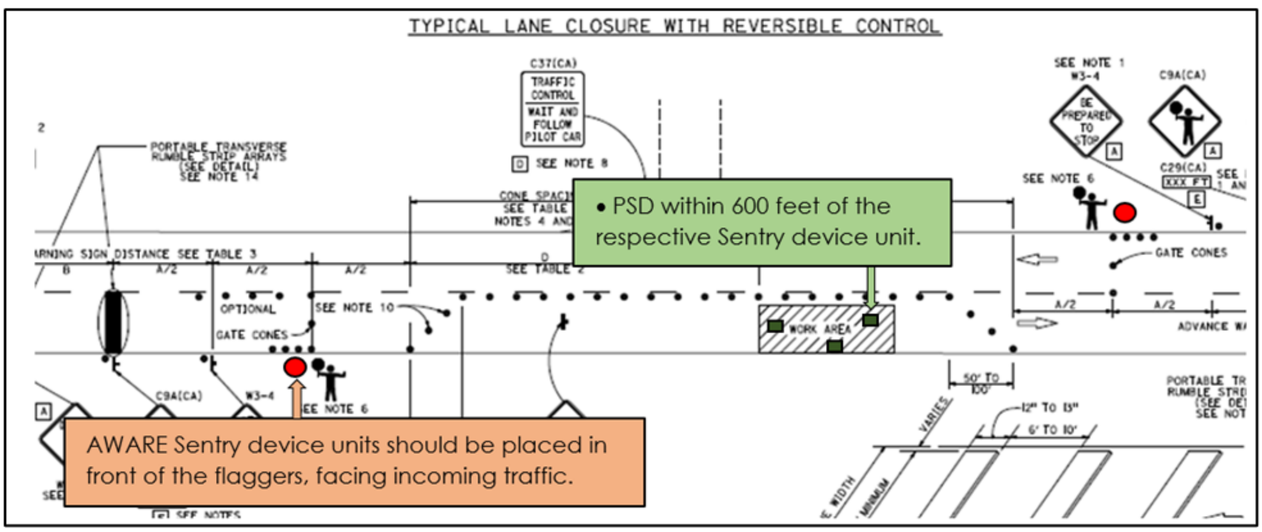


Figure E.19 Recommended Deployment Plan for AWRAE Sentry on a Standard T-13 Closure

AWARE Sentry – Additional Setup Requirements and Things to Watch out For

1. The AWARE Sentry system has a range of 600 feet. at which it starts detecting vehicles approaching a work zone. The on-board radar continuously monitors the vehicle's trajectory and speed and depending on internal calculations, makes a prediction if the vehicle's approach is dangerous enough to trigger an alarm warning both the vehicle and the workers in the work zone.

2. The AWARE Sentry system has several capabilities and ability to record detailed information on any incidents that trigger the alarm. This requires set up by the supervisor before deployment in a work zone, which includes:
    a. Setting up a “Safe Speed” limit in the system. Approaching vehicles exceeding the “Safe Speed” will trigger the alarm.
    b. Typical recommendation is to set the “Safe Speed” to 10 mph below the speed limit of the road.
    c. Setting up what types of alarm/alerts are triggered, e.g., flashing LED lights, audio alarm, WorkTRAX alarm. Each can be controlled individually in the system setup to either activate or not.
    d. Setting up a Wi-Fi connection between the AWARE Sentry unit and mobile phone application to download incident/activation data at the end of the day. AWARE also records a video of an incident when alarm is triggered 10 seconds before and up to 20 seconds after an incident.
3. Remember to set the “Safe Speed” for each work zone depending on the speed limit if different from previous use.
4. Additional capabilities and set up are accessed through a mobile application. Instructions on the installation and use of mobile application will be provided separately later.

APPENDIX F

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

Appendix F: Caltrans Traffic Control System Tables for Lane and Ramp Closures and T13-T14 Standard Traffic Control Plan

2015 REVISED STANDARD PLAN RSP T9

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

REGISTERED CIVIL ENGINEER

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.

REGISTERED PROFESSIONAL ENGINEER — Devinder Singh — No. C50410 — 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		
					X	Y	Z **
	TANGENT 2L	MERGING L	SHIFTING L/2	SHOULDER L/3	TAPER	TANGENT	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

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

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.

