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Implementation and Assessment of Highway Intrusion Technologies

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16. Abstract

Highway workers face dangers from distracted drivers and challenging work zones, which results in thousands of incidents annually in the U.S. Traditional safety measures, though beneficial, highlight a need for advanced intrusion alert technologies. While many state DOTs are exploring these technologies, research gaps persist regarding their effectiveness in alerting drivers and workers. This study aims to evaluate the efficiency and implications of four commercial intrusion technologies, with a focus on drivers' and workers' cognition and response. Results offer practical guidelines and a decision-making tool to assist INDOT in selecting the optimal technology. The ultimate goal is to significantly reduce incidents in highway zones in Indiana and nationwide.

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EXECUTIVE SUMMARY

Introduction

Highway construction and maintenance work zones often pose serious safety threats, with a notable number of injuries and fatalities. Intrusion alert technologies have become popular solutions, especially since distracted driving is a major cause of work zone incidents. However, despite their increasing usage, concerns about their effectiveness, such as false alarms and complicated setups, persist. Past studies have evaluated these alarms' basic functions, but there is a need to further investigate how well they notify drivers and on-site workers, especially since these technologies continue to evolve. Although some contractors occasionally use these alarms in Indiana, there is a lack of standardized guidelines, solid evidence supporting their efficiency, or an understanding of their acceptance among drivers. Therefore, a thorough evaluation of the current intrusion technologies in the market is essential for enhancing work zone safety.

This research delved into a comprehensive understanding of intrusion alert technologies by reviewing existing knowledge and practices. Through preliminary and pilot tests, the study assessed the primary features of these technologies, and insights were further enriched by feedback from transportation departments and contractors. The research also closely examined drivers' and workers' responses to these intrusion alerts in order to develop a tool that guides them in the selection of the most suitable intrusion technology. This study aimed to enhance safety measures by extending the adoption practices in US highway construction zones through insights into the technologies' effective deployment. All results in this report were extracted from the intrusion technologies obtained in 2021.

Findings and Implementation

For INDOT and contractors to enhance work zone safety, the findings are listed as follows.

- No singular intrusion technology was universally effective for all safety concerns in work zones.
- There continues to be a need for more innovative designs with distinctive auditory signals.
- Physiological measurements suggest that the existing alert systems were ineffective in instilling a sense of urgency in drivers.
- Different features and setups in technologies can lead to varying driver responses, and combining strengths from multiple systems might be beneficial.
- Challenges exist in distinguishing sounds between some devices like SonoBlaster and AWARE.
- Despite recognizing alerts, many workers continued their tasks instead of evacuating. These findings highlight the need for worker training and system refinement by manufacturers.

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1. INTRODUCTION

1.1 Problem Statement

Highway construction and maintenance work zones have continuously shown significant safety issues with a large number of fatalities and injuries (AASHTO, 2022). To address this problem, intrusion alert technologies have received tremendous attention as the work zone intrusion caused by distracted drivers is one of the main reasons for work zone accidents (Gambatese et al., 2017; Hanomchoeng et al., 2010). Despite the growing interest in these intrusion alarms by transportation agencies to improve work zone safety, several studies indicated these technologies' limitations regarding technical implementation (e.g., their inefficiency, frequent false alarms, complex setup procedures) and user acceptance (Burkett et al., 2009; Novosel, 2014). While previous research studies examined the general effectiveness (e.g., deployment effort, sound level) of these technologies, there is still a significant research gap in investigating how well these intrusion technologies alert the driver and workers. In addition, these technologies are evolving and have been through many improvements and modifications, and further research is imperative to ascertain their chances of acceptance by workers and contractors. More importantly, while limited contractors in Indiana might sporadically use these technologies, there is no adoption protocol, best practices, or verified evidence of the cost-effectiveness of these technologies in improving safety by the Indiana Department of Transportation (INDOT). Therefore, there is a critical need to investigate the effectiveness, implications, and practices of four commercially available intrusion technologies in enhancing work zone safety.

1.2 Background

Highway construction and maintenance work zones have a significant impact on traffic conditions. The speed differential between maintenance operations and the traveling public can lead to potential collisions between approaching vehicles and the mobile work zone. Additionally, work zones disrupt the usual traffic flow and patterns due to changes in the roadway layout. This creates challenges for drivers as they navigate through signs, barrels, and lane changes while keeping their vehicles under control (Silverstein et al., 2016).

Highway workers are also frequently required to do their work in close proximity to moving traffic during road construction and maintenance activities. On high-speed roads, workers are required to work next to passing cars with only a row of tubular markers or drums separating them. For both the workers and the passing cars, this job site condition poses a severe risk, and various factors such as unsafe road conditions, reckless workers, misplaced drums, and distracted drivers can cause collisions, resulting in work zone injuries and fatalities. Moreover, one of the primary causes of such accidents is the at-risk behavior of distracted drivers while approaching work zones. The deliberate ignorance of traffic control devices and posted signs, using a cell phone while driving, and exceeding speed limit beyond the posted work zone speed limit were some of the main identified risks in recent years (Awolusi & Marks, 2019; Cottrell, 2015). Numerous late-night tasks, inconsistent work zones, and greater vehicle miles traveled are additional factors that can contribute to an increase in work zone crashes (Arditi et al., 2005; Gambatese & Zhang, 2016). When an intrusion occurs and motorists enter work zone areas disregarding the compliant regulatory signs and warnings, it may result in worker injuries and fatalities (Hanomchoeng et al., 2010). Since 2013, there has been around a 60% increase in the total number of fatalities due to work zone crashes. The statistics showed that, in 2021, about 956 work zone fatalities were observed due to work zone crashes, leading to 164 worker fatalities. Furthermore, the total number of work zone injuries caused by injury crashes was 42,000.

The accompanying fatalities, injuries, and property damage in a work zone crash can result in significant expenses, depending on crash severity. In addition to these expenses, prolonged travel delays and potential damage to expensive products in transit are also costly. Despite the potential hazards and associated accrued significant costs due to aging infrastructure, there is a considerably growing need to repair and maintain existing roads and construct new roads. As a result, safety in work zones is a top priority for the Federal Highway Administration (FHWA), state DOTs, the transportation industry, and the community (Mishra et al., 2021). Transportation agencies around the country are actively looking for cutting-edge technologies and safety measures to warn drivers, ensure safe travel through work zones, reduce the likelihood of incursions, and ensure the safety of construction and maintenance workers (Bryden et al., 2000; Sakhakarmi & Park, 2022; Ukkusuri et al., 2016).

To warn drivers, various studies have suggested using rumble strips, including modified rumble strips and portable plastic rumbling strips (Anderson et al., 2016; Hanomchoeng et al., 2010; Miles et al., 2006; Noyce & Elango, 2004). Additionally, experts have suggested deploying technologies such as truck-mounted warning devices that redirect wayward vehicles to reduce the impact, intrusion alert technologies that warn drivers as well as workers through audio and visual signals in case of work zone intrusion, graphic-assisted changing message signs to improve the ability of drivers to identify available lanes, rumble strips to alert drivers by vibratory stimuli, dynamic signs and portable radar-based speed monitoring displays to warn drivers concerning their increased speed, and mobile barriers that are intended to improve safety in short-term work zones (Anderson et al., 2016; Fontaine et al., 2000; Hanomchoeng et al., 2010). While many safety precautions (e.g., truck-mounted attenuators, rumble strips, speed monitoring displays) help considerably with enhancing work zone safety, the

TABLE 1.1
General descriptions and system types associated with selected intrusion technologies

System Type	Description	Examples
Kinematic	Activated with the help of an impact device attached to a traffic control device. When a vehicle strikes the device, workers are alerted through a warning sound.	SonaBlaster
Pneumatic/Microwave	Makes use of pneumatic hoses attached to a pressure sensor which acts as a transmitter device. Siren and strobe lights are activated when a vehicle passes over the hoses (AOIS, n.d.).	Traffic guard worker alert system
Radar-Based	The radar sensors continuously monitor and identify potential work zone intrusion by scanning the incoming vehicles and their speeds. Warns the vehicle driver and workers through a siren and strobe lights. The workers are also alerted through a Personal Safety Device (PSD), which acts as a vibratory unit (AsphaltPro, n.d.).	AWARE system
Radio-Based	Consists of impact-activated smart lamps and a Portable Safety Alarm (PSA) device that acts as a signal receiver. The PSA alerts the workers through a 3-tone siren and visual flashing lights when activated. Smart lamps with various sensitivity levels transmit a radio signal when impacted or moved that can be retransmitted through a series of smart cones until it reaches the PSA. An optional sentry laser unit is activated when the emitted ultrasonic beam is obstructed.	Intellicone

increasing number of intrusions calls for designing and implementing emerging intrusion alert technologies to warn drivers and workers when errant vehicles intrude into the work zone. Several State DOTs have already begun examining the use of intrusion alert technologies to alert field workers and mitigate work zone intrusions (Gambatese et al., 2017; Khan et al., 2019; Marks et al., 2017; Mishra et al., 2021; Novosel, 2014; Ullman & Iragavarapu, 2014).

As shown in Table 1.1, intrusion alert technologies that can be categorized into microwave, pneumatic, kinematic, radar-based, or radio-based systems are intended to recognize work zone intrusion. These technologies are the alarm units used in active work zones to deter errant vehicle drivers from entering the work zone by alerting workers and drivers of approaching vehicles. Some of these alarms use sensors located close to the border of the work zone to detect oncoming vehicle intrusion and warn the workers that their protective zone has been violated with the help of visual alerts and sound alarms positioned either close to the workers or near the boundary of work zone or vibratory haptic devices attached to the workers' hardhat or vest (Mishra et al., 2021; Park et al., 2016). If these intrusion alarms are successfully implemented, they could increase highway safety in both stationery and mobile work zones and are aimed to be a potential measure to safeguard both highway workers and the general public (Brown et al., 2015). Greater safety makes employees feel truly secure and will help boost output because it will allow them to focus better on the job at hand and worry less about possible vehicle intrusion.

1.3 Research Goal

To achieve the research goal, this study includes the following tasks.

1. Document the current state of knowledge and practices of intrusion alert technologies through a comprehensive literature review of previous studies and work practices (Chapter 2).
2. Conduct a preliminary evaluation and pilot-controlled testing to assess functional characteristics in the deployment and operation of intrusion technologies these intrusion (sound levels, alarm duration, and work zone coverage) (Chapter 3).
3. Synthesize the current status, best practices, enablers, barriers, and challenges associated with using work zone intrusion technologies based on DoTs' and contractors' inputs (Chapter 4).
4. Examine drivers' visual and auditory risk perceptions and responses to work zone intrusion alert technologies (Chapter 5).
5. Examine workers' visual and auditory risk perceptions and responses to work zone intrusion alert technologies (Chapter 6).
6. Develop a decision-making matrix based on contextual analysis to help select the most appropriate work zone intrusion alert technologies (Chapter 7).

The findings of this research provided detailed information on the identification and testing procedures of technologies and offered guidelines and recommendations for adopting these technologies for practitioners and professionals in the highway construction sector in highway construction and maintenance work zones. This study also provided valuable insights into the functional characteristics of four commercially available intrusion technologies through detailed evaluations of their effectiveness, called road safety professionals' attention to incorporating required modifications in designing and implementing these technologies to enhance work zone safety. The long-term outcome of this study is to significantly reduce the injuries and fatalities in construction work zones in Indiana and across the country.

2. TASK 1: LITERATURE REVIEW TO UNDERSTAND CURRENT STATE KNOWLEDGE AND PRACTICES OF INTRUSION ALERT TECHNOLOGIES

In this task, a comprehensive and systematic literature review was conducted. This review aimed to grasp the foundational knowledge associated with commercially available intrusion alert technologies, their characteristics, and functionalities, as well as insights from studies previously conducted by other DOTs.

2.1 Highway Work Zone Intrusion Technologies

The Work Zone Safety Technologies (WZST) can be classified as follows based on their objective.

1. Speed Reduction Systems (SRS).
2. Intrusion Prevention and Warning Systems (IPWS).
3. Human-Machine-Interaction Detection Systems (HMIDS).

The SRSs are used to reduce the traveling speed of the vehicles in advanced warning areas, transmission areas, buffer areas, and work areas. These systems can have a direct or indirect physical impact on the traveling vehicle. IPWS technologies are deployed in an active work zone to avoid the intrusion of errant vehicle drivers into a work zone by warning them of the imminent danger due to the vehicle intrusion in a work zone. HMIDs are the technologies employed in a work zone to alert the workers as well as equipment operators of a forthcoming collision between the workers and the equipment (Nnaji et al., 2020). Technologies like drone radar and radar speed displays were implemented in highway work zones by state DOT's on controlled sites and live projects. Such evaluation studies concluded that speed enforcement systems can provide a considerable return on investment by reducing the economic and social costs associated with work zone accidents (Soole et al., 2013). Generally, evaluation studies on speed reduction technologies reported benefits like significant motorist speed and variance reduction, increased productivity, improved driver experience within the work zone, improved comprehension of safety instructions, and improved perceived worker safety (Nnaji et al., 2020).

Sometimes, traffic-related hazards are very hard to avoid, so the degree of exposure is reduced by using Positive Protection Systems (PPS). PPS are the engineering control mechanisms mainly used to minimize the impact of intruding vehicles. Some examples of PPS are concrete barriers, ballast-filled barriers, shadow vehicles, guardrails, impact attenuators, sand barrel arrays, truck-mounted or trailer-mounted impact attenuators, etc. While such systems can effectively reduce the impact of the intruding vehicle, this could cost DOTs and contractors in the US up to $1.1 million annually, whereas the resulting crash cost saving of just $196,885 (Ullman & Iragavarapu, 2014). Whereas intrusion alert technologies have low life cycle cost (on average $19,000, which is calculated based on their capital cost, annual maintenance cost, salvage value, disposal cost, etc.) and are primarily designed to alert the highway work zone workers of the incoming vehicles intruding the workspace (Mishra et al., 2021). Intrusion alert technologies are primarily designed to alert the highway work zone workers of incoming vehicles intruding on the workspace. A review of prior publications and state of practice suggested that there are four intrusion technologies are commercially available as of November 2022, namely SonoBlaster, Intellicone, Traffic Guard Worker Alert System (WAS), and Advance Warning And Risk Evasion (AWARE) that have been evaluated by multiple U.S. DOTs in recent years (Cathy, 2010; Eseonu et al., 2018; Khan et al., 2019; Marks et al., 2017; Mishra et al., 2021; Novosel, 2014; Theiss et al., 2017). These systems, however, are constantly changing and have undergone numerous upgrades. Therefore, additional auxiliary research is crucial to examine their effectiveness after improvement and modifications. The four commercially available intrusion technologies were considered for this project. Table 2.1 describes currently available intrusion sensing technologies based on their working principle. The Intellicone Smart Closure System, developed by Highway Resource Solutions in the United Kingdom, comprises Portable Site Alarms (PSA) that can be deployed near the work zone to alert workers about the imminent threat due to oncoming vehicles. In their recent development, the sentry laser was added to the system, which is a device that emits an ultrasonic beam and activates the siren alarm when this beam is obstructed.

- *The Intellicone Smart Closure System*, developed by Highway Resource Solutions in the United Kingdom, comprised of Portable Site Alarms (PSA) that can be deployed near the work zone to alert workers about the imminent threat due to oncoming vehicles. In their recent development, the sentry laser was added to the system, which is a device that emits an ultrasonic beam and activates the siren alarm when this beam is obstructed.
- *SonoBlaster*, developed by Transpo Industries, is an impact-activated work zone intrusion alarm that warns workers and drivers with an audible alarm. The alarm devices are simple to put on traffic cones or barricades, and warnings are set off when intruding cars hit them.
- *The Traffic Guard Worker Alert Technology (WAS),* developed by Astro Optics, consists of trip hoses, a pressure sensor, a wireless transmitter, a Portable Alarm Case (PAC) with an auditory and visual alarm, and Personal Safety Devices (PSD) with vibratory haptic alarm that get triggered when the vehicle runs over the trip hoses (AOIS, n.d.).
- *The Advance Warning and Risk Evasion (AWARE),* developed by OldCastle, is a radar-based technology that continuously monitors the speed of the oncoming traffic (maximum 64 vehicles simultaneously), location, and possible trajectory to detect potential intrusion and alerts the vehicle driver and workers through a combination of flashing lights and siren alarm (AsphaltPro, n.d.)

TABLE 2.1
General description of intrusion alert technologies

Intrusion Technology	Components	Description	Country of Origin	States Tested	Cost per Unit	Website	Manufacturer/ Vendor Specifications
Kinematic (SonoBlaster)	Main unit Mounting assembly Cocking pin CO2 cartridge	Activated with the help of an impact device attached to a traffic control device. When a vehicle strikes the device, workers are alerted through a warning sound.	United States	California, New Jersey, Alabama, Kansas, and Oregon (Cathy, 2010; Khan et al., 2019; Nnaji et al., 2020; Novosel, 2014; Marks et al., 2017)	$98.95 for one unit and accessories and $23 for a pack of 10 CO2 cartridges	https://www.tapconet.com/product/sonoblaster-work-zone-intrusion-alarm-and-accessories	Sound level of 125 dB, 15 seconds alarm duration
Pneumatic-Microwave (Traffic Guard Worker Alert System)	Pneumatic trip hoses Portable alarm case Personal safety device Wall charger Handheld remote (optional)	Pneumatic hoses are attached to a pressure sensor which acts as a transmitter device. Siren and strobe lights are activated when a vehicle passes over the hoses (AOIS, n.d.).	United States	California, Alabama, Tennessee, Oregon (Awolusi & Marks, 2019; Khan et al., 2019; Mishra et al., 2021; Nnaji et al., 2020)	$1,667 for one complete set	https://www.aoindustrialsupply.com/product/worker-alert-system/	1,000 feet transmission range between the pressure sensors and portable alarm case
Radar-Based (Advance Warning and Risk Evasion)	The main unit consists of a RAVEN sensor, strobe lights, and alarm WorkTRAX (personal safety device)	The radar sensors continuously monitor and identify potential work zone intrusion by scanning the incoming vehicles and their speeds. Warns the vehicle driver and workers through a siren and strobe lights. The workers are also alerted through a Personal Safety Device (PSD), a vibratory unit (AsphaltPro, n.d.).	United States	Alabama, Tennessee, Texas (Awolusi & Marks, 2019; Mishra et al., 2021; Theiss et al., 2017; Ullman & Trout, 2016)	$15,000	–	Can detect vehicle speed up to 45 mph, scans 64 vehicles at a time
Radio-Based (Intellicone)	Smart cones Portable site alarm consisting of flashing lights and alarm Sentry laser	Consists of impact-activated smart lamps and a Portable Safety Alarm (PSA) device that acts as a signal receiver. The PSA alerts the workers through a 3-tone siren and visual flashing lights when activated. Smart lamps with various sensitivity levels transmit a radio signal when impacted or moved that can be retransmitted through a series of smart cones until it reaches the PSA. An optional sentry laser unit is activated when the emitted ultrasonic beam is obstructed.	United Kingdom	California, Alabama, Tennessee, Kansas, Oregon (Awolusi & Marks, 2019; Khan et al., 2019; Mishra et al., 2021; Nnaji et al., 2020; Novosel, 2014)	$35–$100 per day on a lease basis	https://www.highwayresource.co.uk/digital-services/intellicone-smart-taper/	3-tone sirens designed to cut through background noise, 150 feet transmission range between the smart cones

There were conflicting results from these studies; for example, Nnaji et al. (2018) concluded that the Intrusion alert technologies generated a 74 to 90 dB sound level when activated 50 feet away from the workers, whereas Marks et al. (2017) reported a lower sound level for the same technologies at similar distances which were in between 62 and 70 dB. Some of the key takeaways from these studies are that intrusion alert systems can improve worker safety. However, they still cannot allow sufficient reaction time and include several false alarms, unnecessary set-up time, and the inability to hear the alarms in the presence of ambient noise.

Proximity Warning Systems (PWSs) are designed to trigger an audio alarm when workers are in the close vicinity of the work zone equipment which might affect worker safety. According to (Nnaji et al., 2020), PWSs are considered a viable option for reducing construction equipment-worker collisions in most cases. Another type of PWS is a Visual-based Warning System (VWS), which acts as an alert technology to warn the workers visually of the forthcoming accident. However, despite the potential benefits of work zone intrusion sensing systems, challenges have been identified. Awolusi and Marks (2019) note limitations such as nuisance alerts, which can desensitize employees, substantial space requirements for installation, significant time and effort for setup, durability issues, and misalignment of detection areas. These factors have hindered the widespread adoption of these technologies in enhancing work zone safety. It is important to note that all the commercially available technologies that have been evaluated by the previous studies could not be as effective as they promise in every highway work zone situation due to varying conditions of the highway settings. Every highway work zone has unique features and can cause the failure of commercially available technologies even though they are effective in other highway work zones. Hence, further testing of intrusion technology in various scenarios can help demonstrate the advantages and limitations of these systems (Awolusi & Marks, 2019).

The effectiveness of work zone-related safety technology has been the subject of numerous studies by state DOTs and other public/commercial organizations. Work zone safety solutions such as an automated flagger assistance device, directional alarm system, warning light, work zone intrusion alert technology, and portable traffic signs have all been studied to improve work zone safety (Brown et al., 2015; Wang et al., 2011).