NOTES:

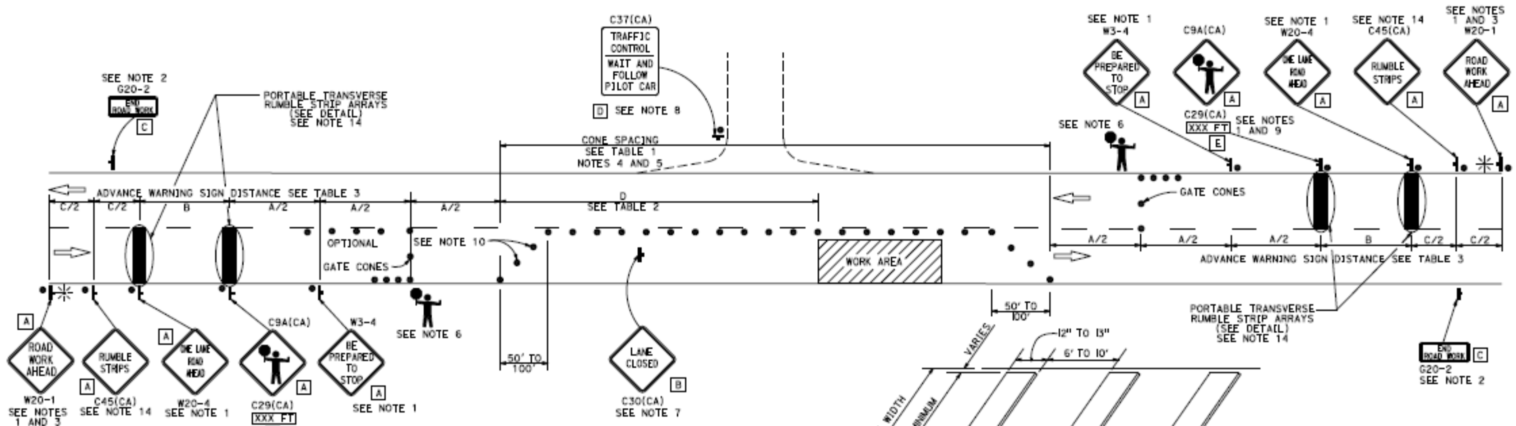
See Standard Plan T9 for tables.

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.

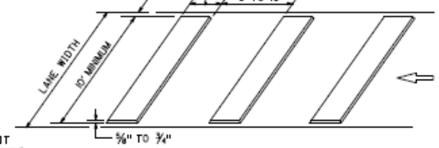
California codes are designated by (CA). Otherwise, Federal (MUTCD) codes are shown.

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

LEGEND

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

SIGN PANEL SIZE (Min)

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

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

TRAFFIC CONTROL SYSTEM FOR LANE CLOSURE ON TWO LANE CONVENTIONAL HIGHWAYS

NO SCALE

T13

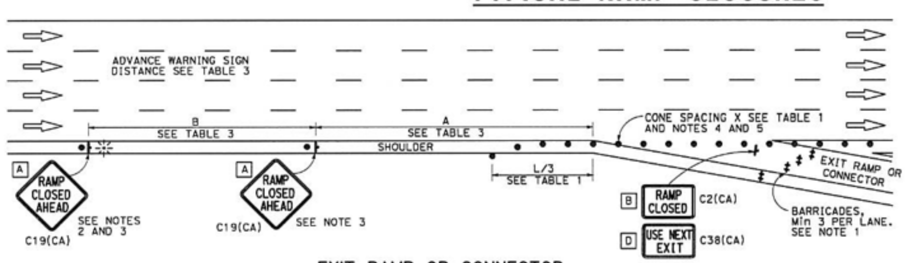
Dist	COUNTY	ROUTE	POST MILES TOTAL PROJECT	SHEET No.	TOTAL SHEETS