The study conducted by the New Jersey DOT found that the kinematic intrusion systems (i.e., Sonoblaster) can be primarily used for lower speeds (30 mph) and volume roads due to problems with setting up the device and its durability (Cathy, 2010). Numerous researchers claimed that kinematic systems had weak performance because of a laborious setup process, poor durability, and frequent misfires while being set up and stored (e.g., Cathy, 2010; Khan et al., 2019; Marks et al., 2017; Nnaji et al., 2018; Novosel, 2014). In addition, the Kansas DOT evaluated two systems, kinematic (i.e., Sonoblaster) and radio-based intrusion systems (i.e., Intellicone). The study's findings revealed that workers had a positive attitude toward the devices; however, it was noted that the kinematic system setup was apparently challenging, and the radio-based system alerts were insufficiently loud for use in noisy surroundings. A wireless sensor network-based intrusion alarm was created during the pilot testing of the radio-based system (Intellicone) and tested for temporary work zones. Although 100% precision in detection was not seen during the experiments, the results from the tests revealed that the radio-based system was trustworthy and accurate (Novosel, 2014).

Further, Texas A&M Transportation Institute researchers put AWARE through a rigorous testing process in 2016 by verifying whether the alarm system activates when the vehicle speed is above lane speed or not. It was found that AWARE performed flawlessly during their testing, causing no false alarms at any point in the test. However, one major issue raised by subjects was how similar the alarm sirens were to those of emergency and law enforcement vehicles (Theiss et al., 2017; Ullman & Trout, 2016). In 2017, Oregon DOT also examined kinematic (SonoBlaster), radio-based (Intellicone), and pneumatic-microwave-based systems (WAS) in both controlled and real-world work zones. According to the findings of their study, all three technologies were efficient at warning workers. However, it was argued that their high cost (e.g., radio-based systems) would probably prevent some companies from actually implementing them (Gambatese et al., 2017; Nnaji et al., 2020). Recently, Tennessee DOT assessed three intrusion technologies (Intellicone, AWARE, and WAS) in controlled testing and live work zones. Given its live tracking capability, Intellicone was recognized as ideal for protracted lane closures and is highly useful for keeping track of the current status of construction zones. AWARE was reported as a technology that is easy to set up, accurate in detecting intrusions and warning the workers, and suitable for mobile work zones. Given the limitations with restricted range and delayed alarm activation, WAS was thought to be only suitable for projects with short tapers (less than 500 feet in length) and slow vehicle activity zones (less than 30 mph) (Mishra et al., 2021). While previous studies argued that these intrusion alert technologies could prove effective in improving worker safety, they did not allow sufficient reaction time, involved continuing false alarms, unnecessary setup time, and inability to hear the alarms in the presence of ambient noise (e.g., Gambatese et al., 2017; Khan et al., 2019; Mishra et al., 2021; Novosel, 2014). This has also impeded the extensive applications of these technologies in work zone safety (Awolusi & Marks, 2019).

Furthermore, since each work zone location has distinctive qualities, the solutions frequently need to be altered to suit the requirements of the specific highway construction/maintenance project scenario (Ozan, 2020); and can cause the failure of commercially available technologies as each work zone has unique characteristics (e.g., vehicle density, speed limit, ambient noise environment). Hence, further testing of intrusion systems in various scenarios can help demonstrate these systems' advantages and limitations.

2.2 Detailed Description of Selected Intrusion Technologies

An extensive literature review on intrusion alert technologies was conducted to identify the general information, advantages, and disadvantages of these technologies, which are shown in Table 2.2.

The following section presents detailed information on commercially available intrusion alert technologies as of November 2022.

2.2.1 SonoBlaster

SonoBlaster is a dual alert work zone intrusion alarm used to simultaneously warn workers and drivers of the intrusion vehicles to help prevent crashes and injuries in highway work zones. The SonoBlaster is a kinematic highway intrusion alert technology that produces a warning sound to alert workers when it is struck by a vehicle- known as an impact-activated system (Awolusi & Marks, 2019). Typically, the SonoBlaster can be mounted on the usual traffic control channelizing devices such as cones, drums, barricades, delineators, and A-frames. However, since the system activation depends on the vehicle's impact, its best practice is to use traffic cones because some heavier channelizing devices might not tilt, and the system might not get activated if an intrusion occurs. The whole unit is made of hard plastic except for the CO2 cartridge (Novosel, 2014). It has a built-in carbon dioxide (CO2) powered horn that blasts at 125 decibels to signal the highway workers that their protective zone has been breached. When the SonoBlaster unit mounted on the channelizing devices is struck by the vehicle, the face of the CO2 cartridge is punctured with a hole by an internal firing pin, and the escaping gas produces the alert sound through an air-pressure horn (Khan et al., 2019). The main components of the SonoBlaster are the SonoBlaster Alarm Unit, Disposable CO2 cartridge, and mounting bracket (for mounting it on channelizing devices). The main components of the SonoBlaster are shown in Figure 2.1.

2.2.1.1 Setup and operation of SonoBlaster. For the setup and operation of SonoBlaster, first, it needs to be attached to the traffic channelizing devices (cone, barrels, etc.) according to the instructions from the manufacturer. Then attach the mounting bracket to the base of the traffic cone and SonoBlaster unit to the mounting bracket while turning the knob to the unlock position. Cock the SonoBlaster unit with the help of cocking pin and turn the knob to the locked position to install the CO2 cartridge in the red compartment. Properly orient the CO2 cartridge and set the cone on

TABLE 2.2
Detailed description of the intrusion technologies

Intrusion Alarm	Advantages	Limitations	Audible	Visual	Haptic
SonoBlaster	Loud sound levels (125 dB) Easy to deploy and transport Easily recognizable in ambient noise	More false negatives No control over the duration of the alarm Inconsistent alarm duration Not suitable for weather below 32°F Lengthy initial setup (12–22 minutes)	✓	×	×
WAS	Provides both visual and auditory alerts Included wearable PSD to offer vibratory alerts to workers	Not suitable high-speed roadways (more than 30 mph) Connection issues between the sensors and difficult to transport Delayed activation	✓	✓	✓
AWARE	Easy to deploy Has effective flashing strobe lights Easy to deploy and transport Includes wearable PSD to provide auditory and vibratory alerts to warn workers	Effectiveness reduces for tapers longer than 500 feet Alarm is similar to emergency vehicles	✓	✓	✓
Intellicone	Easy to setup High coverage area Very durable against the vehicle impact	Not viable for lengthy closures Difficult to store and transport Relatively low sound levels (55 to 65 dB)	✓	✓	×

Note: ✓ = present, × = not present.

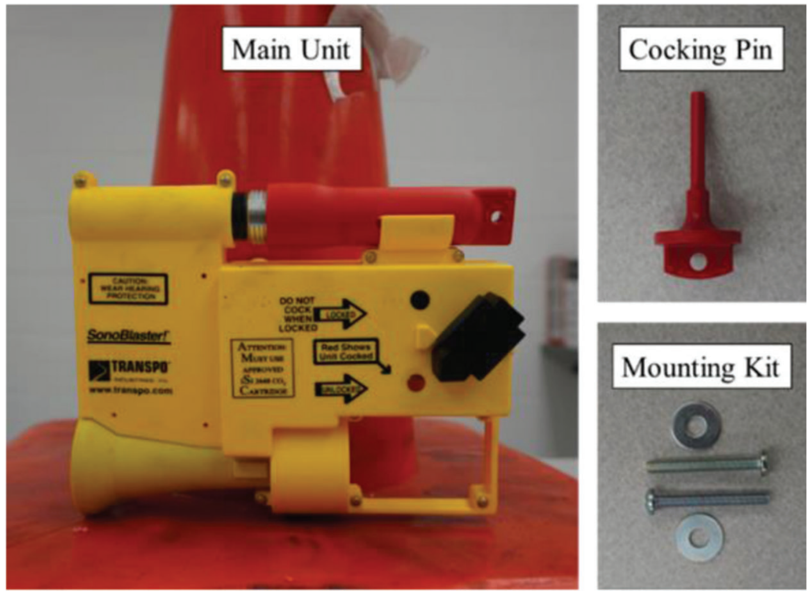


Figure 2.1 SonoBlaster intrusion alarm components.

the highway work zone while the knob is still turned to the locked position. Once placed on the highway work zone, rotate the control knob from locked to unlocked. The SonoBlaster triggers the alarm if the cone is tilted by more than 70° or struck by the intruding vehicle. Novosel tested the SonoBlaster to determine the angle at which the unit triggers its alarm. The unit was mounted on a traffic cone without the CO2 cartridge installed in the unit. Then the cone and the unit assembly were slowly tipped by hand until the firing pin could be heard firing.

The SonoBlaster is considered inconsistent for the duration of the alarm. The manufacturer claims of SonoBlaster alarm duration is 15 seconds; however, previous studies reported the actual alarm duration varied from 15 to 90 seconds (Khan et al., 2019), ranging from 3 to 80 seconds (Novosel, 2014) and varied from 7 to 41 seconds with a median of 14 seconds (Gambatese et al., 2017). The reasons behind the inconsistency are found to be related to the CO2 cartridges, size, and position of the hole, which is punctured by the firing pin. Sometimes, the hole could be punched at the center and sometimes towards one side, leading to an inconsistent duration of alarms (Khan et al., 2019). The alarm duration is considerably less (less than 14 seconds) when the SonoBlaster alarm is tipped such that the orientation of the horn is towards the ground after the impact. The emitted CO2 gas or water vapor around it may get condensed, which could be the reason for the shorter alarm duration for this orientation (Novosel, 2014). Suppose the SonoBlaster unit is activated consecutively in weather conditions below 32°F; ice will start accumulating inside the nozzle. As a result, false-negative cases may be observed, such as no activation of the alarm even when the vehicle intrudes into the work zone.

The SonoBlaster is a unidirectional intrusion alarm, so the sound levels vary with different orientations of the SonoBlaster unit. The sound level of the SonoBlaster is loudest when oriented directly towards the receiver and quietest when oriented towards the ground after being struck by the vehicles (Novosel, 2014). The SonoBlaster alarm is at its peak sound level within the first second of its firing and gradually drops as the pressure in the cartridge drops. The alert can be heard above background noise when the sound level is initially at its highest level. However, its distinctiveness also decreases as the sound intensity drops (Novosel, 2014).

The SonoBlaster is easy to deploy (weighing approximately 10 lbs. including the traffic cone) and requires special care to be taken during the pre-deployment of the system. However, transporting the assembly of the SonoBlaster unit and cone to highway work zones via truck is challenging. Moreover, while withdrawing the cones from the body truck to set up on the highway work zones, the cone may get tilted more than 70°, activating the alarm while the control knob is in unlock position (Khan et al., 2019). The approximate time taken for the initial setup of the whole assembly of SonoBlaster varies from 12 to 22 minutes; however, the setup of SonoBlaster is quite burdensome due to the non-compatibility of the brackets with the cones. The durability of the SonoBlaster unit is also an issue, as the whole unit assembly is subjected to the impact of intruding vehicles.

2.2.2 Traffic Guard Worker Alert System (WAS)

The WAS is lightweight, with an alarm unit (weighing 4 lbs.) and an easy-to-transport system that sends the signal wirelessly to the alarm unit and

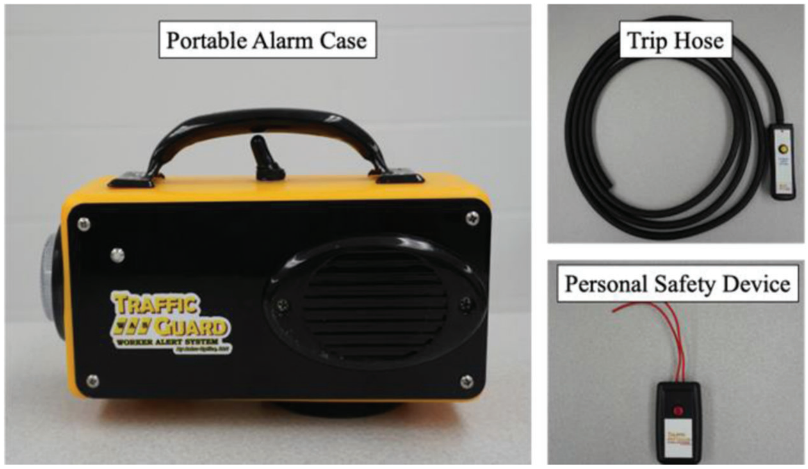


Figure 2.2 WAS components.

personal safety devices mounted on the workers. The WAS assembly includes a trip hose (a pneumatic tube) with a pressure sensor and wireless transmitter, a rechargeable alarm unit, a Portable Alarm Case (PAC) that has a pulsing sound and flashing light, and a Personal Safety Device (PSD) with audible and vibrating alarms as shown in Figure 2.2. The WAS is a pneumatic and microwave-based highway work zone intrusion alert system as it utilizes the pneumatic tubes (i.e., trip hose) and a transmitter-receiver feature to connect the alarm unit and trigger the alarm signal when a vehicle intrudes the work zone. The trip hose can be placed ahead or behind the workers with enough distance in between to provide ample reaction time for the workers when the vehicle intrudes into the work zone. The length of the trip hose that comes with this assembly is 12 feet. However, the length of the trip hose can be extended further as per the needs of the highway work zone. However, the manufacturer recommends up to the 50-foot length.

Standard Features

- Wireless 12-foot trip hose with pressure sensor.
- Rechargeable alarm unit with flashing light with magnet and handle.
- Loud audible siren.
- Optional heavy-duty carrying case.

Operational Accessories

- Personal Safety Device (PSD) vibration unit.
- Personal Safety Device (PSD) with trigger vibration unit.
- Wall charger for flashing unit.

2.2.2.1 Working and operation. When the vehicle passes over the trip hoses deployed across the lane in the highway work zones, the inbuilt pressure sensor gets activated, and a signal is transmitted through the transmitter to activate the alarm unit and PSDs. The alarm unit provides visual and audio warnings, while the PSD units provide auditory and vibratory alert warnings to allow enough reaction time for workers to escape out of the intruding vehicle's path. The auditory alerts are provided through the earbuds by connecting them to the audio jack provided on top of the PSDs. The alarm unit has a rechargeable battery and can be charged by using a wall charger (Marks et al., 2017). The pressure sensor and the handheld remote use 2 AA batteries while the personal safety device with an included earpiece uses 2 AAA 1.5V copper top alkaline batteries to function (AOIS, n.d.).

The Deployment Steps

1. First, deploy the trip hoses on the highway work zone in a transverse direction across the lane. Turn on the pressure sensor of the trip hose with the help of the power button provided.
2. The pressure sensor will be calibrated automatically until the Light Emitting Diode (LED) flashes several times.
3. The alarm unit comes with a magnet so that it can be attached to any construction equipment or structure or placed on a flat surface in a work zone. Establish the alarm unit in a suitable location while turning it on by pressing the power button provided under the handle. The unit should be placed such that the green LED on the side of the unit is visible.
4. Attach the Personal Safety Devices (PSDs) with the workers' safety gear, such as hard hats, vests, or PPEs, etc.
5. The system can be validated by stepping on one of the trip hoses to test if everything is working properly. The sensor light will turn red, indicating that the trip hose is working properly.

The pressure sensor can send a signal wirelessly to the alarm unit and PSDs up to 1,000 feet away, which is claimed by the manufacturer. However, in the study by Khan et al. (2019) the maximum transmission range during the testing was 400 feet with a clear line of sight and 300 feet with a vehicle obstructing the line of sight. Also, the range between the trip hose and PSD was found to be approximately 125 feet. In another study conducted by Gambatese et al. (2017) 100% transmission was recorded at 300 feet for the alarm unit, while all the PSDs lost the transmissions when the WAS was triggered at 100 feet or farther.

It takes around 15 to 20 minutes to deploy the four trip hoses, two PSDs, and one handheld remote in the highway work zone (Khan et al., 2019). The duration of the sound alarm was around 2 seconds. The alarm unit has a visual alarm light source only on one side of the unit, so it is difficult for the workers to notice it as it is effective only when the light source is within range of sight of the workers. Also, out of 38 trials conducted by Khan et al. (2019) some issues were observed, including false negatives and several cases of delay in alarm activation for both PSDs and alarm units.

The WAS is recommended to be employed on two-lane curved roadways and stationary operations. The system was considered ineffective for the work zone on freeways due to the high traffic speeds and risk exposed during the deployment. Marks et al. (2017) also have recommended this system for short tapers and short-term or mobile highway work zone projects. There are a few concerns regarding the sound intensity of the alarm unit in the presence of ambient noise such as live traffic and equipment noise. Khan et al. (2019) have addressed this problem by employing multiple alarm units in the work zone as all units use the same frequency transmitted by the pressor sensor. The vibration feature of the PSD was considered effective in alerting the workers, but it failed to alert the workers while moving around. The possible reason could be the workers may not feel the vibrations during the movement or accidentally got out of the device's transmission range (Khan et al., 2019). Some durability issues were also observed as one of the trip hoses became ineffective during the experiments. In another study by Mishra et al. (2021), the WAS was found to be suitable for short tapers, mobile work zones, and short-term repairs away from the roadways (e.g., on shoulders) because of its quick and easy deployment. Moreover, during the live testing of the technologies, the workers reported that the vibratory alerts from PSD were noticeable but found ineffective while operating the concrete breaker. Workers were skeptical about the effectiveness of WAS in covering larger work zone perimeters, whereas several lags in the activation of PSDs were also observed. Hence, WAS seems to be impractical for use in work zones where workers are too close to the traffic (Mishra et al., 2021).

In the study by Marks et al. (2017) the vibratory units of the PSDs were deemed to be ineffective because the vibratory alert had delays ranging from 1 to 2.5 seconds, with an average delay of 0.37 seconds over the 15 trials performed. The experimental trials also showed that the vehicle drivers took more time to stop the vehicle when they heard the alarm sound when the Traffic Guard Worker Alert System was deployed in a work zone. This may be the case because when the vehicle runs over the pneumatic trip hose, it does not make any loud impact noises as it does with the other intrusion system. Hence, the drivers are not provided with additional alerts apart from the audio and visual alerts from the alarm system (Marks et al., 2017). With the current system design, the activation button on the alarm unit has a high chance of getting activated manually during transportation. This may not be the issue in practice as employees can easily notice such activation during the deployment. Still, it is recommended to remove the batteries of the devices while it is being transported to avoid the issue of manual activation.

Due to its flexibility, this system has the advantage of deploying the trip hose to any configuration. The pressure sensor should be positioned towards the shoulder to avoid any accidental damage from vehicular traffic. Khan et al. (2019) suggested adding more than one speaker in an alarm unit for higher sound levels. Also, to increase the functionality of the device, audio alerts on the PSDs without the requirements of earbuds are recommended. The transmission range of the trip hose pressure sensor increased sufficiently when the pressor sensor was held at an elevated distance from the ground surface. Hence, something as simple as a hook must be provided in future trip hoses to allow them to hang it on cones at a higher level from the ground surface. To determine the ideal distance for the deployment of the system, specific information on the required reaction times for workers needs to be specified. This information will also be useful in determining how far out the system could be deployed in order to be useful (Khan et al., 2019).

2.2.3 Advance Warning and Risk Evasion (AWARE)

Advance Warning And Risk Evasion (AWARE) is an innovative work zone intrusion detection and alarm system that relies on the detection of vehicles crossing the predetermined perimeter (Figure 2.3). Oldcastle Materials, Inc., (now Oldcastle), in collaboration with a subcontractor from the US defense industry, developed a state-of-the-art workzone intrusion and worker alert system to deploy within its work crews nationally (Ullman & Theiss, 2019). AWARE uses a target threat detection and tracking methodology to logically assess the approaching vehicle's speed, location, and possible trajectory (Theiss et al., 2017). When AWARE is deployed in a highway work zone, the radar-based sensor detects the threats due to the intrusion of incoming vehicles in two flat-shaped regions, as shown in Figure 2.4. Based on the manufacturer's report, it is being used in more than 40 states mainly for flagging operations by contractors. As shown in Figure 2.4, while the short-range zone stretches up to 200 feet ahead of the alarm and spreads 45 degrees on either side of the centerline, the long-range zone in red stretches up to 500 feet ahead of the alarm and spreads 10° on both sides (Theiss et al., 2017).

In case of an intrusion or threat to the highway work zone workers, the workers are alerted through a device called WorkTRAX, by providing auditory and haptic alerts of the incoming intrusion. WorkTRAX is a small device that can be worn in a hardhat, in a vest, or as an armband (Ullman & Theiss, 2019). The AWARE also has flashing lights that are mounted on work vehicles or

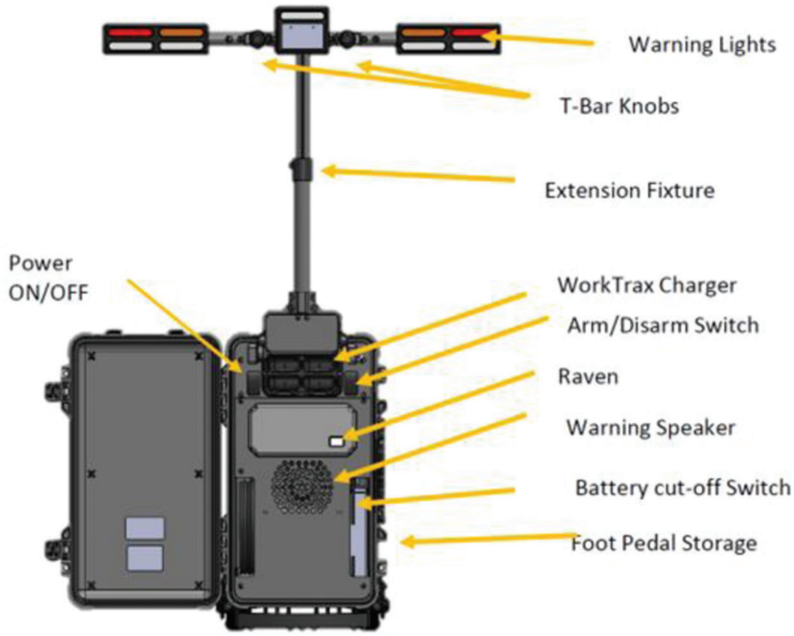


Figure 2.3 Components of Advance Warning and Risk Evasion (AWARE).

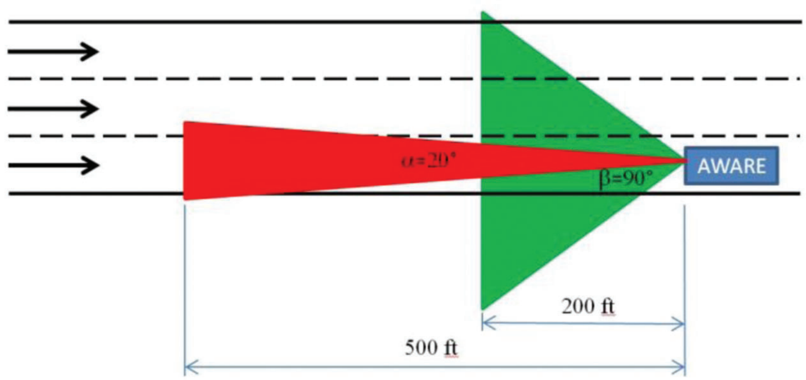


Figure 2.4 AWARE threat detection region (Theiss et al., 2017).

the equipment where the Radar sensor is positioned, and the sound alarm is focused on the direction of impending traffic. These flashing lights and sound alarms get activated to signify an alert to the driver of an intruding vehicle if an errant vehicle has intruded into the work zone. On the activation of the AWARE system, it learns the proper travel pattern of an imminent vehicle and automatically defines the zones where the same vehicle is allowed to travel and where it is not. The system does not get activated if the vehicle speed is below 15 miles per hour (mph) in order to avoid false alarms due to the work vehicles and equipment moving into and around within the work zone (Ullman & Theiss, 2019).

Minnesota Department of Transportation coordinated the deployment of the system on an Oldcastle road crew with the objective that the Technical Advisory Panel (TAP) could make visits to the site. The efforts were successful in demonstrating the potential of the AWARE system for detecting the intrusion of the vehicles and alerting the work crews as well as intruding vehicle drivers. The research purpose was to obtain raw individual vehicle trajectory data generated by the system for further analysis to assess the intrusion behavior in detail, but this was not possible because of some data storage and synthesis issues related to the AWARE system. The developers are working on resolving this issue to enhance the detection and the warning algorithm and resolve the issues with the data storage and synthesis challenges as well.

Ullman and Trout (2016) conducted a study to assess the performance of the AWARE in a closed course environment to verify the alarm system produces the intrusion alert when the vehicle is at a distance based on the threat detection conditions and the set of rules of Stopping Sight Distance (SSD) of the vehicle. The study was also intended to validate that the intrusion alerts were not activated when the threat-detecting conditions did not warrant. The flagger operations were also evaluated on different trajectories of the vehicle. The AWARE system accomplished a 100% success rate in terms of accurately activating and not activating the intrusion alert in the form of warning lights and audible alarms in various conditions. Similarly, the Work TRAX device achieved a 97% success rate which was measured in various device locations, scenarios, and vehicle trajectories. The approach vehicles used for this testing were equipped with a Trimble GPS using Real-Time Kinematic (RTK) satellite navigation to continuously track the approach vehicle position through corrected GPS data. The dash-mounted camera was also used to capture the forward scene view from the approaching vehicle (Theiss et al., 2017). The sentry provides three different types of alerts by activating and deactivating the visual, audio, and vibratory alerts based on the Stoppage Sight Distance (SSD) (Mishra et al., 2021). The alerts are mainly as follows.

1. Only WorkTRAX is activated.
2. WorkTRAX + warning lights are activated.
3. WorkTRAX + warning lights + sound alerts are activated.

Figure 2.5 Components of Intellicone.

In this study, AWARE was found to be the loudest among other alarms, and the maximum transmission range was found to be around 400 feet (Mishra et al., 2021). Its accuracy in detecting the vehicles was evaluated by testing it under three scenarios. Under all these scenarios, the sentry performed with 100% accuracy, and no false alarm was observed during the trials. AWARE was the most accurate among other tested technologies and was best suited for work zones with medium tapers and where flagging is required. The overall workers' feedback was positive; however, using a mobile application for configuration did not seem right.

2.2.4 Intellicone

Intellicone is a kinematic and radio-based system that includes a Portable Site Alarm (PSA), Traffic Management Unit (TMU), motion-sensitive cone lamps, etc., which transmits an electronic warning signal when impacted by the intruding vehicle in the form of auditory and visual alarms in a work zone (Figure 2.5). The set of integrated lamps and impact sensors called Unipart Dorman ConeLITE transmits a signal when impacted, and PSA units act as signal receivers to activate the signal alarms. The lamps are equipped with yellow Light Emitting Diodes (LEDs). The cone lamps are mounted on top of standard traffic cones or channelizers with the help of a single bolt, and the manufacturer also offers to customize them according to our needs to fit them on the other channelizing devices. When cone lamps are activated, the sensors become active, and the lamps start to flash at steady intervals. These lamps can also be used as sequential lighting if preferred. The sensors have a three-axis accelerometer that can measure tilt and impact and transmit a 433-Megahertz radio frequency signal toward the PSA. The PSA units are required to be close enough to receive a signal from cone lamps, else the signal is transmitted through a series of cone lamps until the signal reaches the PSA unit. The signal is repeated through a sensor network, which acts as a mesh network. The cone lamps (impact sensors) use a 6V carbon-zinc heavy duty lantern battery, while the Portable Site Alarm (PSA) uses an internal rechargeable battery (Marks et al., 2017).

The PSAs are web-enabled alarm units that use general Packet Radio Service (GPRS)/Global System for Mobile (GSM) communications and GPS sensors. Intellicone offers various communication elements between the work zone site and the central command center. The intrusion alerts are sent in the form of text messages, alarm sounds, cloud notifications, or by any electronic system. In the United States, some of its communication functions are not available at the time of publishing this report. The manufacturers plan to deploy such features in the United States by using a roaming SIM alternative.

2.2.4.1 Descriptions and features of the Intellicone components

1. *Portable Site Alarm (PSA)*
   The PSA is equipped with an audio-visual alarm technology designed to cut through the background noise with its 3-tone siren. It uses two types of flashing LEDs; green light means the system is live with no alerts, and red light signifies an errant vehicle intrusion. The PSA unit has three types of variants: Y-series, which connects to Intellicone sensors via short-range radio frequency with a 164-foot range, R-series with a 164-foot range, and O-series with a 656-foot range (Khan et al., 2019). Each PSA has a unique ID number printed on it, which is essential to connect the PSAs to the web interface.

2. *Traffic Management Unit (TMU)*
TMU is an additional unit that is used to manage real-time responses to breaches, web portal management of various Intellicone systems, text message alerts, and GPS location tracking. This is an optional unit used to store all the intrusions related to being uploaded to the cloud platform.

3. *Unipart Dorman ConeLITE®*
Communicates with other lamps and PSA by sending a signal when pushed, impacted, or tilted.

4. *Synchro-GUIDE*
Similar to the ConeLITE sensors, Synchro-GUIDE uses wireless impact detection technology to communicate with the other sensors and the Intellicone PSA. It has an additional feature of sequential flashing lamps by synchronizing the flash.

5. *Sentry Laser*
The sentry unit consists of a motion sensor that uses an ultrasonic single-ended sensor to activate the alarm when the emitted beam is breached or obstructed.

2.2.4.2 Setup deployment, and operation

1. Deploy the Unipart ConeLITE and/or sentry units on a standard traffic cone. The lamps will get activated if pushed, impacted, or tilted, and the sentry unit activates when the continuously emitted ultrasonic beam is breached or obstructed to trigger an alert signal to the PSA.
2. The TMU is attached to a cone or any other traffic feature and placed within the 164-foot range from the Intellicone sensor barrier of lamps and sentry (Khan et al., 2019).
3. The PSA units are then deployed on a cone, and the assembly is positioned at a suitable location close to the workers in a work zone.

The PSA unit can trigger an audio alert of 55 to 65 dBA while emitting a flashing LED alarm at 400 feet when tilted or impacted (Novosel, 2014). Novosel also measured the maximum transmission distance in two different ways: first, the transmission distance between the PSA unit and sensor unit, and transmission between two sensor units. The maximum transmission distance with 100% transmission rate was found to be 350 feet between a sensor and the alarm, while the maximum transmission distance between the sensors with 100% transmission was found to be 450 feet (Novosel, 2014). This demonstrates that multiple sensors are likely to be adopted in a work zone in order to properly transmit a signal to the alarm unit. However, the manufacturer has recommended a 50-meter (150-foot) distance between the sensors; the actual transmission distance was found to be much greater than this. In a study by Khan et al. (2019) the maximum distance between the lamp and PSA and between two lamps was found to be 100 feet. Novosel also conducted a series of tests to determine the alarm activation angle of the Intellicone sensor. The activation angle of the Intellicone sensor was found to be 19.2° from horizontal. The battery life of the Intellicone alarm unit is approximately 23 hours with its green light on (Novosel, 2014), whereas Khan et al. found it to be around 50 hours. The sensors with sequential lighting can be used in a work zone for nearly 10 days or more, which explains that Intellicone alarms are most likely to be deployed in short-term or temporary work zones.

In the study conducted by Khan et al. (2019) ten Intellicone cone sensors were used. Intellicone sensors have the option of five different sensitivities: very high, high, medium, low, and very low. The sensitivity of the smart cones depends on the level of effort required to activate the alarm such that very high sensitivity cones are susceptible to low vibrations or movement (for example, with a simple vibration from the passing traffic, the alarm gets activated), whereas very low sensitivity cones are susceptible to strong impacts only. However, it was argued that numerous false negatives were observed due to adopting a combination of Intellicone lamps of varying sensitivity. The varying sensitivity of the lamps may seem to have interfered with the Intellicone operation. Lamps with high sensitivity get activated when the cone is picked or moved, while low-sensitivity lamps only get activated when dropped on the pavement. The manufacturer recommends using the same sensitivity lamps in a work zone. In most studies, the Intellicone was found to be easy to deploy.

The only negative point observed about the Intellicone was the difficulty hearing the alarm due to its sound volume. Although, the sound of the Intellicone alarm is distinctive and recognizable due to its three-tone sound. Mishra et al. (2021) addressed this issue by conducting the experimental trials in four perpendicular directions, and sound intensities were found to be somewhat consistent in all directions. Although the sound intensity of PSA was even less than the construction equipment, the alarm was more noticeable due to its high-pitched and distinct sound. The duration of the alarm was also consistent with the longest-lasting alarm among other alarms with 20 seconds duration. The maximum transmission range was observed at 350 feet with 100% transmission. Few delays were observed between the alert activation and intrusion detection, and the likelihood of false alarms was found to be higher with Intellicone. Workers expressed their concerns over the frequent knocking down of the cones mounted with sensors by the passing vehicles, and moving the alarm is troublesome as all sensors and alarms must be moved, and they get triggered easily.

2.3 Conclusion

The initial phase of the project was devoted to conducting a comprehensive review of intrusion alert technologies, aiming to discern prior findings and discernible research gaps. From this literature survey, several gaps were identified. Although numerous studies have examined the implications of these technologies, primary functionalities—like sound level, transmission range, deployment ease, and frequency of false alarms—were primarily evaluated under controlled or limited environmental conditions. Hence, further investigation is crucial to define these technologies' performance across more diverse scenarios. Additionally, most research concentrated on the alerts' impact on workers, with only a handful examining the repercussions on drivers. Moreover, no study incorporated cutting-edge wearable technologies, which could yield quantifiable data on whether workers or drivers actually hear the alarms, comprehend the associated risks, and subsequently adopt safety measures. This underscores the pressing need for a deeper dive into the effect of intrusion alert systems on both drivers and workers. Furthermore, while past research has provided recommendations for the practical deployment of each technology, it is unclear what the best technology choice is under varied construction circumstances. Consequently, a decision-making matrix becomes imperative to guide the selection of the most fitting system for a given scenario.

3. TASK 2: PRELIMINARY TESTING OF WORK ZONE INTRUSION ALERT TECHNOLOGIES

In this task, the preliminary tests on the selected technologies were conducted to test if they function well and provide the required alerts. All the experimental trials were conducted in a parking lot facility at Bowen Laboratory at Purdue University (Figure 3.1). Several trials were carried out on each technology mainly to evaluate these technologies for the following three parameters.

1. Sound levels.
2. Transmission range (if applicable).
3. Duration of the alarm.

Table 3.1 summarizes the schedule of the preliminary testing. Only one technology was tested per day to adequately assess the technology for the selected parameters. During the preliminary testing, no specific deployment layout or traffic plan was used. The deployment was done based on the efficient location based on each device's characteristics.

Preliminary testing mainly involved evaluating the intrusion systems for their sound levels (in decibels) at three different distances (at 150 feet, 200 feet, 250 feet from the sound alarm), duration of the sound alarm (in seconds) after each activation, and transmission range (in feet) between the sensors if involved. The sound levels were measured by pointing the sound meter directly toward the sound alarm at three different distances from the sound alarm. The duration of the alarm is measured as the total period for which the sound alarm lasts after its activation. The transmission range measures the maximum work zone coverage within which the intrusion alarm can transmit the activation signal toward the alarm unit. The transmission range measured here is the maximum effective distance the technology can transmit the activation signal between the sensors involved. The purpose of preliminary testing was to see if intrusion technologies work correctly, provide the necessary warnings, and collect data on operation, setup procedure, steps in deployment, and miscellaneous observations. No vehicle was used in preliminary testing, and all technologies were activated manually by the research team members. The southern end of the parking lot was closed completely by mounting traffic cones to avoid any entry of the vehicle into the testing area. A video recording camera was positioned near the testing site to record all the trials.

- *Sound Levels:* The sound level readings were conducted using the SperScientific Digital Sound Meter at three different distances from the main alarm unit: 150 feet, 200 feet, and 250 feet. The literature review of the previously published reports on intrusion alert technologies indicated that these three distances are the critical distances at which maximum fluctuations in sound level readings can be observed. With the help of a ground marking spray, distances were marked wherever necessary. Three sound level readings were recorded at each distance from the alarm units of respective intrusion technology.

Figure 3.1 Location of preliminary testing.

TABLE 3.1
Preliminary testing schedule

Description	AWARE	SonoBlaster	WAS	Intellicone
Date	09/05/2021	09/11/2021	09/19/2021	11/10/2021
Applicable Parameters to Test	1. Sound level 2. Transmission range 3. Duration of alarm	1. Sound level 2. Duration of alarm	1. Sound level 2. Transmission range 3. Duration of alarm	1. Sound level 2. Transmission range 3. Duration of alarm

- *Transmission Range:* The transmission range computation applies only to AWARE, WAS, and Intellicone. As SonoBlaster is a mechanical device, there is no transmission between the source and the receiver. The transmission range varies with the technology, but it can be defined as the maximum effective transmission range within which all the technologies will run successfully or the maximum coverage the systems can provide. This was managed by verifying the activation of sensors and alarms at different distances from each other by moving away from the transmitter sensor. It should be noted that the measured transmission range is determined after verifying the transmission between the transmitter and receiver three times, and the systems might work beyond this distance but not with a 100% success rate.
- *Duration of the Alarm:* The duration of the alarm was measured with the help of a stopwatch, from when the alarm is activated until the time the alarm lasts. Several trials were conducted to calculate the average duration of the alarm sound for each technology.

Figure 3.2 Deployment of AWARE.

3.1 Advance Warning and Risk Evasion (AWARE)

The trials for AWARE were conducted by keeping the AWARE Sentry on STOP PADDLE MODE and activating the alarm through the base station application on the iPhone. Figure 3.2 shows how the AWARE Sentry unit was deployed in a parking lot facing the north entrance of the facility.

3.1.1 Sound Level Testing

The sound levels of the AWARE alarm at each distance were recorded using a sound meter held 5 feet above the ground surface by one of the research team members. The AWARE Sentry alarm is somewhat similar to emergency vehicles such as law enforcement, firefighting, etc. The sound levels vary throughout one cycle of the alarm because of the sweeping tone of the alarm. Due to this reason, the most stable sound levels for each cycle were recorded. Table 3.2 shows the sound levels recorded at distances of 150 feet, 200 feet, and 250 feet. The sound level of the background noise in the test location was 62 dB (according to CDC, normal conversation is about 60 dB, so this was identified as a moderate sound level (CDC, 2022)). While sound levels of each intrusion technology were recorded beyond 250 feet as well (at 300 feet, 350 feet, 400 feet, etc.), the recorded sound levels were equal to the sound levels of the background traffic noise, i.e., 62 dB. Hence, the activated sound alarm of the intrusion technology was inaudible beyond 250 feet from the sound alarm unit. These distances were also recommended by previous studies conducted by different DoTs (Gambatese & Zhang, 2016; Khan et al., 2019; Marks et al., 2017; Mishra et al., 2021).

The sound levels from the distance of 150 feet to 200 feet decrease drastically, whereas, beyond 200 feet, there is a very minor change in sound levels. Figure 3.3 shows the graphical presentation of the average sound level reading at these three distances. One of the important observations is that the sound levels of the alarm decrease by almost 50% if the sound meter is directed away from the AWARE Sentry. The WorkTRAX unit also makes a small beeping noise every time the alarm is activated. The sound level of the beeping alarm of the WorkTRAX unit was found to be 72.2 dB when the sound meter was held 3 feet away from it.

3.1.2 Transmission Range

The transmission range for AWARE was recorded as the maximum effective transmission distance over which AWARE Sentry can transmit the alert signal to

TABLE 3.2
Sound levels of AWARE Sentry

Distance from Sound Meter (Feet)	Trial No.	Sound Level (dB)	Average
150	1	85.5	85.4
	2	83.8	
	3	86.9	
200	1	75.5	76.3
	2	77.3	
	3	77.1	
250	1	75.8	75.5
	2	75.6	
	3	75.2	

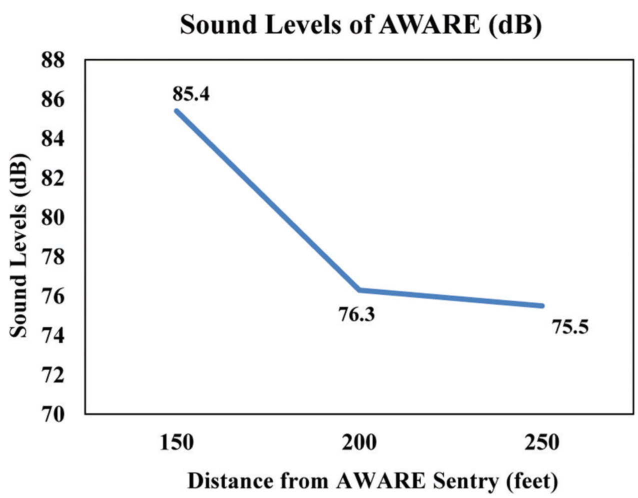


Figure 3.3 Sound levels of AWARE alarm.

the WorkTRAX unit. This was achieved by verifying the activation of the WorkTRAX unit at various distances till the maximum effective distance for transmission was calculated. The alarm is activated several times at each location to verify the 100% transmission between the sentry and WorkTRAX. This was conducted for each of the four WorkTRAX units. All the WorkTRAX units stopped functioning at a distance of 511 feet and 5 inches. Beyond this distance, the transmission may be observed but not with a 100% success rate. Figure 3.4 demonstrates the method adopted to determine the effective transmission range for AWARE.

3.1.3 Duration of Alarm

AWARE Sentry alarm triggers in a number of cycles and runs until the vehicle has cleared the travel lane or changed the speed below the alert threshold of AWARE. Three trials were conducted to measure the duration of one cycle with the help of a stopwatch. Table 3.3 shows the duration of alarms for the three trials. The average duration of the AWARE Sentry alarm is about 4.82 seconds.

3.2 SonoBlaster

The preliminary testing of SonoBlaster involved the measurement of sound levels and duration of the alarm. As it is a mechanical device, it does not include any transmission between the source and the receiver. The SonoBlaster unit needs to be attached to a standard traffic cone with the help of the mounting assembly provided with each unit. One such traffic cone assembly mounted with SonoBlaster unit was used for the preliminary testing. Figure 3.5 shows the deployment of the whole assembly on a testing site. The SonoBlaster unit uses a CO2 cartridge to blow compressed air into the inbuilt air horn whenever the cone is tipped or struck to fall on the ground. The firing pin inside the SonoBlaster unit punctures a hole on the top of the CO2 cartridge after the cone is tilted or tipped to blow out the air through the air horn. All the trials were managed by manually tipping the SonoBlaster mounted on a traffic cone by one of the research team members. Each CO2 cartridge can be used only once to trigger the alarm and needs to be replaced after each activation. The SonoBlaster needs to be cocked with the cocking pin before it can be deployed for use.

3.2.1 Sound Level Testing

The SonoBlaster and traffic cone assembly were made to fall on the ground manually by tipping it by one of the research team members such that the orientation of the alarm horn is towards the ground surface after falling on the ground surface. The radical change in the sound level readings from 150 feet to 250 feet can be observed in Table 3.4. Figure 3.6 shows the graphical representation of sound level readings recorded for the SonoBlaster. The sound can be heard very effectively even beyond 250 feet. The sound levels are affected by the position of the hole punctured by the firing pin. If the location of the hole punctured in the face of the CO2 cartridge face is at the center, the sound levels of the alarm are higher as compared to the sound levels if the hole is punctured anywhere else on the face of the CO2 cartridge.