REGISTERED CIVIL ENGINEER
October 30, 2015
PLANS APPROVAL DATE

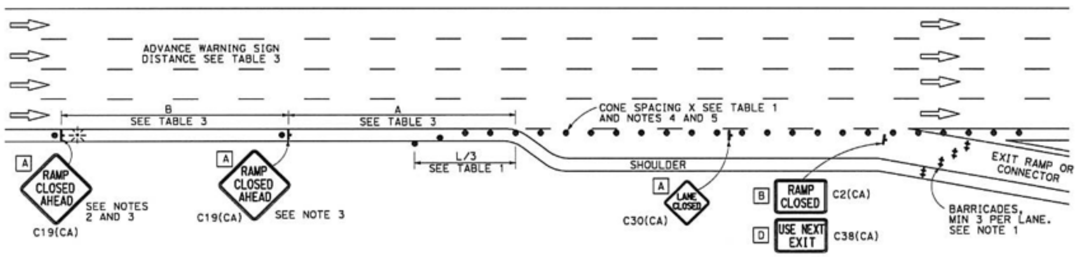
THE STATE OF CALIFORNIA OR ITS OFFICERS OR AGENTS SHALL NOT BE RESPONSIBLE FOR THE ACCURACY OR COMPLETENESS OF SCANNED COPIES OF THIS PLAN SHEET.

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

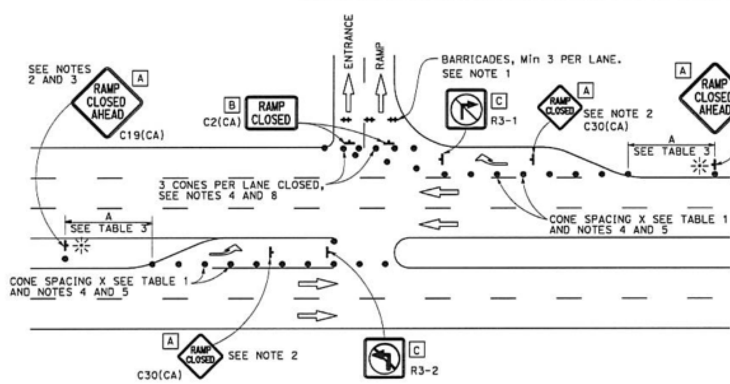
TYPICAL RAMP CLOSURES



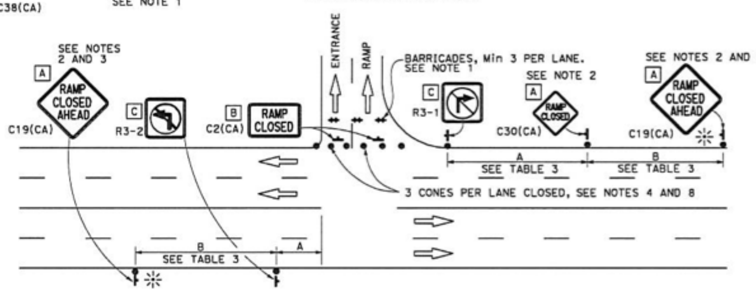
EXIT RAMP OR CONNECTOR



EXIT RAMP OR CONNECTOR WITH ADDITIONAL LANE



ENTRANCE RAMP WITH TURNING POCKETS



ENTRANCE RAMP WITHOUT TURNING POCKETS

SIGN PANEL SIZE (Min)

- A 48" × 48"
- B 48" × 30"
- C 36" × 36"
- D 48" × 36"

LEGEND

- ● TRAFFIC CONE
- TEMPORARY TRAFFIC CONTROL SIGN
- BARRICADES
- PORTABLE FLASHING BEACON

NOTES:

1. Barricades shall be Type I, II, or III for closures lasting one week or less and Type III for closures lasting longer than one week.
2. In addition to placing the C19(CA) "RAMP CLOSED AHEAD" and C30(CA) "RAMP CLOSED" signs, black on orange overlay plates with the word "CLOSED" may be mounted, as directed by the Engineer, on all guide signs that refer to the closed ramp. The letter size on the overlay shall be the same as the guide sign.
3. Each advance C19(CA) "RAMP CLOSED AHEAD" sign shall be equipped with at least two flags for daytime closure. Each flag shall be at least 16" × 16" in size and shall be orange or fluorescent red-orange in color. A flashing beacon shall be placed on top of the first C19(CA) sign during hours of darkness.
4. All cones used for ramp closures during the hours of darkness shall be fitted with retroreflective bands (or sleeves) as specified in the specifications.
5. Portable delineators, placed at one-half the spacing indicated for traffic cones, may be used instead of cones for daytime ramp closures only.
6. At least one person shall be assigned to provide full time maintenance of traffic control devices, unless otherwise directed by the Engineer.
7. The existing "EXIT" signs shall be covered during ramp closures.
8. A minimum of 3 cones shall be placed transversely across each closed lane and shoulder.

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.

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

TRAFFIC CONTROL SYSTEM FOR RAMP CLOSURE

NO SCALE

T14