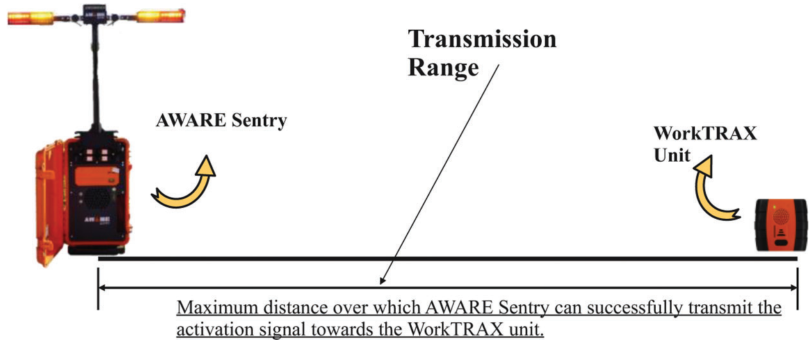


Figure 3.4 Transmission range of AWARE alarm.

TABLE 3.3
AWARE Sentry alarm duration

Description	Trial No.	Duration (Sec)	Average
One Cycle of AWARE Sentry Alarm	1	4.94	4.82
	2	4.69	
	3	4.82	

3.2.2 Duration of the Alarm

During the sound level reading, determining the alarm duration was also managed for each trial with the help of a stopwatch. The duration of SonoBlaster alarm ranges from 9 to 27 seconds. Table 3.5 shows the duration of the alarm sound recorded for four different trials. The duration of the alarm depends on the size of the hole punctured on the face of the CO2 cartridge by the firing pin. To test this hypothesis, several trials were also conducted to understand the relation between the hole size and the alarm duration. If the size of the hole is small, the observed duration of the alarm was higher than when the size of the hole punctured was relatively larger. This is due to the fact that the larger size of the hole results in a greater amount of CO2 gas rushing out of the cartridge in less time. There is no specific reason that could be certain to define the size of the hole punctured, but one possible reason could be the amount of force used to strike/tip the cone. The higher the force, the larger will be the size of the hole punctured on the face of the CO2 cartridge and vice versa.

TABLE 3.4
Sound levels of SonoBlaster alarm

Trial No.	Distance from Sound Meter (Feet)	Sound Level (dB)
1	150	85.4
2	200	81
3	250	78

3.3 Traffic Guard Worker Alert System (WAS)

The traffic guard worker alert system includes trip hoses with a pressure sensor, a portable alarm unit, a Personal Safety Device (PSD), and an optional handheld remote with a trigger. The trip hose with a pressure sensor can be activated by manually stepping on it to trigger the alarm. Whereas the handheld remote with a trigger can be used to activate the whole system by pressing the trigger button. During the preliminary testing, the pressure sensor was activated by stepping on it to create enough pressure in the trip hose to activate the pressure sensor to transmit an activation

Figure 3.5 Deployment of SonoBlaster.

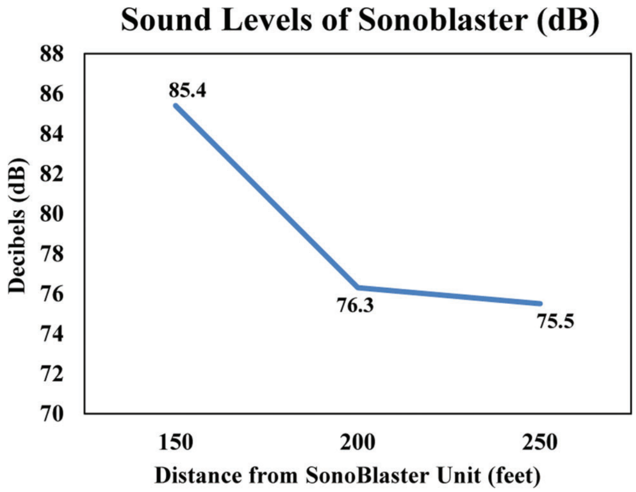


Figure 3.6 Sound levels of SonoBlaster.

TABLE 3.5
SonoBlaster alarm duration

Trial No.	Duration of Alarm (Seconds)
1	27
2	9
3	14
4	13

signal to the alarm units and the personal safety devices. Figure 3.7 demonstrates the deployment of WAS on a testing site.

3.3.1 Sound Level Testing

For the sound level testing, the WAS intrusion alarm was tested for two conditions: (1) when the alarm unit was placed on a flat ground surface, and (2) when the alarm unit was attached to a side of the car 1.5 feet above the ground surface to assess the variations in the sound levels of the alarm sound. The portable alarm case has an inbuilt magnet at its bottom that allows this unit to be attached to any metallic surface. Figure 3.8 shows the setup of the portable alarm case. For both conditions, the sound levels were recorded at three distances: 150 feet, 200 feet, and 250 feet, with the help of the sound meter. Table 3.6 and Table 3.7 represent the sound levels recorded during the experiment for WAS when the alarm unit was placed on the ground and attached to a car, respectively.

The variation in the alarm sound levels was observed more when the alarm was positioned on a ground surface than the sound levels when it was attached to a car. However, the sound levels recorded at each distance are found to be greater on the ground surface than when it was attached to a car. Figure 3.9 shows the relationship between the sound levels recorded for both conditions. The effectiveness of the alarm sound to be heard was found to be greater when the alarm unit was placed on the ground.

3.3.2 Duration of Alarm

During each trial for the sound level testing, the duration of the alarm for each trial was also measured with the help of a stopwatch. A total of 18 trials were conducted for the measurement of the duration of the alarm. The average duration of the alarm was found to be 5.2 seconds (see Table 3.8). After each alarm activation, the PSDs vibrate for some time. The duration of the vibratory alert of the PSDs is approximately 7 seconds.

3.3.3 Transmission Range

The transmission range of the WAS intrusion alarm was measured in two different ways: (1) between the pressure sensor and alarm unit, and (2) between the pressure sensors and PSDs. The maximum transmission range between both combinations was achieved by verifying the successful transmission at various distances until the distance is obtained beyond which the alarm unit is not able to receive the transmission signal from the pressure sensor. The transmission range means the maximum distance within which the portable alarm unit can always receive the transmission signal from pressure sensors. Similar to this, the transmission range between the pressure sensor and PSD was computed. Table 3.9 shows the transmission ranges between the WAS devices.

Both PSDs were tested for computing the transmission range between the pressure sensor and PSD. The first PSD stopped functioning beyond 21 feet, and the reason could not be ascertained immediately, but the manufacturer was notified about the issues, and later on, it was deemed to be a defective device. The second PSD worked perfectly and the range between the trip hose pressure sensor and PSD was measured to be approximately around 210 feet. Although the manufacturer's specifications mention the range between the pressure sensor and alarm unit as 1,000 feet, the maximum range during the preliminary testing was found to be approximately 400 feet. The transmission range may be affected to some extent by the type of area in which the system is deployed. For example, the transmission range could be affected if operating at high wireless network densities such as in a city where many wireless devices are functioning near the worksite. Therefore, further investigation is necessary to examine the environmental factors that influence the transmission performance of intrusion alert technology.

3.4 Intellicone

The preliminary testing of the Intellicone system involved one Portable Site Alarm (PSA), six smart cones with six smart batteries, and one sentry laser. The smart cones can be mounted on the standard traffic cones while the smart battery is inserted inside them, and the lamp gets turned on automatically when mounted on the cones. The sentry laser is a device that

Figure 3.7 Deployment of WAS.

Figure 3.8 Setup of WAS portable alarm unit.

TABLE 3.6
Sound levels of WAS alarm when placed on the ground

Sr. No.	Distance from Sound Meter (Feet)	Trial No.	Sound Level (dB)	Average
1	150	1	73.8	75
		2	73.8	
		3	77.4	
2	200	1	72.7	72.6
		2	72.1	
		3	73.1	
3	250	1	70.0	69.8
		2	69.3	
		3	70.1	

TABLE 3.7
Sound levels of WAS alarm when attached to a car

Sr. No.	Distance from Sound Meter (Feet)	Trial No.	Sound Level (dB)	Average
1	150	1	68.9	70.4
		2	72.2	
		3	70.1	
2	200	1	68.7	70.4
		2	70.8	
		3	71.7	
3	250	1	68.2	69.7
		2	70.4	
		3	70.4	

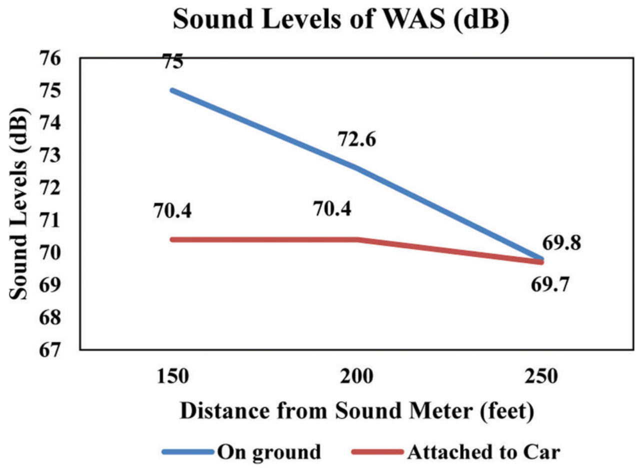


Figure 3.9 Relationship between sound levels.

TABLE 3.8
WAS alarm duration

	Duration of Alarm (Seconds)			
Trial No.	**On Ground**	**Average**	**Attached to a Car**	**Average**
1	4.85	5.1	5.22	5.2
2	4.81		5.28	
3	4.81		5.19	
4	5.28		5.22	
5	5.28		5.22	
6	5.13		5.19	
7	5.12		5.22	
8	5.32		5.15	
9	5.15		5.16	

detects the movement within its calibrated range and triggers the alarm. The sentry laser is also directly connected to the PSA and can transmit the alert signal to the PSA whenever the movement is detected within its calibrated range. When the PSA is turned on, the blue light flashes, indicating the alarm is connected to the GPS and ready to deploy. When the smart cones, mounted on traffic cones, are moved, tipped, or struck, the alert signal is sent to the PSA to activate the intrusion alarm. Similarly, when the movement is detected within the calibrated range of the sentry laser, the inbuilt alarm in the sentry laser is triggered, and the alert signal is sent toward the PSA to activate the alarm. The smart cones and sentry laser are not connected to each other, but the sentry laser could transmit the activation signal through a series of smart cones. The system also sends an alert text message and email to the supervisor or the person in charge of the work zone with the date and time of the event, affirming the work zone has been breached. Currently, the cellular network feature is not available in the United States but will be made available by using a roaming SIM in the future. Figure 3.10 shows the deployment of Intellicone on the testing site.

3.4.1 Sound Level Testing

The sound level testing of the Intellicone system was carried out in two ways: (1) sound levels for the PSA, and (2) sound levels for the sentry laser. Sound levels for PSA were tested at 150 feet, 200 feet, and 250 feet distance between the sound meter and the PSA, whereas the sound levels for the sentry laser were tested from 15 feet with 15 feet increment until 105 feet distance was reached. The sentry laser sound alarm blasts relatively with lesser sound levels than the PSA. The distance interval was kept to a minimum to observe the variation between the sound levels. The Intellicone PSA is an omnidirectional alarm with three alarm speakers separated by a 120° angle. Hence, at each distance, sound levels were measured for each speaker by orienting each speaker towards the sound meter for each trial. This way three different sound readings were recorded at each distance. Table 3.10 and Table 3.11 show the sound levels recorded for PSA and sentry laser at different distances, respectively.

The PSA has a three-tone alarm that is very distinctive and can be noticed even in a noisy environment. Due to its three-tone sound, it can easily cut through the background noise and can be heard easily. There was not much variation observed between the sound levels at three different locations. Figure 3.11 and Figure 3.12 show the graphical representation of average sound levels for PSA measured at 150, 200, and 250 feet.

A steady decrease in the sound levels of the sentry laser was observed from 15 feet to 75 feet. After 60 feet, a relatively small reduction in the sound level reading can be observed. The sound level of the sentry is lower as compared to the sound level of PSA. When the sentry detects a motion within its calibrated area, the sound alarm of the sentry and PSA get triggered simultaneously if both are within the range. If both devices are positioned close to each other, the sound alarm of the sentry is almost masked by the PSA's

TABLE 3.9
Transmission ranges between the WAS sensors

Sr. No	Description	Transmission Range (Feet)	Notes
1	Sensor & PSD – 1	21′ 10″	Defective Device
2	Sensor & PSD – 2	209′ 4″	–
3	Sensor & Siren Unit	401′ 11″	–

Figure 3.10 Deployment of Intellicone on the testing site.

TABLE 3.10
Sound levels of portable site alarm (PSA)

Distance from Sound Meter (Feet)	Trial No.	Sound Level (dB)	Average
150	1	69.3	69.8
	2	67.5	
	3	72.6	
200	1	67.6	67.1
	2	65.7	
	3	68.0	
250	1	66.4	65.6
	2	64.7	
	3	65.6	

TABLE 3.11
Sound levels of sentry laser

Distance from Sound Meter (Feet)	Trial No.	Sound Level (dB)
15	1	74.5
30	2	67.8
45	3	66.2
60	4	64.3
75	5	62.1
90	6	61.2
105	7	61.3

sound alarm. The PSA sound levels exactly near the speaker range from 102 dB to 105 dB.

3.4.2 Duration of Alarm

The duration of the alarm was measured for both PSA and the sentry laser as soon as the alarm was activated. For PSA, the alarm duration was calculated by performing several trials to measure the duration by tipping off the cone mounted with the smart cone. The average duration of PSA is 50 seconds. The sentry laser continues to sound the alarm until the obstruction has cleared the path of the emitted ultrasonic beam. For the measurement of the duration of the sentry laser alarm, the alarm was activated by just waving the hand through the beam, and the duration of the alarm was measured. After each activation, the sentry lasts for 6 seconds and stops. However, it will continue to be activated until the calibrated zone of the laser is violated.

3.4.3 Transmission Range

The transmission range was measured in five different ways (Table 3.12).

1. Between the smart cones and PSA.
2. Between the sentry laser and PSA.
3. Detection range of sentry laser.
4. Between adjacent smart cones.
5. Sentry laser and smart cones.

The smart cones and sentry laser are directly connected to the PSA but are not related to each other. However, the sentry laser can transmit the activation sensor through a series of smart cones to the PSA.

1. *Between the smart cones and PSA.*
   The transmission range between the smart cones and the PSA was achieved by activating the PSA by tipping the smart cones at linear distances from the PSA until the distance at which there is no transmission between the PSA and the smart cones. The maximum transmission

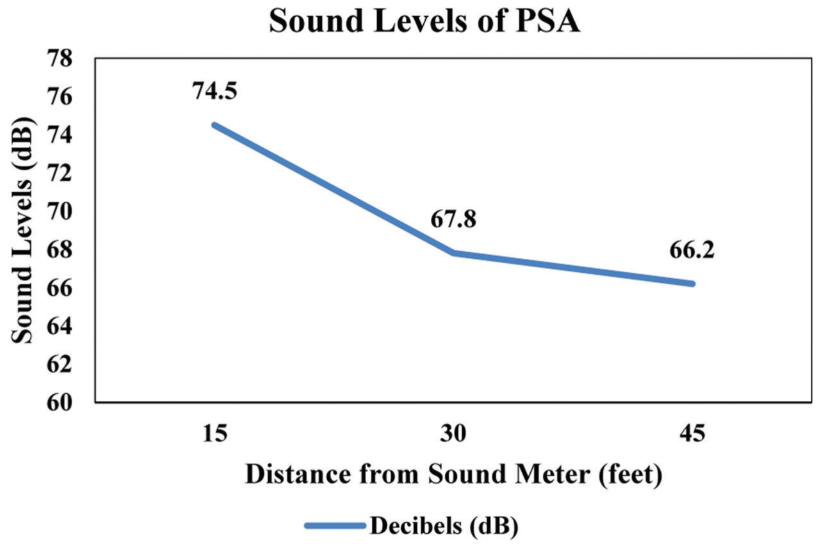


Figure 3.11 Sound levels of PSA.

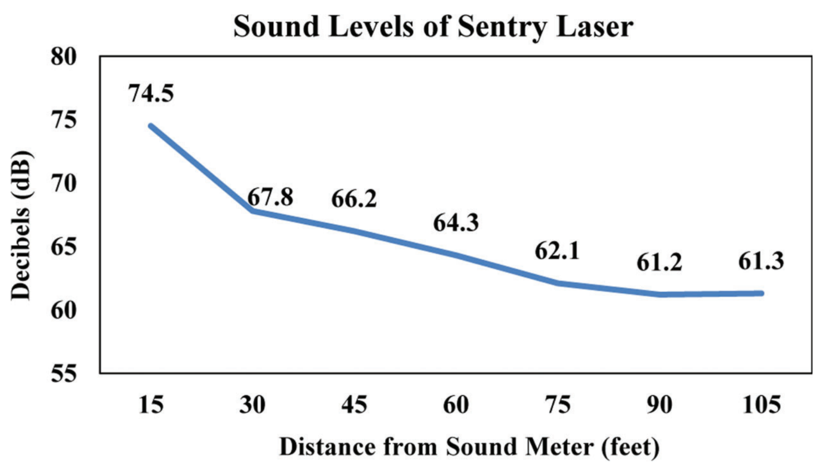


Figure 3.12 Sound levels of sentry laser.

TABLE 3.12
Transmission ranges of Intellicone sensors

Sr. No.	Description	Transmission Range (Feet)
1	Cone and PSA	49′
2	Sentry Laser and PSA	48′ 5″
3	Detection Length of Sentry Laser	27′ 6″
4	Smart Cones to Smart Cone	76′
5	Sentry Laser and Smart Cones	42′

range between the PSA and smart cones is the effective transmission distance within which tipping the cone will always activate the PSA.

2. *Between the sentry laser and PSA.*
A similar procedure was followed for computing the transmission distance between the sentry laser and the PSA by activating the sentry at different locations to verify the activation of the PSA at those locations.

3. *Detection range of sentry laser.*
The maximum calibrated range of the sentry was determined by breaching the ultrasonic beam by one of the research team members until the maximum calibrated range was achieved. The maximum detection range of the sentry laser was found to be around 28 feet.

4. *Between adjacent smart cones.*
The six smart cones were arranged in a series with 25 25-foot distance between them, and only the last smart cone was used to calculate the transmission distance by impacting it at various distances from the series of smart cones. The distance was achieved such that beyond this, there is no activation of PSA after impacting the last smart cone.

5. *Between adjacent smart cones.*
To calculate this, the smart cones were arranged in a series and the sentry laser was positioned after the last smart cone. The sentry laser was activated by obstructing the laser at various distances to calculate the maximum transmission distance.

TABLE 3.13
Summary of the findings from the tests for each technology

Parameter	Key Takeaways
Sound Level	AWARE and SonoBlaster were the loudest, but it does NOT mean they were the most effective. Intellicone has the advantage of cutting through the background noise due to its 3-tone alarm sound.
Transmission Range	Due to the long detection range of AWARE's RAVEN sensor can cover up to 512 feet of work zone coverage. For Intellicone, with six smart cones, the transmission coverage was 280 feet but can be increased considerably by using more smart cones. The maximum transmission between the alarm unit and pressure sensor for WAS was 402 feet.
Duration of Alarms	The alarms of Intellicone lasted for 50 seconds (PSA) and unlimited (sentry laser) until the obstruction was cleared. SonoBlaster showed the most inconsistency with total alarm duration (duration range: 9 to 27 seconds). AWARE runs in cycles of 5 seconds until vehicle speed is above the threshold speed.

3.5 Conclusion

The aim of this task was to assess the performance of each intrusion alert technology based on three primary criteria: sound level, alarm duration, and transmission range. Table 3.13 provides a summary of the essential findings from the tests. These findings were utilized to design the experimental layout of pilot testing in Section 4.2.

4. TASK 3: EVALUATION OF WORK ZONE INTRUSION ALERT TECHNOLOGIES

This task aims to examine the proficiency and efficiency of different intrusion alert technologies by (1) synthesizing the current and suggested practices, facilitators, obstacles, and challenges tied to the use of intrusion technologies, based on input from DOTs and contractors, and (2) evaluating their performance and functional attributes, such as sound levels, alarm precision, duration, and work zone coverage, under controlled settings. The results provide valuable insights into the overall effectiveness of each technology. This information assists safety professionals within transportation agencies and contractors in making more informed choices when selecting and investing in these technologies.

4.1 Online Evaluation Survey Report

From the literature review of the work zone intrusion technologies, the four technologies that were identified to have the competency of being adopted for improving the work zone safety were selected. Detailed information on the selected work zone intrusion technologies was documented to conduct the discussions with the manufacturers of each technology and the procurement procedure associated with the intrusion technologies. In the first phase of the research plan, the online evaluation survey was developed and distributed among the participants of different organizations in the United States, who have previously used this system for improving highway work zone safety. The main goal of this survey was to assess and compile the all-inclusive details on the current implementation of these technologies in the United States to help develop the evaluation framework for the testing of intrusion technologies. The evaluation survey was published online on September 3, 2021, and 54 responses were collected.

4.1.1 Survey Framework

The evaluation metric of the work zone survey was to extract the concerns, opinions, and expectations of the participants to better understand the benefits and limitations of the highway work zone intrusion technologies. To achieve this objective, a web-based questionnaire was developed that had several distinct sections: (1) demographic information including the affiliated organization, job title, years of experience in the respective area, and state in which they are working; (2) familiarity with each intrusion technology; (3) pre-deployment process; (4) practicality and reliability of the technology; (5) alert system; and (6) issues and concerns about the technology. The survey questions were distinct and developed based on the characteristics of each selected highway work zone intrusion technologies to attain detailed and concise responses from the participants. Moreover, this survey was performed as an essential resource to develop the protocol for the research and define the goals and objectives for testing the highway work zone intrusion technologies. The questions aimed to develop a better understanding of the intrusion technologies usage, and the respondents' experience and familiarity with the technologies to further verify the effectiveness, reliability, and impact of these alert technologies on highway work zone safety. Before being sent to all respondents, the survey was pilot tested on five respondents familiar with this topic whom we asked to provide comments and feedback on the survey questions and report any issues that needed to be revised in the survey.

The target population includes state DOTs, transportation agencies, and highway construction and maintenance contractors who are familiar with work zone intrusion alarms due to their roles within their agency/company. To develop the sampling frame, the safety director of each state DOT was contacted as potential knowledgeable respondents. The survey was distributed via email with an explanatory cover letter and a link to a web survey, and a follow-up reminder email was sent after 3 and 6 weeks. The participants' responses demonstrated vital evidence to understand factors like deployment and retrieval time, the usefulness of the feature and triggering mechanism, sound alarm levels, worker productivity, and issues related to the durability of the alert technologies (Appendix A).

4.1.2 Results

4.1.2.1 Demographic information. The first part of the survey was related to the participants' demographic information to assess the trend of these technologies in different states, organizations, and job titles. Figure 4.1, Figure 4.2, and Figure 4.3 show that most of the participants were from the various departments of transportation and construction companies with the job titles of supervisor, executive manager, and safety manager. Participants from states such as Iowa and Indiana contributed most to the survey responses. In terms of familiarity with the system, Figure 4.4 demonstrates that all respondents from various states used the AWARE the most, while only a small number of respondents utilized the other intrusion alarm technologies. However, out of the 54 participants who responded, 15 were affiliated as general contractors, and the rest were from transportation agencies (DOTs). Furthermore, out of 54 responses, 35 participants, which is more than 50% of the participants, were unfamiliar with any intrusion technology. From Figure 4.5, it can be observed that the AWARE was considered to be the most effective intrusion alarm in improving work zone safety.

The average experience of respondents in the construction area was 17 years (ranging from 5 years to 30 years, with a standard deviation of 7 years). At least one response was received from 32 different states, and most responses were received from Indiana (six responses), as shown in Figure 4.3.

4.1.2.2 Current trend of technologies used for improving work zone safety. Figure 4.4 shows that AWARE was the most used technology (representing 12 states) among all the respondents from different states, whereas only three respondents out of the 54 participants used the SonoBlaster (representing three states), four had used WAS (representing four states),

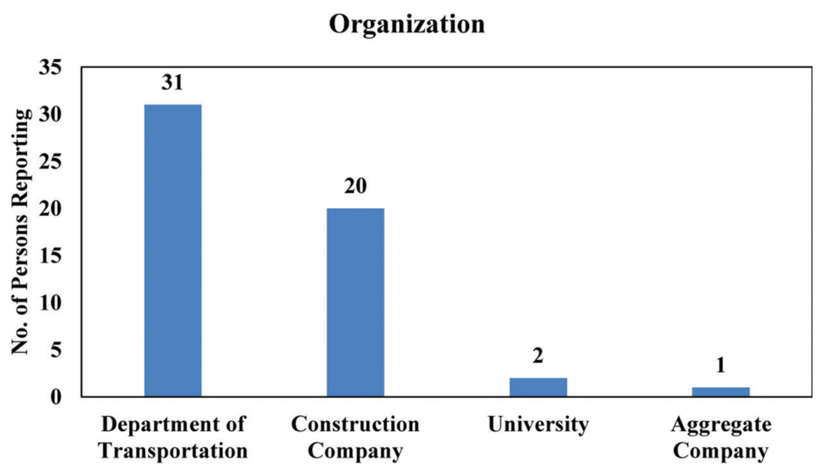


Figure 4.1 Organization of the participants.

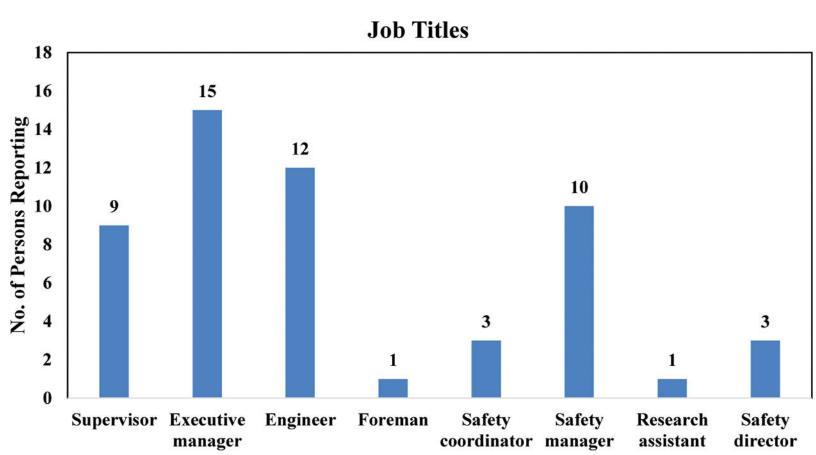


Figure 4.2 Job titles of the participants.

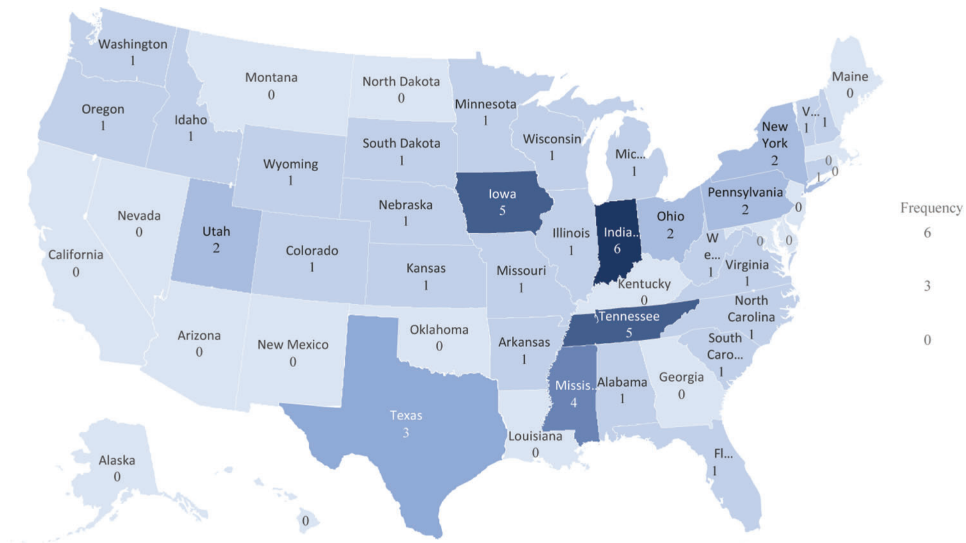


Figure 4.3 Rate of responses from different states.

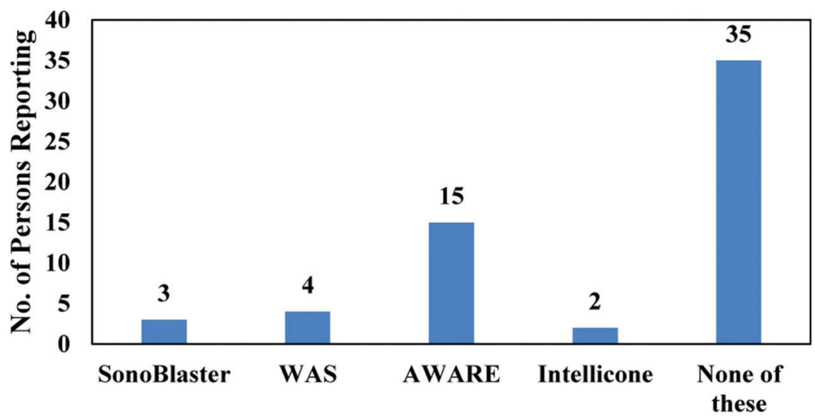


Figure 4.4 Usage trends of the technologies.

and two had used Intellicone (representing two states). Due to the smaller number of responses for the Sono-Blaster, WAS, and Intellicone, the current implementation of these technologies on highway work zones would not be evaluated effectively. These graphs also include the responses of those who used more than one intrusion technology. Instead, more information on these technologies would be documented during the preliminary testing phase.

4.1.2.3 Effectiveness of intrusion alert technologies in mitigating accidents and improving work zone safety. The participants who have used AWARE ranked the intrusion technology as the most effective with "very effective" and "moderately effective" as the highest-marked options among all. Figure 4.5 shows the effectiveness ranked by the participants. SonoBlaster was the only device that received the lowest ranking in terms of overall effectiveness in improving work zone safety. Both Intellicone and WAS were marked as moderately effective technologies by the participants.

4.1.2.4 Deployment of the technologies. Technologies such as SonoBlaster and WAS were reported to be more suitable for deployment when used for short-term highway work zone operations whereas Intellicone was reported to be suitable for both moderate and long duration highway work zone operations. The deployment of AWARE was marked as suitable for almost all types of highway work zone operations with the highest votes for short and moderate-duration highway work zone operations. Figure 4.6 shows the suitable deployment of the technologies. Also, the time taken by the technologies to deploy in a work zone is shown in Figure 4.7. Data shows that SonoBlaster and Intellicone take more time to deploy in a work zone as compared to WAS and AWARE.

4.1.2.5 Effectiveness of the intrusion alert technologies

1. *SonoBlaster*
   The overall performance of the SonoBlaster intrusion alarm was marked as poor by the respondents in terms of control throughout the alarm, determining the direction of the intrusion, providing adequate reaction time, and

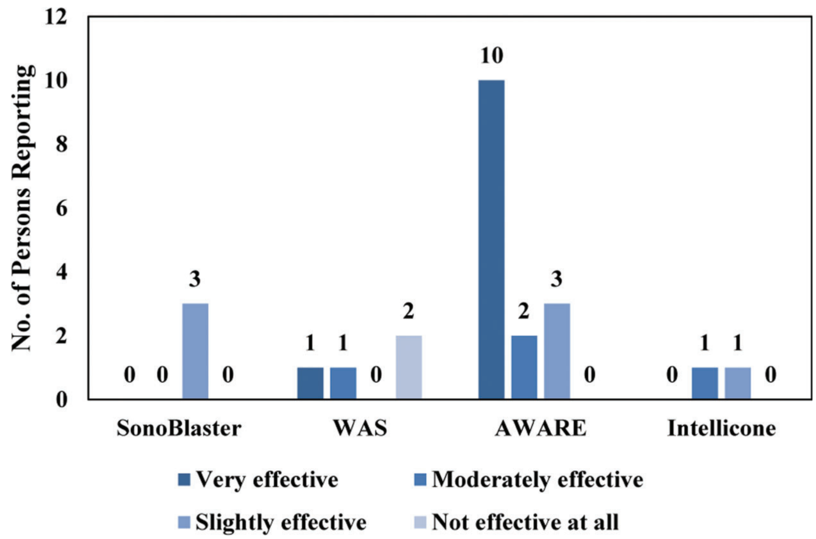


Figure 4.5 Effectiveness of the technologies.

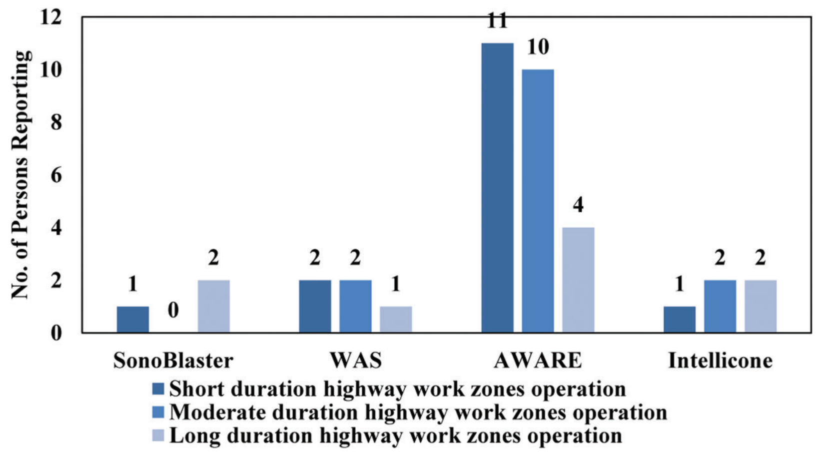


Figure 4.6 Deployment based on the type of highway.

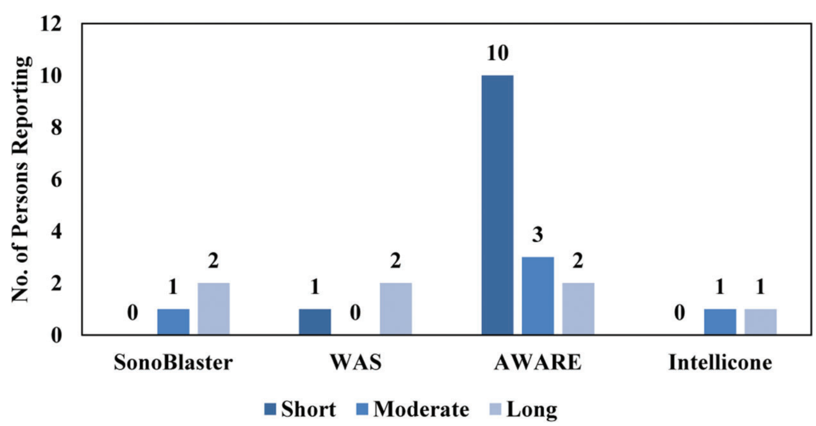


Figure 4.7 Time taken for the deployment.

improving worker productivity. The survey responses about the effectiveness of SonoBlaster in terms of the alert system are shown in Figure 4.8.

2. *Traffic Guard Worker Alert System (WAS)*
Figure 4.9 shows the survey responses recorded for the general evaluation of WAS in terms of overall

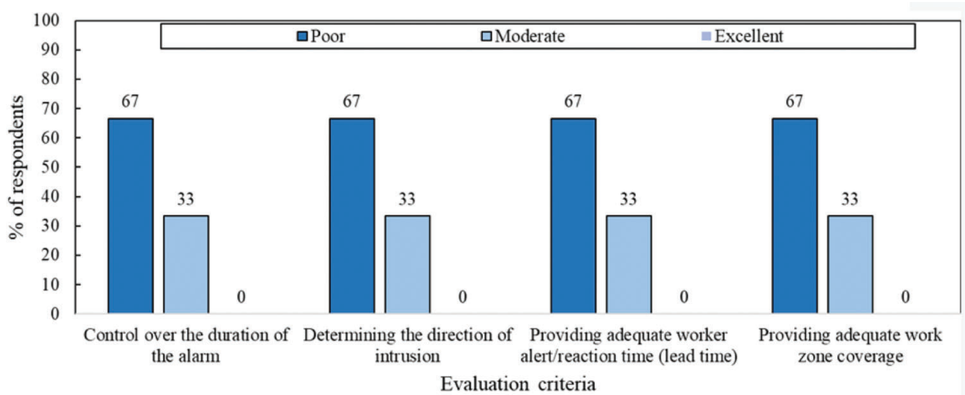


Figure 4.8 General effectiveness of SonoBlaster (n = 3).

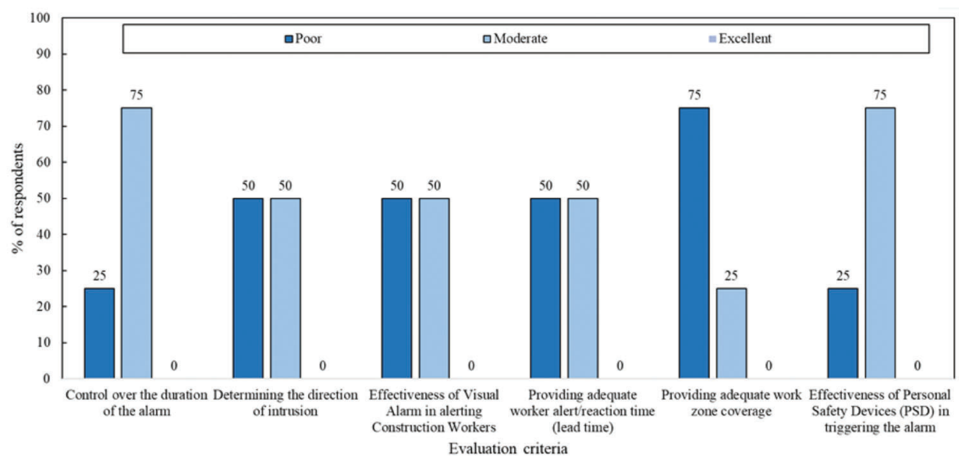


Figure 4.9 General effectiveness of WAS (n = 4).

effectiveness in improving work zone safety. The WAS performs well in terms of the distinctiveness of the sound alarm and alerting the workers through PSDs during work zone intrusion. However, respondents ranked WAS as poor in parameters such as determining the direction of the intrusion, effectiveness of the visual alarm, adequate reaction time, etc. The survey responses from the participants are shown in Figure 4.9.

3. *Advance Warning and Risk Evasion (AWARE)*
   The overall view of the participants towards the effectiveness of AWARE for improving highway work zone safety is positive, as shown in Figure 4.10. The AWARE performs "excellent" in visually and audibly alerting the workers, being distinctive in identifying the alarm sound, providing maximum work zone coverage, etc. In almost every parameter, the participants claim the AWARE as either "excellent" or "moderate."

4. *Intellicone*
   Intellicone was reported as very effective in alerting the workers through the sound alarm and being distinctive in identifying it in the presence of construction operation ambient noise. The only category in which Intellicone scores "poor" is control over the alarm's duration and determining the intrusion's direction. Figure 4.11 shows the survey responses recorded for Intellicone to evaluate the overall effectiveness.

4.1.2.6 Frequency of false alarms. In terms of barriers highlighted by previous studies, the participants were also asked to report the effectiveness of these intrusion technologies regarding the frequency of false alarms (either false positives or negatives), activation during setup, and ineffective to be heard by workers. As seen in Figure 4.12, participants indicated the false-positive issue with regard to SonoBlaster and AWARE. One participant reported WAS has possible problems related to false negatives, while the rest reported it in the other remaining categories. In addition, participants reported SonoBlaster activation during setup as a serious concern.

4.1.2.7 Durability. The durability of the intrusion technologies was assessed in two ways: (1) ability to withstand the wear and tear, and (2) resistance towards the environmental impact. In terms of the durability of the intrusion technology, the SonoBlaster scored the lowest among the respondents. Since more respondents used AWARE, the overall rating for AWARE regarding durability was rated as "moderate" or "excellent" mostly. WAS and Intellicone were reported as moderate for withstanding the wear and tear and resistance to the environmental impacts. Figure 4.13 shows the

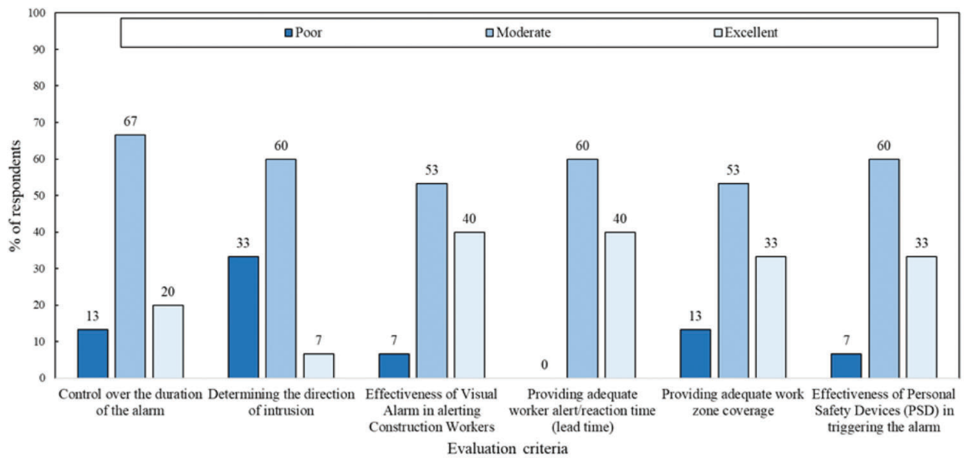


Figure 4.10 General effectiveness of AWARE (n = 15).

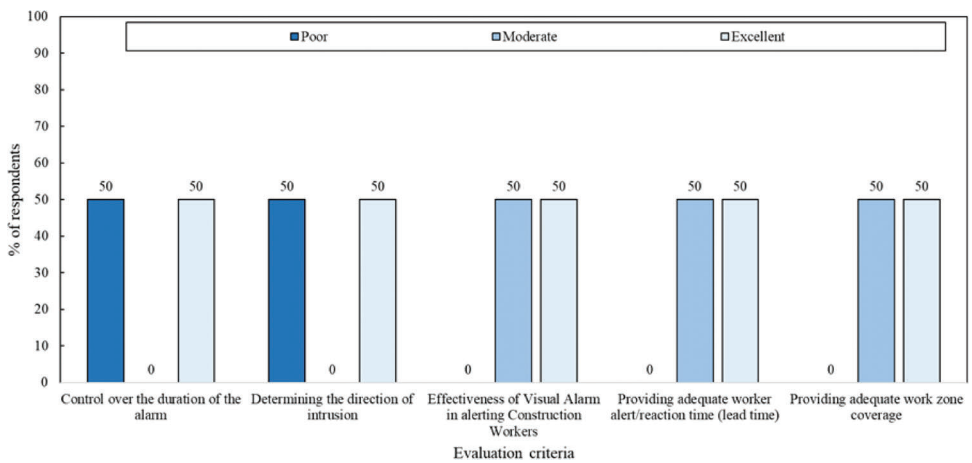


Figure 4.11 General effectiveness of Intellicone (n = 2).

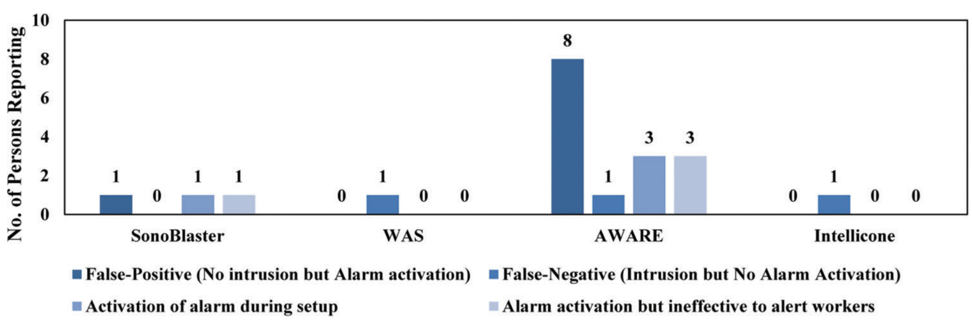


Figure 4.12 Frequency of false alarms.

survey responses from the participants to rank the intrusion technologies in terms of durability.

4.2 Pilot Testing of Work Zone Intrusion Alert Technologies

The preliminary evaluation of the intrusion alert technologies was performed on a closed-to-traffic location made available by INDOT by conducting a series of pilot tests on four of the selected intrusion alert technologies in daylight conditions. For this purpose, simulated lane closure on a two-lane road was set up with the help of channelizing devices such as cones as per the Indiana traffic guideline. Figure 4.14 shows the layout of the experimental site along with the deployed locations of intrusion technologies.

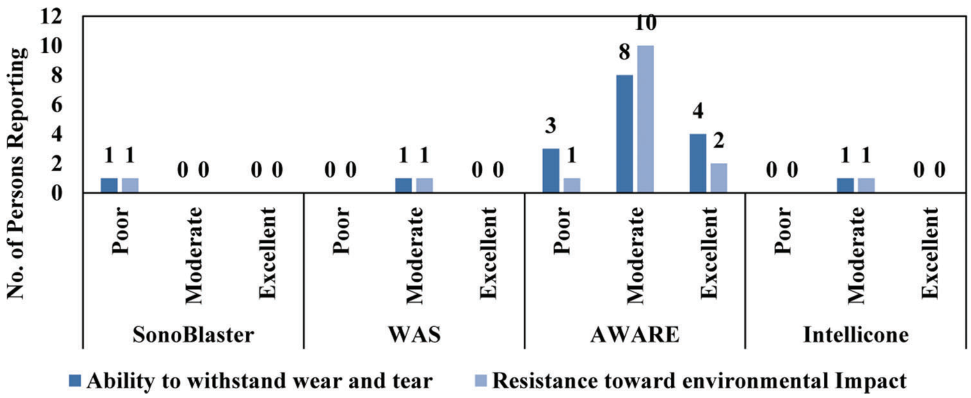


Figure 4.13 Durability of intrusion technologies.

TABLE 4.1
Pilot testing schedule and field conditions

Description	AWARE	WAS	SonoBlaster	Intellicone
Date/Time	09/25/2021	09/25/2021	10/07/2021	10/07/2021
No. of Lanes	2	2	2	2
No. of Lanes Closed	1	1	1	1
Speed Limit	45 mph	45 mph	45 mph	45
Weather (temperature, avg. wind speed)	72°F, 10.6 mph average wind speed	72°F, 10.9 mph average wind speed	64°F, 7.5 mph average wind speed	64°F, 7.5 mph average wind speed
Entrance of Vehicle	Taper	Taper	Taper	Taper
Taper Length	440 feet	440 feet	440 feet	440 feet
Taper Cone Spacing	40 feet	40 feet	40 feet	40 feet

TABLE 4.2
Data collection trials for pilot-controlled work zone testing

System	Conditions	Description
AWARE	1. Alarm near taper 2. Alarm near workspace	Two locations for the deployment of the alarm unit
WAS	1. Toward the oncoming vehicle 2. Away from the oncoming vehicle	Orientation of the alarm unit
SonoBlaster	1. In the taper cones 2. In the buffer cones	Deployment at two different locations
Intellicone	Q.1 PSA is active Q.2 PSA + Sentry is active	Combinations of two sound alarms

The objective of these tests was to collect data on the following.

1. Intrusion technology information.
2. Functional characteristics in deployment and operation.
3. The ideal distance for technology deployment.
4. Camera setup for an effective view of trials.
5. Suitability as per general work zone information and conditions.
6. Miscellaneous observations.

Table 4.1 summarizes the schedule and field conditions for the four work zone intrusion technologies. Two technologies were tested per day to adequately collect data for each intrusion technology.

After careful consideration, several trials were managed by intruding a sedan vehicle to investigate each technology considering its unique specifications, as shown in Table 4.2.

The best practices that will be helpful in improving the operational characteristics noticed during the pilot testing were adopted for further field experimental trials (Chapter 5 of this report). A video recorder was positioned to record the experimental trials. A total of 6 trials were performed for each intrusion technology. Each system was evaluated at a time by deploying it according to its functional requirements observed during the pilot testing, and the vehicle intruded into the work zone at 35 and 45 mph to activate it. For each

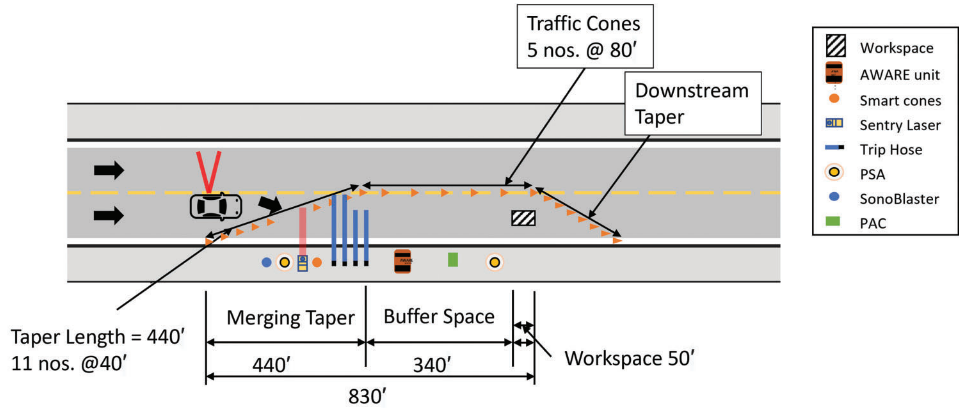


Figure 4.14 Layout of the experimental site for pilot-controlled work zone testing.

Figure 4.15 Deployment of each intrusion alert technology during pilot-controlled work zone testing: (a) SonoBlaster, (b) WAS, (c) AWARE, and (d) Intellicone.

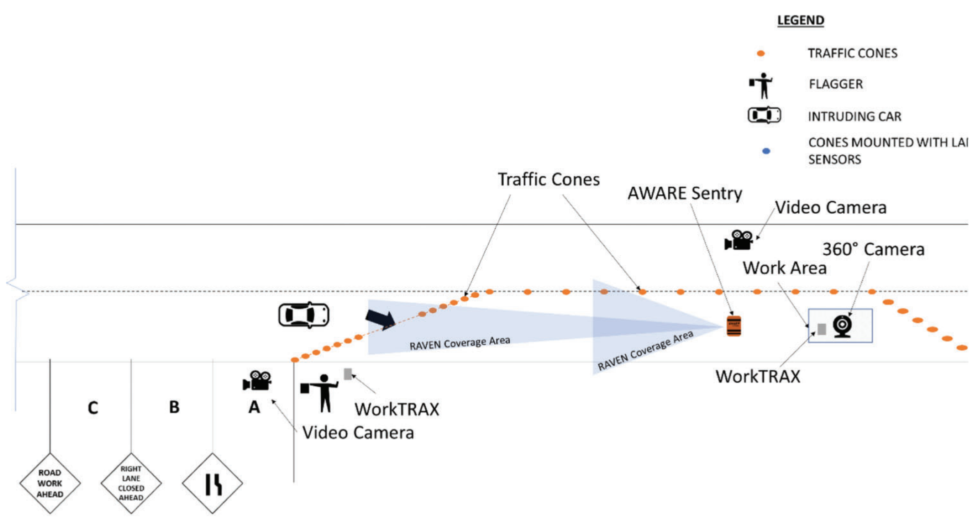
trial, the stoppage distances (i.e., the distance that a driver needs to safely bring a vehicle to a complete stop after braking) and stoppage durations (i.e., the duration that a driver needs in order to safely bring a vehicle to a complete stop after braking) were measured during this experiment. Simultaneously, miscellaneous observations were noted for general evaluation of the intrusion technologies. Figure 4.15 shows the deployment of each intrusion technology during the pilot-controlled work zone testing.

4.2.1 Pilot Testing of AWARE

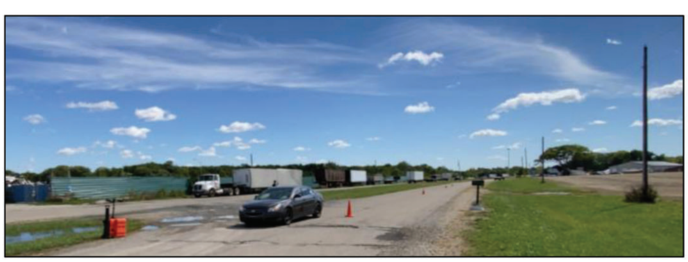
The AWARE sentry flagger unit was tested based on the work zone layout developed in the preliminary protocol where the unit was deployed near the worker's worksite facing toward the oncoming vehicle in the work zone. Four trials were conducted by intruding the vehicle into the work zone from the taper. The WorkTRAX devices were also distributed among the research team members to ensure the activation of vibratory alerts every time intrusion was detected. The deployment layout of AWARE is shown in Figure 4.16. The trials were conducted by keeping the AWARE Sentry on STOP PADDLE MODE to detect the intrusion of a vehicle when it enters the work zone. The base station application on the iPhone was utilized to set the speed limit and configure siren alerts, flashing visual alerts, and WorkTRAX alerts. The speed limit was set to 45 mph for all trials, whereas all types of alerts, i.e., visual alert, WorkTRAX alerts, audio alerts, etc. were turned on.

4.2.1.1 Functional characteristics in deployment and operation. Table 4.3 and Table 4.4 describe the pre-deployment and actual work zone process, issues, characteristics, and observations noted during the pilot testing of AWARE. Even though the AWARE unit weighs 51 lbs., due to the attached transporting wheels, it is very easy to carry, deploy, and setup. Both visual and audio alarms were activated as expected based on the base station configuration. No false positives or negatives were observed during the pilot testing. Out of the 12 trials performed, the RAVEN sensor successfully detected the oncoming vehicle and activated the siren alarm for all trials.

4.2.1.2 Miscellaneous observations. Table 4.5 summarizes the general observations and feedback from the research team during the pilot testing of the AWARE. The sentry is very easy to carry and deploy in the work zone and quickly connects to the available servers. During each trial, the sentry activated the alarm effectively per the base station configuration, and no issues were observed for the system activation. Hence, the sentry performed 100% in detecting intrusion and activating the intrusion alarm whenever



(a)



(b)

Figure 4.16 (a) Deployment layout, and (b) actual deployment of AWARE during the pilot testing.

TABLE 4.3
Pre-deployment functional characteristics and operation of AWARE

Functional Characteristics	Description
Setup Process	Charge the AWARE sentry unit at least 24 hours before use, as the battery may drain out gradually if not used. While charging the unit, always ensure that the battery switch is always turned to a connected position, away from us. The battery will not get charged if the switch is positioned to a disconnected mark. Ensure all the WorkTRAX units are properly fixed into their respective slots in the sentry unit while charging the unit. Despite its heavyweight, the sentry has a very rugged outer carrying case with wheels, so it is very efficient to carry it while transporting it to the worksite.
Setup Time	It takes approximately 2 to 3 minutes to set up the sentry unit before turning it on for use.
Setup Issues	None

TABLE 4.4
Functional characteristics and operation of AWARE

Functional Characteristics	Description
Deployment Process	Setup the sentry unit in a work zone at a location facing towards the oncoming vehicle that will be effective in alerting the workers and drivers in case of intrusion. Open the case; lift, raise, and unfold the strobe light bar. Turn the power ON and arm the system by switching ON the arm button. Remove the foot pedal for use and position the sentry for use. Press and hold one of the WorkTRAX units' switches till a beeping sound is heard. Connect the device to the iPhone by Bluetooth and open the Base Station application. The active sentry unit will be highlighted in the base station app where the sentry can be configured for switching the alerts and defining the speed limits. The yellow flashing light in raven indicates the unit is connected to the internet and ready to use. The alert flashing lights will also flash once the sentry unit is active and ready to use. Distribute the WorkTRAX units and switch them on by pressing and holding the switch till the vibration alert is heard.
Deployment Time	Approximately 5–6 minutes are required for the sentry to connect to the available servers after switching it on.
Deployment Location	Initially, the sentry was positioned near the worksite, as shown in Figure 4.16. Then, it was positioned near the taper due to insufficient audio level for drivers. During the trial tests, the sound levels were checked from inside the car after the alarm activation to determine the efficient location where sound levels were effective such that the driver could hear the alarm in the first few seconds after activation. Then, the sentry was shifted to this new location close to the taper, where it could detect the intrusion as soon as the vehicle passed the taper line.
Issues	No false alarms were detected during the tests, i.e., false positives and negatives. All the WorkTRAX units were activated whenever the intrusion was detected.
Battery Issues	The unit was fully charged 12 hours before the actual testing and used for around 2 hours. No battery issues were detected during the testing, and the battery indicator was one bar below the maximum level after the testing.

TABLE 4.5
Miscellaneous observations and feedback

	Description
Issues During Activation/Setup/Removal	No issues were observed during the activations and setup of the sentry. The sentry unit performed accurately during all trials. i.e., the sentry performed well in activating the alarm when the conditions were satisfied and did not trigger when the condition did not demand.
Challenges in Deployment and Operation	Very easy to deploy and gets connected to GPS on its own. Sometimes, more effort is required to mount the WorkTRAX units with the strap assembly provided.
Durability Issues	None

required. The WorkTRAX units were also activated every time the intrusion was detected, and it was confirmed by each research team member.

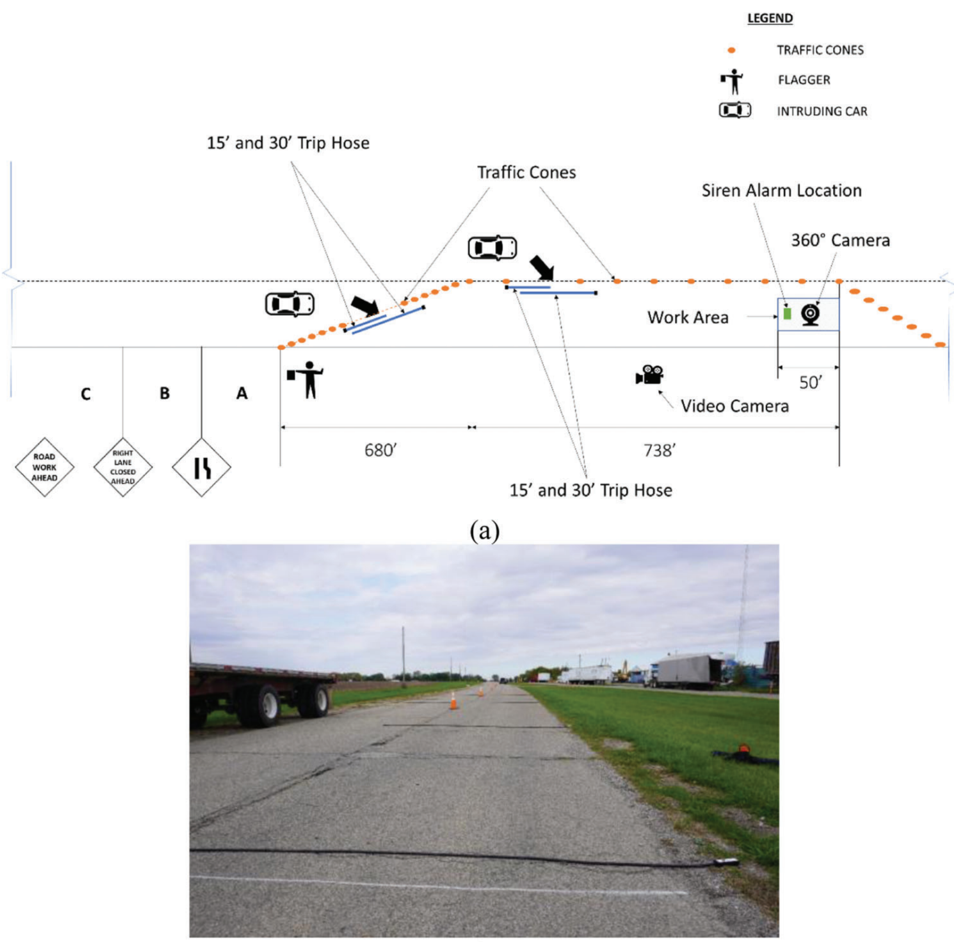
4.2.2 Pilot Testing of Traffic Guard Worker Alert System (WAS)

For the pilot testing of WAS, the entire set of the assembly was procured from AstroOptics Industries. The equipment includes the following.

1. Two 15-foot wireless trip hoses with sensor.
2. Two 30-foot wireless trip hoses with sensor.
3. Rechargeable Alarm/flashing light with magnet.
4. Two personal safety devices with a trigger option.
5. Wall charger for flashing alarm unit.
6. Handheld remote with manual trigger option.

The trip hose sensors were deployed, as shown in Figure 4.17. One 15-foot and 30-foot trip hose near the taper and parallel to the direction of an intrusion in the buffer region. Several trials were conducted to learn the triggering mechanism of the system. In some trials, the system failed to activate when the vehicle passed over the trip hoses. The possible reason could be the angle between the tires and trip hose alignment whenever the vehicle passes over them. When the vehicle tires run over the trip hoses, the pressure created in the trip hoses is less compared to the pressure created when both front and rear tires run over the trip hoses simultaneously. Hence, the deployment of the trip hoses was changed and placed perpendicular to the direction of a vehicle with 40 40-foot distance between the two trip hoses, as shown in Figure 4.17. The alarm unit was attached to one side of the truck with the help of an inbuilt magnet that was attached to the bottom of the alarm unit. The Personal Safety Device (PSD) was handed to the research team members to verify the activation after each intrusion. The trials were conducted for both conditions such as the location of the PSD was upstream and downstream from the alarm unit.

4.2.2.1 Functional characteristics in deployment and operation. Table 4.6 summarizes the pre-deployment and actual work zone deployment process, the issues confronted, and setup time for the procedure, etc. WAS does not involve a tedious setup process; however, it involves issues such as failing to connect with accompanying sensors. Trip hoses of WAS are difficult to store and transport as they may get activated if placed



(a)

(b)

Figure 4.17 (a) Deployment layout, and (b) actual deployment of WAS during the pilot testing.

TABLE 4.6
Pre-deployment functional characteristics and operation of WAS

Functional Characteristics	Description
Setup Process	Charge the alarm unit at least 12 hours before use. The batteries of the handheld remote, trip hoses, and PSD are suggested to be removed while transporting because the sensors may get turned on accidentally and lose power. Turn on the alarm unit, trip hose sensors, and PSDs. The pressure sensors can be verified if they work properly by stepping on them. To confirm this, the green light will turn red.
Setup Time	It takes approximately 15–20 minutes to set up the pressure sensors, alarm unit, and PSDs.
Issues	Out of the four deployed trip hoses, two 30-feet hoses were not working even after stepping on them.

TABLE 4.7
Functional characteristics and operation of WAS

Functional Characteristics	Description
Deployment Process	Deploy the trip hoses on the ground as per the deployment layout, starting from the taper with the pressure sensors near the shoulder. Deploy the alarm unit near the workers on the ground or attach it to the side of the vehicle with the help of a magnet at the bottom. Switch on the trip hose pressure sensors by pressing the switch at the top. The green light will blink and eventually stop, indicating the device is ready to set up. Switch on the alarm unit. The unit will make a short beep indicating the device is ready to set up. Hand over the PSDs and handheld remote to workers.
Deployment Time	It takes approximately 3–5 minutes to switch on and connect all the sensors with the alarm unit.
Issues	The trip hoses are lightweight to carry, but if placed together, they may get entangled, increasing the efforts to separate them. The frequency of false negatives is more when the orientation of the trip hose deployment is at an angle to the direction of the vehicle. Sometimes, a 3- to 4-second delay was also observed in the activation of the alarm unit after the vehicle had passed over the trip hoses.
Battery Issues	None
Retrieval Process	It takes approximately 10–12 minutes to remove and store all the sensors for transportation.

together due to the sensitive activation switch. Moreover, there are chances of getting entangled with each other and increasing the efforts to separate them while deployed in a work zone (Table 4.7). The continuous movement of vehicles, equipment, trucks, etc., can also cause the trip hoses to get entirely displaced from their original position (observed after four trials). The attached pressure sensors are delicate and could get broken if passed over by such vehicles.

4.2.2.2 Miscellaneous observations. There were many instances of false negatives as well as delays in WAS alarm activation during the experimental trials. Table 4.8 lists the observations documented during the pilot testing of WAS. The frequency of false negatives increases with the increase in contact location between the tire and trip hose from the attached pressure sensor (approximately more than 5 feet from the pressure sensor), as well as a lower duration when the tire and trip hoses stay in contact. Out of 12 trials performed during the testing, the system resulted in false negatives for eight trials (33% success rate). WAS was found to be inoperative in cold conditions (below 32°F), and the system was sent back twice to be fixed.

4.2.3 Pilot Testing of SonoBlaster

To test the SonoBlaster intrusion alarm, 10 SonoBlaster units were procured from the manufacturer TAPCO. Two of the SonoBlaster units were mounted on two standard traffic cones with the help of the mounting assembly provided with each unit. The SonoBlaster uses standard carbon dioxide (CO2) cartridges to blow air through the built-in air horn whenever an oncoming vehicle hits or tips the traffic cone. No particular deployment layout was incorporated to conduct the pilot testing on SonoBlaster; instead, the traffic cone mounted with the SonoBlaster unit was tipped manually by hand by one of the research team members at the instant the vehicle entered the work zone. Figure 4.18 shows the deployment layout for the SonoBlaster on an off-road site.

TABLE 4.8
Miscellaneous observations and feedback

Observations	Description
Issues During Activation/Setup/Removal	The pressure sensors attached to the trip hoses sometimes take time to connect with the alarm unit if placed away from the alarm unit (around 300–400 feet). Before turning on the pressure sensors, they need to be kept near the alarm unit at around 100–150 feet range to efficiently get connected to the alarm unit. If the intruding vehicle has a higher speed (45–55 mph), the trip hoses may fail to activate the pressure sensors due to insufficient contact time between the tires and trip hoses. This system is most suitable for low-speed limit highway work zones. The frequency of the 30-foot trip hose sensor getting activated decreased as the contact location between the tires and the trip hose increased from the pressure sensor during the trials. The alarm unit stopped working in the cold weather (below 32°F).
Challenges in Deployment and Operation	Easy to deploy the trip hoses and alarm unit even for just one person. The alarm light is on one side of the alarm unit, and workers may not notice the visual alert if the speaker's orientation is toward the workers. It is impossible to keep the orientation of both the alarm light and alarm speaker toward the workers/common direction.
Durability Issues	After 2–3 trials, one of the pressure units' cases was observed to be damaged to some extent. The sound could be heard from the inside of the handheld remote due to a loose screw. The alarm unit speaker was also displaced from its original position inside.

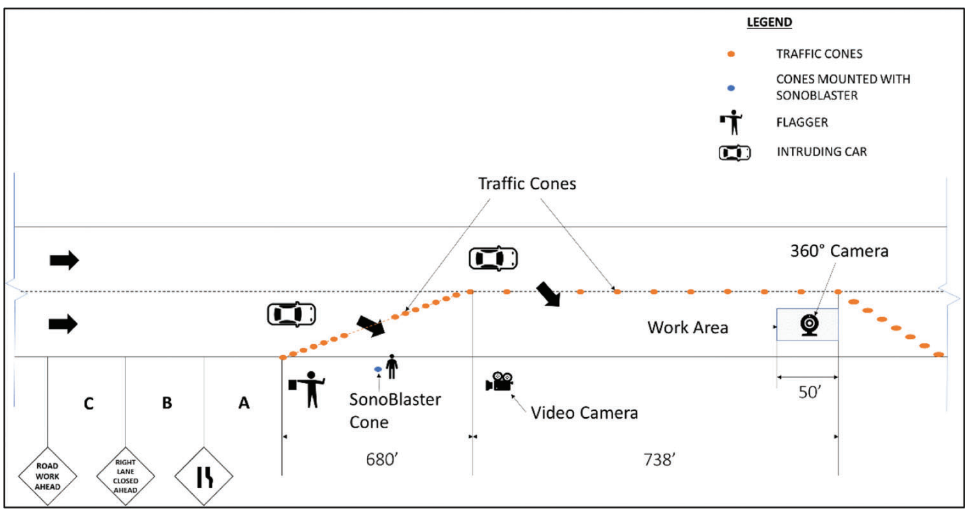


Figure 4.18 Deployment layout of SonoBlaster during the pilot testing.

4.2.3.1 Functional characteristics in deployment and operation. Table 4.9 summarizes the pre-deployment and actual work zone deployment process, the issues confronted, and setup time for the procedure, etc. The weather conditions affect the functionality of SonoBlaster which is very sensitive to weather conditions and may not function well or even fail to function if the temperature is below degrees 32°F. In such situations, the ice particles obstruct the SonoBlaster mechanism and cause the dysfunction of the alarm after the first trial (i.e., when tested in cold weather of around 19°F, the SonoBlaster pin failed to puncture a hole on the CO2 cartridge for 4 of the trials out of 12 trials due to accumulation of ice particles (66% success rate)) (Table 4.10).

4.2.4 Pilot Testing of Intellicone

For the pilot testing of Intellicone, 12 smart lamp cones (with smart batteries), 2 Portable Site Alarms (PSA), and 1 sentry laser were used to assess their operational performance in an off-road testing site. The smart batteries were attached to the smart lamp first, and each was then deployed on standard traffic cones. The cone lamps get activated when attached to the top of the traffic cones. With the help of the online website platform, one work zone project was created precisely at the off-road pilot testing location on the map. This project is helpful in obtaining information such as the number of devices deployed, frequency of the intrusion alarms, battery percentage of the devices, etc.

TABLE 4.9
Pre-deployment functional characteristics and operation of SonoBlaster

Functional Characteristics	Description
Setup Process	Mount the SonoBlaster unit with the standard traffic cone with the help of the mounting assembly provided with each SonoBlaster unit. Make a hole in the side of the traffic cone with the help of the 25 mm drill bit. Insert the top mounting screw from the inside with the washer and keep it loose. Mark the second hole for the SonoBlaster while aligning the unit in a vertical position and insert the lower mounting screw from the inside and tighten both screws firmly with the traffic cone.
Setup Time	It takes approximately 12–15 minutes to mount one SonoBlaster with the traffic cone.
Issues	Due to the slant side of a traffic cone, the SonoBlaster unit could be a little tilted after mounting with it. The SonoBlaster cannot work if attached in any other orientation than its normal orientation. The cone spacer (provided) can be used to reduce the tilt caused by the slant side of a cone, but if the slant angle is lower, the effect cannot be compensated beyond a certain extent.

TABLE 4.10
Functional characteristics and operation of SonoBlaster

Functional Characteristics	Description
Deployment Process	Deploy the traffic cones mounted with a SonoBlaster unit on a site. Turn the control knob to unlock the position. Cock the unit by using a cocking pin till a clicking sound is heard. Insert the CO2 cartridge into the nozzle while the control knob is turned to the unlocked position. Place in the CO2 cartridge holder. Position the control knob to the locked position to avoid false alarm activation and place the unit in the desired position. Switch the control knob to an unlocked position, and the unit is ready to be used.
Deployment Time	It takes approximately 3–5 minutes to cock and insert CO2 cartridges in one SonoBlaster unit.
Issues	Sometimes, the CO2 cartridge is not fixed properly into the nozzle and may get loose after the impact; hence, false negatives could be observed. Every time the CO2 cartridge is used, the cartridge gets very cold and sometimes leaves snow particles in the nozzle. If consecutively used for the subsequent trial, the snow particles obstruct to puncture a hole in the cartridge face.

The sentry laser was deployed near the entrance of the work zone, and a total of 12 smart cones were deployed on the traffic cones and arranged as shown in Figure 4.19. The smart cones work in a loop and can transmit the signal from cone to cone until it reaches the Portable Site Alarm (PSA). The alarm was activated manually near the entrance of the work zone as soon as the vehicle entered. The signal gets transmitted through a series of smart cones and the PSA gets activated.

4.2.4.1 Functional characteristics in deployment and operation. Table 4.11 summarizes the pre-deployment and actual work zone deployment process, the issues confronted, the setup time for the process, etc. for Intellicone. Separate trials were conducted for both Intellicone smart cones and Intellicone sentry laser, i.e., to activate the intrusion alarm, smart cones and sentry laser were used for separate trials. Intellicone was observed to take longer time (approx. 10–15 minutes for 15 smart cones, 2 PSAs, and 1 sentry laser) and involved more steps in setting up as compared to other intrusion alert technologies, e.g., the process of attaching batteries with smart cones and heavy weight of sentry laser (40 lbs.) (Table 4.12).

4.2.4.2 Miscellaneous observations. All the Intellicone sensors performed as expected, and there was not a single instance of false positive/negative (Table 4.13). No delay was observed in activating the PSAs during the experimental trials. The Intellicone did not result in false alarms when activation was through the smart cones; however, it was observed that the sentry laser was unable to detect the vehicle intruding at a speed of 45 mph, which can lead to false negatives. Also, if there is a frequent movement of workers/equipment in the work zone, the sentry laser can lead to frequent false positives as it is activated if its detection zone is violated. Out of the 12 trials performed, six trials involved activating the system through the sentry laser when the vehicle entered the work zone. The sentry laser resulted in only three successful activations (total 50% success rate).

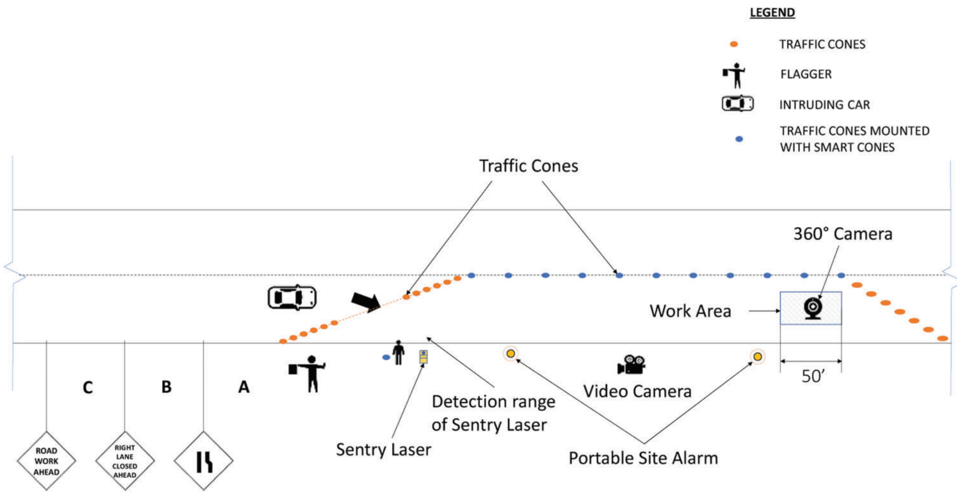


Figure 4.19 Deployment layout of Intellicone during the pilot testing.

TABLE 4.11
Pre-deployment functional characteristics and operation of Intellicone

Functional Characteristics	**Description**
Setup Process	Attach the smart batteries with the smart cones. The batteries can be inserted in any orientation. Mount the smart cones (inserted with batteries) on top of the standard traffic cones. The lamp will turn on, indicating that the assembly is ready to deploy. Charge the PSAs a day prior to their use.
Setup Time	It takes approximately 15–20 minutes to prepare all the sensors ready to deploy.
Issues	Smart cones need to be a bit closer to PSA for the first time establishing the connection. The PSA alarm was activated when one of the smart cones was inserted with the smart battery.

TABLE 4.12
Functional characteristics and operation of Intellicone

Functional Characteristics	**Description**
Deployment Process	Position the smart cone and traffic cone assembly in taper and buffer regions such that the distance between the adjacent cones is not more than 50 feet. Deploy the PSA near the worker and one near the entrance of the work zone. Press and hold the on/off switch to activate the PSA. The location indicator will turn red, indicating that the unit is getting connected to the GPS, and once done, the indicator light will turn green. The PSA warning light will change to a steady red light, which means the unit is functional and ready to deploy. For the sentry laser, before turning it on, first deploy it in a desired location. Connect the power cable from the battery box to the socket on the top right of the sentry and press the on/off switch. The sensor will power on automatically and begin the calibration process. The alarm will sound when movement is detected in front of the unit. Ensure that the distance between the sentry laser and the nearest smart cone does not exceed 42 feet.
Deployment Time	It takes approximately 10–15 minutes to deploy all the sensors and PSAs on a testing site.
Issues	Sentry laser results in infrequent false alarms.
Battery Issues	None
Retrieval Process	It takes approximately 18–20 minutes to remove and store all the sensors for transportation.

TABLE 4.13
Miscellaneous observations and feedback

Observations	Description
Issues During Activation/Setup/Removal	When connected to the PSA, the smart cones can function more than its measured transmission range, but once they get disconnected, they again need to be placed within the 50-foot distance from the PSA. While activating the sentry, if the detection zone of the sentry laser is obstructed, the sentry and PSA alarm could get triggered.
Challenges in Deployment and Operation	The sentry laser is heavy and very difficult for a single person to deploy, and it does not have rolling wheels to move from one place to another.
Durability Issues	After impacting smart cones manually, some small scratches were observed on their body. However, due to the durable outer case, the lamp and battery were completely secured.

4.2.5 Summary of Pilot Testing

Table 4.14 describes the characteristics, issues, and observations noted during the deployment and operation of each intrusion alert technology in preliminary tests. To further elaborate on the effectiveness of these intrusion technologies, the findings regarding best practices and limitations from this chapter will be used to design the experiment in the following chapters to assess drivers' and workers' reactions to these technologies.

4.3 Development of Evaluation Criteria for Selecting Intrusion Technologies

For each intrusion alarm, the attributes determining the technology preference were derived from the preliminary (Chapter 3), pilot and controlled testing results (Chapter 4), manufacturers' websites, and literature review of previous studies (Chapter 2), as shown in Table 4.15. Key criteria include deployment simplicity, coverage in work zones, overall system reliability, trigger mechanism efficacy, and distinctiveness of the alert sounds. These metrics serve as a comprehensive guide for highway safety stakeholders when deciding on the right intrusion technology, or even a blend of multiple technologies, to ensure the safety of highway construction workers. Table 4.15 outlines each evaluation criterion, its ideal features, and the discovery phase. For instance, an intrusion system that offers a trio of alerts (auditory, visual, and haptic vibratory) can be especially effective for night operations in moderately sized work zones. Conversely, workers might be reluctant to wear personal safety devices (PSDs) in more complex construction environments. In such scenarios, audio and visual alerts might suffice. The proposed evaluation criteria contribute to developing a metric-based decision-making framework (discussed further in Chapter 7) to help the industry stakeholders adequately address the specific work zone-related issues using the most suitable intrusion technology or combination of technologies.

4.4 Conclusion

This task delved into the efficacy of intrusion technologies for enhancing safety within work zones. The study used literature reviews, evaluation surveys, and controlled tests to pinpoint key metrics that can guide stakeholders in choosing and investing in these systems. However, despite manufacturers' continuous efforts to refine these devices, results indicate that they still present challenges such as lengthy setup times, inaccurate alarms, and dependability concerns, thereby hindering their widespread adoption. Moreover, the research reveals that no singular intrusion technology is a solution for all safety concerns in highway work zones. Given the specific nature of the work environment, a synergistic approach combining various technologies might be the key to maximizing safety. Among the evaluated systems, AWARE emerged as the top choice based on criteria like deployment ease, sound clarity of the alarm, system reliability, alarm accuracy, and alert type. This was followed by Intellicone, WAS, and SonoBlaster. The study also underscores the need for innovations in intrusion technology, emphasizing designs that consider distinctive auditory signals, ensuring they are distinct enough to cut through the typical work zone noises and are sufficiently loud to alert both on-site workers and passing motorists.

It is essential to note a limitation of the research presented in this chapter: the evaluation of these technologies occurred in controlled work zone settings without the influence of significant background noise. To truly grasp the pros and cons of each solution, more extensive field testing is recommended in diverse traffic conditions, various operations, and through an in-depth examination of workers' reactions to these technologies post-activation (this limitation is addressed in the next chapters.

TABLE 4.14
Functional characteristics of four selected intrusion alert technologies

Functional Characteristics	AWARE	WAS	SonoBlaster	Intellicone
Deployment Process	Setup the sentry unit in a work zone facing the oncoming vehicle. Open the case; lift, raise, and unfold the light bar. Turn the power ON. Connect the sentry to the iPhone by Bluetooth and set the design speed using the base station application.	Deploy the trip hoses with a pressure sensor on the ground. Deploy the alarm unit on the ground surface or attach it to the side of a car. Switch on the trip hose of the alarm unit. The unit will make a short beeping sound, indicating the device is ready to set up. Hand over the PSDs and handheld remote to workers.	Deploy the traffic cones mounted with a SonoBlaster and turn the control knob to unlock position. Cock the unit using a cocking pin till a clicking sound is heard. Insert the CO2 cartridge. Attach the red cap and position the assembly with the control knob positioned to unlock.	Position the smart cones attached to smart cones while adjacent cone distance not more than 50 feet. Deploy and turn on the PSA and wait until the unit gets connected to the GPS. Deploy the sentry laser and turn on the unit.
Deployment Time	Approximately 5–6 minutes.	Approximately 3–5 minutes.	8–10 minutes to attach the unit to the cone and 3–5 minutes to cock and insert the CO2 cartridge in one SonoBlaster unit.	Approximately 10–15 minutes.
False Positives or False Negatives	None (100% success rate in detection and activation).	High rate of false negatives (33% success rate).	Loose fitting of CO2 cartridge can result in false negatives. Freezing of CO2 cartridge results in inactivation (66% success rate)	Sentry laser fails to detect high-speed vehicles (more than 45 mph) and results in false negatives (50% success rate).
Issues During Activation/ Setup/Removal	None	Pressure sensor failure under high-speed conditions. Delays in activation if alarm unit placed at maximum transmission range. The contact location of the tire and trip hoses, as well as contact duration, influences the frequency of activation. The visual alarm is not visible. It is impossible to keep the orientation of both the alarm light and alarm speaker in the same direction.	The tedious process to mount a unit with a traffic cone. Cones cannot be stacked on top of each other after mounting and require more space.	Smart cones need to be a bit closer to PSA while getting connected the first time. Sentry laser results in infrequent false alarms
Battery Issues	None	The battery of pressure sensors may drain out in a day if kept on.	N/A	None

(Continued)

TABLE 4.14
(Continued)

Functional Characteristics	AWARE	WAS	SonoBlaster	Intellicone
Challenges in Deployment and Operation	Mounting WorkTRAX with the safety straps.	The time-consuming process of developing a connection between the alarm unit and the sensors. Hard to store and transport the trip hoses.	Cold weather impacts the functionality of SonoBlaster. Difficult to remove the CO2 cartridge protective cap due to freezing of CO2 cartridge. If activated consecutively within a short interval, ice particles accumulate and affect the activation.	Time-consuming setup of smart cones and batteries especially for long work zones. The sentry laser is heavy and very difficult for a single person to deploy due to the dispossessing of wheels.
Durability Issues	None	Very poor build quality of pressure sensors and alarm unit.	Moderately durable to vehicle impacts.	None
Best Practices	Suitable for stationary flagging operation. Might not be effective in work zones with curvature. The position should be near the taper to allow sufficient reaction time for drivers to react.	Suitable for lower speed limits and low traffic density work zones (less than 30 mph). To be effective, the length of the trip hose must be kept at 15 feet at the most even though the option is provided by the manufacturer. To be effectively noticed by workers, the orientation of the alarm should be towards workers.	Should be avoided in cold weather conditions (below 32°F). Suitable for stationary work zones with less traffic density. Most useful if deployed in both taper and buffer areas to cover all intrusion points.	Suitable for lengthy lane closures (more than 1,000 feet). A combination of sentry laser and PSA alarm is more effective.

TABLE 4.15
Proposed evaluation criteria for selecting intrusion technologies

Evaluation Criterion	Description	Ideal Characteristics	Research Methods
Deployment	Efforts required to set up the technology to be ready for use	Easy, straightforward, and less time-consuming	Pilot-controlled testing, lit review
Work Zone Coverage	An area that can be covered once deployed	Provide maximum work zone coverage	Pilot-controlled testing, lit review
Transportation and Storage	Convenience in handling the technology	Ease in conveying, removal after use, and storing back to the vehicle	Preliminary, pilot-controlled testing, lit review
Alert Type	Loudness of alarm and various alert types (visual, audio, haptic)	Loud alarms and multiple alarm types are preferred	Preliminary, pilot-controlled testing
Sound Distinctiveness	The uniqueness of the alarm sound	Noticeable in the presence of live traffic and construction background noise	Evaluation survey, preliminary testing
Frequency of False Alarms	Rate of false positives and false negatives	Few or no false alarm	Literature review, pilot-controlled testing

5. TASK 4: DRIVERS' PERCEPTION AND RESPONSES TO WORK ZONE INTRUSION ALERT TECHNOLOGIES

Even though intrusion alert technologies primarily aim to warn workers, understanding how distracted drivers respond to these alerts is crucial. One of the main reasons for accidents in work zones is the risky behavior of drivers who are not paying full attention. Overlooking traffic signals and signs, using a mobile phone while driving, and driving faster than the designated speed limit in the work zone are among the primary risks observed recently. Accordingly, the driver's reaction can significantly influence both the likelihood and severity of work zone accidents. For instance, if a driver quickly reacts and brakes upon hearing a warning alarm, it can reduce the chance of severe injuries and fatalities due to the reduced vehicle speed. This chapter examined the drivers' cognitive processes and behaviors using cutting-edge wearable technology, including eye trackers, medical wristbands, and neuroimaging sensors. Then, the findings from this task will be used in decision-making criteria concerning the alerts' effectiveness on drivers.

5.1 Methods

5.1.1 Experimental Design and Data Collection

A controlled off-road site, designed to simulate a work zone, was used for a field test. The layout and setup of four intrusion alert technologies are shown in Figure 5.1. The chapter focused on studying how drivers react to alarms and safety concerns. Therefore, impact-driven technologies like SonoBlaster and Intellicone were manually activated upon vehicle entry into the work zone.

Following the experiment explanation, subjects wore wearable sensors: Tobii Pro Mobile Eye-Tracker to observe visual scanning, Empatica E4 wristbands to monitor physiological and emotional responses, and fNIRS to track cognitive and neurophysiological reactions to alarms (Lee et al., 2022; Poolavdand & Hasanzadeh, 2022). Eye-tracking recorded fixation duration, count, and saccade path to analyze attention strategies. Empatica E4 measured Electrodermal Activity (EDA), indicating affective responses and risk perception. fNIRS captured brain activity, providing insights into cognitive processes during high-risk driving.

Twenty participants with varying driving experience completed the trials. These tests were conducted internally. All drivers had normal hearing and vision. Participants started with a mock trial to familiarize themselves with the process. Each driver completed eight trials, with two intruding speeds (35 and 45 mph) for each of the four technologies. Drivers were instructed to brake upon hearing the intrusion alarm, and they had no prior knowledge of the alert type or timing of alarm activation. Data collected included stoppage distance, reaction duration, stoppage duration, and sound pressure levels inside and outside the car (Table 5.1). Semi-structured interviews were conducted after each trial to gather drivers' feedback on the intrusion technologies.

5.1.2 Data Analysis

To analyze how drivers distribute their attentional resources, the windshield view of each participant was divided into three Areas of Interest (AOIs) using Tobii Pro Labs software. Illustrated in Figure 5.2, these AOIs comprised the left area (depicting live traffic), middle area (representing the road and worksite with workers), and right area (showcasing intrusion technologies and equipment). AOIs were activated after alarms were triggered, and participants' fixation durations were extracted to evaluate attention distribution (i.e., where drivers direct their visual focus and for how long). A comparative analysis was also performed to investigate whether diverse driving experiences influenced alarm perception and visual scanning strategies.

Physiological data commonly contains noise and motion artifacts due to sensitivity to body movement.

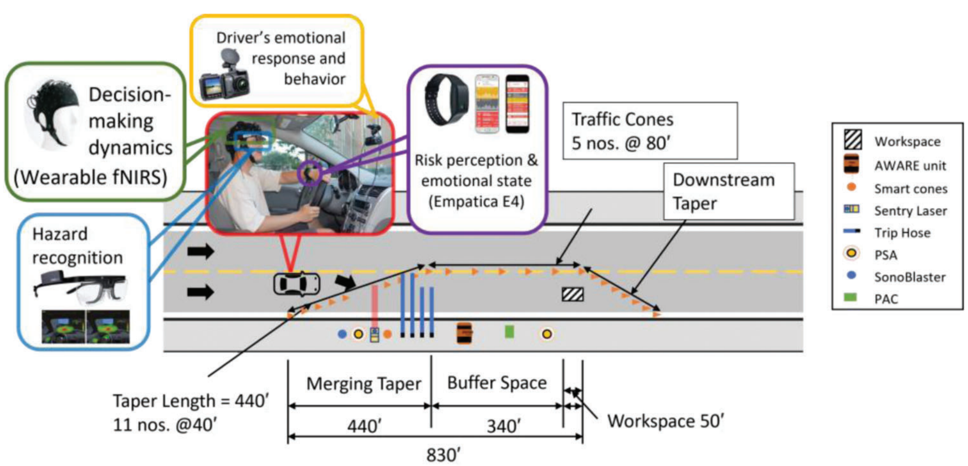


Figure 5.1 Experimental layout of the field test.

TABLE 5.1
List of data collected during the experiment

Metric	Description
Stoppage Distance	The distance that a driver needs to safely bring a vehicle to a complete stop after braking
Reaction Duration	Time taken by a driver to react and press the brake after the activation of the alarm
Stoppage Duration	The duration that a driver needs in order to safely bring a vehicle to a complete stop after braking
Sound Pressure Levels	Sound pressure levels in dB from inside and outside of the car

Figure 5.2 Example image of the AOIs.

To assess risk perception and responses, neuro-psycho-physiological signals (EDA and fNIRS) were preprocessed to remove artifacts. For EDA data, the Ledalab package (a MATLAB-based toolbox) was employed for noise removal and feature extraction. A low-pass Butterworth filter was then used to eliminate high-frequency EDA signal noise. EDA signals were decomposed into EDL (tonic) and EDR (phasic). EDR signals predominantly reflected short-term sympathetic responses to external stimuli, serving as a measure of risk perception. Participant EDR signals were scrutinized to understand their perception of technology alarms.

The study utilized fNIRS neuroimaging (Brite) to capture brain activation within auditory cortices based on Oxy-Hb and Deoxy-Hb level changes. While there is a debate in the literature regarding fNIRS metrics for evaluating behavior, changes in Oxy-Hb are often deemed sufficient for estimating cortical activity (Pooladvand & Hasanzadeh, 2022). Ten channels were selected for auditory cortex analysis, with near-infrared light transmitted from optodes. Raw fNIRS signals were processed using the Homer3 package, applying a band-pass filter to eliminate physiological noises. Optical density data were converted to relative hemoglobin concentrations using the modified Beer-Lambert Law (ppf = 6, 6, 6). The General Linear Model (GLM) calculated the Hemodynamic Response Function (HRF) over channels for each participant. GLM accounted for various sources of variance and modeled brain activation signals simultaneously. Physiological responses (like EDR) demonstrate immediate reactions to stimuli, while hemodynamic responses have a lag of around 5 to 7 seconds. To account for signal latency, this study added a 5-second delay to both reaction time and stopping time.

5.2 Results

5.2.1 The Effect of Different Alerting Mechanisms of Intrusion Technologies on Drivers' Attentional Distribution

Figure 5.3 illustrates the distribution of drivers' attention across different AOIs on the windshield after activating the alarm for each intrusion technology until the vehicle came to a complete stop. Regardless of the specific technology, drivers exhibited similar visual scanning patterns. They predominantly directed their attention towards the middle region (average duration for AWARE: 2.14 seconds, Intellicone: 1.62 seconds, SonoBlaster: 1.83 seconds), corresponding to the work zone in real-world scenarios (Figure 5.3). Additionally, in the case of the AWARE system, participants allocated slightly more attention to the right-hand side region and had longer fixation durations in this area compared to the other two technologies (average for AWARE right region: 0.22 seconds, Intellicone: 0.19 seconds, SonoBlaster: 0.14 seconds). Conversely, minimal attention was given to the left region during intrusion situations, with drivers rarely fixating on this area. Figure 5.4 shows the visual scanning patterns of a representative driver, illustrating the concentrated fixation points within the middle region.

Previous studies indicate that the number of years of driving experience can impact a driver's cognitive abilities. In this study, participants were divided into two groups based on their driving experience: novice drivers with less than a year of experience and experienced drivers with over 5 years of experience. The study then compared their visual search strategies in response to warnings. It was observed that there is no significant distinction between novice and experienced drivers, and both groups mainly focused on the middle region.

Overall, while technological variations influenced some aspects of visual attention, the primary area of focus for drivers, regardless of their experience level, was the middle region of the windshield when responding to alarms. This observation suggests that warning alarms exert a limited influence on drivers' visual search behaviors.

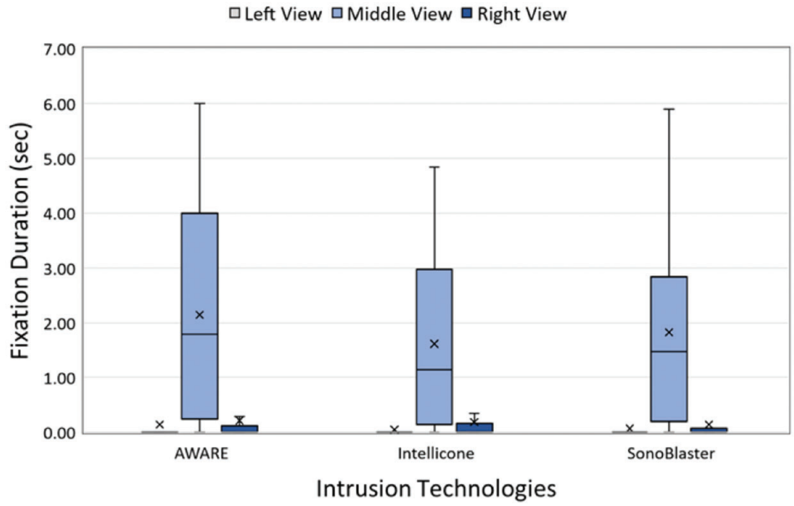
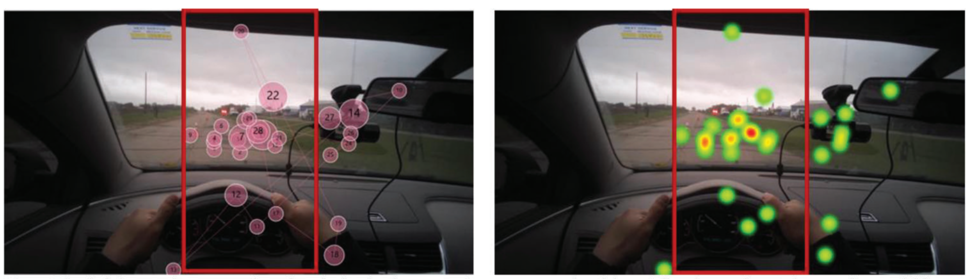


Figure 5.3 Fixation duration across three AOIs for different intrusion alert technologies.



Note: The left image is a gaze plot; the circles in the gaze plot represent the drivers' fixation points. The numbers within them indicate the sequence of the fixations, while the size of each circle reflects the duration of that fixation. The right image is a heat map. The colored regions in the heat map indicate where drivers directed their visual attention. Areas with a red hue highlight spots where drivers focused for extended periods.

Figure 5.4 Visual search strategies of the representative driver.

5.2.2 The Effect of Different Alerting Mechanisms of Intrusion Technologies on Drivers' Risk Perception

Figure 5.5 displays an illustrative physiological signal from a driver, with colored vertical lines indicating specific moments tied to driver perception. The solid blue line (activation time) represents the instance when the alarm is triggered following the detection of an errant vehicle. The dotted blue line (reaction time) signifies the point at which drivers interpret the sensed stimulus and press the brake pedal. Hence, the time at which drivers react to the alarm (dotted blue line) can be understood as the mental perception timing—when drivers actually perceive the alarm, even if the alarms were triggered earlier. The dashed blue line (stoppage time) corresponds to the moment at which the vehicle comes to a complete stop. Additionally, the reaction duration is defined as the span between the solid line and the dotted line, while the stoppage duration is established as the interval between the reaction time and stoppage time (as depicted in Figure 5.5).

EDR means for reaction duration and stoppage duration across the three selected are depicted in Table 5.2. Generally, drivers did not perceive any significant risks or danger from the triggered alarms. For AWARE, the average EDR during stopping duration is lower than the value of reaction duration, while the result of other technologies showed slight increases. These results indicated that the alarms of none of the technologies sufficiently stimulate the sense of urgency in drivers to make them perceive the high risk of the current situation (work zone intrusion). Representative physiological reactions (EDR) of drivers are depicted in Figure 5.6. The signal showed no substantial peaks or consistent elevation during the stoppage duration, even when subjects heard the warning alarm and approached the worksite. Notably, during both durations, the signal did not exhibit pronounced increases when the driver heard the AWARE alarm. Conversely, with Intellicone, a minor signal increase was observed during the stoppage duration. Moreover, while other technologies failed to prompt a sense of urgency during the reaction duration, the driver began to sense a certain level of risk shortly after SonoBlaster activation, which persisted until midway through the stoppage duration. Therefore, in general, drivers failed to perceive any significant risks or dangers from the triggered alarms.

Figure 5.7 and Table 5.3 illustrate the hemodynamic responses of the prefrontal and auditory cortices in relation to each technology. Activation in the prefrontal

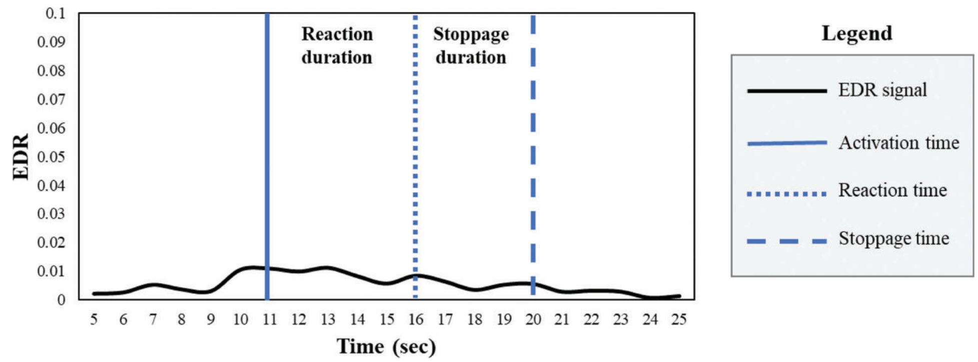


Figure 5.5 Fixation duration across three AOIs for different intrusion alert technologies.

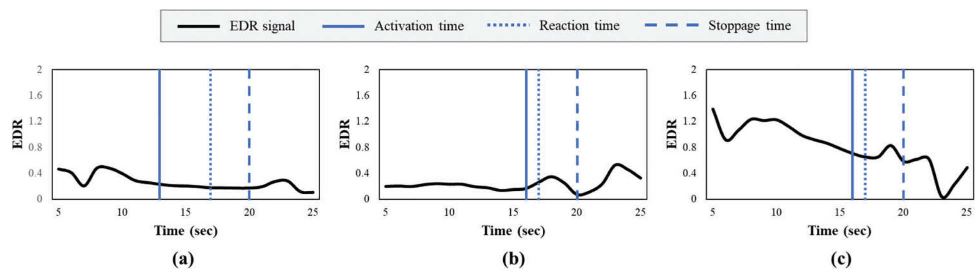


Figure 5.6 Changes in EDR signals associated with one representative driver while intruding a work zone equipped with (a) AWARE, (b) SonoBlaster, and (c) Intellicone.

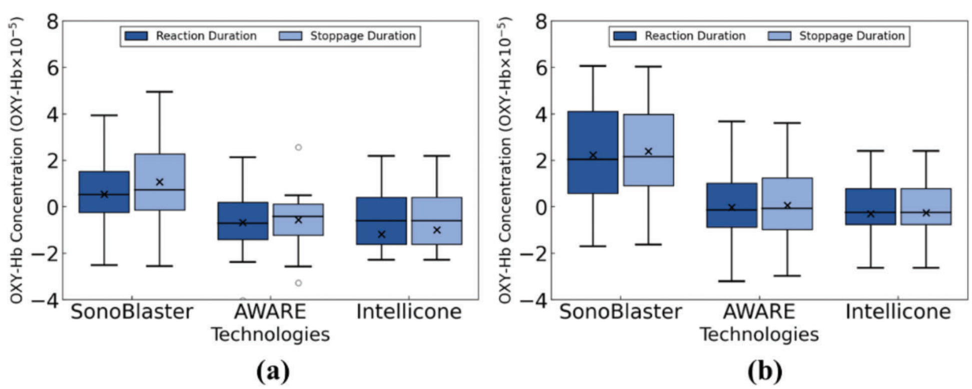


Figure 5.7 Drivers' brain activation in terms of oxy-Hb concentration across different intrusion technologies: (a) PFC activation, and (b) auditory cortex activation.

TABLE 5.2
Drivers' average EDR responses and response measures across intrusion alert technology

	AWARE		SonoBlaster		Intellicone	
Data	**Reaction Duration**	**Stoppage Duration**	**Reaction Duration**	**Stoppage Duration**	**Reaction Duration**	**Stoppage Duration**
EDR	0.150	0.138	0.120	0.177	0.245	0.290

cortex suggests that drivers interpreted relevant information from the situation and utilized it for decision-making. Meanwhile, activation in the auditory cortices indicates that drivers were attentive to the alarm sound from the intrusion technology. In particular, Figure 5.7(b) displays auditory activation across the three technologies for all drivers. This visual representation indicates that SonoBlaster generated greater activation due to its louder siren compared to AWARE and Intellicone. Furthermore, heightened prefrontal cortex (PFC) activation was evident for SonoBlaster during both reaction and stoppage durations, as depicted in Figure 5.7(a). This observation underscores that the auditory alarm of SonoBlaster resulted in amplified

TABLE 5.3
Drivers' average hemodynamic responses and response measures across intrusion alert technology

	AWARE				SonoBlaster				Intellicone			
	Reaction Duration		Stoppage Duration		Reaction Duration		Stoppage Duration		Reaction Duration		Stoppage Duration	
Data	**PFC**	**AUD**	**PFC**	**AUD**	**PFC**	**AUD**	**PFC**	**AUD**	**PFC**	**AUD**	**PFC**	**AUD**
Hemodynamic Responses	-0.68	-0.03	-0.56	0.06	0.27	2.23	1.08	2.39	-1.18	-0.3	-0.99	-0.42

TABLE 5.4
The decibel range of alarm sounds provided by each technology

Intrusion Technology	Decibel Range Measured Inside the Car (dB)	Decibel Range Measure Outside the Car (dB)
SonoBlaster	71–76	78–83
AWARE	67–73	75–85
Intellicone	64–69	65–69

activation within both the auditory and prefrontal cortices.

Table 5.4 shows the decibel ranges for three intrusion technologies. SonoBlaster produces the loudest sounds, registering between 71–76 dB inside and 78–83 dB outside the car. AWARE's decibel readings are 67–73 dB within the car and span from 75 to 85 dB outside, sometimes matching or even exceeding SonoBlaster's peak levels. In contrast, Intellicone consistently outputs the quietest sounds, with measurements of 64–69 dB inside and a closely matching 65–69 dB outside the car. For context, the Centers for Disease Control and Prevention (CDC) indicate that common household appliances, such as washing machines, emit an average sound level of 70 dB (CDC, 2022). Additionally, inside a car, the typical sound levels from urban traffic are perceived to range from 80 to 85 dB. Given these benchmarks, even the loudest readings from SonoBlaster fall short of the noise levels from standard city traffic. This underscores a potential limitation: all three technologies might offer sound levels that are insufficient to adequately foster risk perception among drivers. It is crucial to note that, during this experiment, potential sound influencers like the AC or radio were switched off to ensure accuracy.

Feedback from drivers post-trial further substantiated concerns about the sound levels of these intrusion alert technologies. While many drivers felt that the alarms were sufficiently loud when heard externally, their experiences changed markedly once inside the car. A significant number reported a noticeable drop in the alarm's volume, and several even mentioned they could not hear the alert at all. Interestingly, despite its lower sound levels, Intellicone's alarm was still perceptible to some drivers, attributed to its distinctive sound. This suggests that both volume and distinctiveness play pivotal roles in the effectiveness of these alerts.

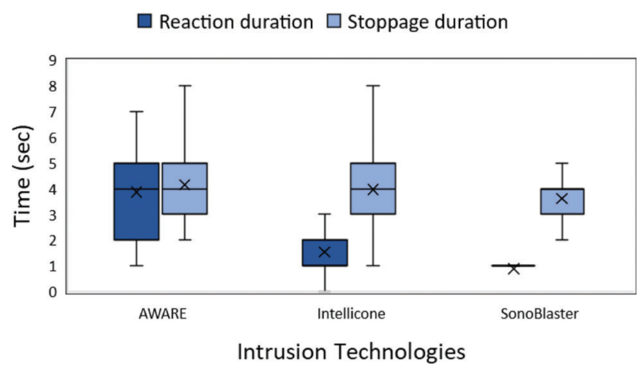


Figure 5.8 Summary of drivers' reactions and stoppage duration for each technology.

Figure 5.8 illustrates the spectrum of drivers' reactions and stoppage durations associated with each intrusion alert technology. The findings indicated that drivers exhibited comparatively shorter reaction durations for Intellicone and SonoBlaster compared to the AWARE system. Notably, drivers could register the alert sound of SonoBlaster roughly a second after activation, with an average reaction duration of 0.9 seconds. Conversely, the AWARE system yielded the most extended reaction durations, averaging 3.88 seconds. Furthermore, as depicted, stoppage durations for all technologies fell within similar ranges (average for AWARE: 4.15 seconds, Intellicone: 3.96 seconds, SonoBlaster: 3.63 seconds), while reaction duration displayed substantial variations.

Overall, the intrusion technologies tested exhibited low sound levels, falling short of amplifying drivers' risk perceptions, and influencing their visual search strategies. To enhance the efficacy of these technologies, there is a dual imperative: not only should the volume be increased, but the distinctiveness of the alarms should also be enhanced to ensure they capture the driver's attention effectively.

5.3 Conclusion

This task used wearable technologies to assess the effectiveness of intrusion alert systems on drivers' reactions during work zone incidents. From eye-tracking data, it was observed that there was no significant difference in how drivers focused on the various technologies. Essentially, the visual alerts from these systems did not significantly impact the drivers' visual patterns, primarily due to the weak visible alert lights, which are difficult to discern on a bright, sunny day.

Physiological measurements (EDR and fNIRS) further reported that the alert systems were not as effective as expected in creating a sense of urgency or enhancing risk perception among drivers. While the Sonoblaster, with its notably louder alarm, did show increased activation in the auditory cortex compared to other technologies, it still did not prompt a strong sense of risk. Interestingly, despite Intellicone's lower volume, its distinct alarm design managed to stand out, hinting at the potential advantages of unique sound signatures. These findings emphasize the significance of having alarms that are not just loud but also distinguishable from everyday environmental noises for swift and precise recognition by drivers. To truly amplify the alarms' impact on the sense of urgency and risk perception, it might be beneficial to deploy more PSA units, thereby intensifying the sound and its effect on drivers. These results underscore the need for alarms that are both loud and distinct from everyday environmental noises to be promptly and accurately recognized by drivers.

Moreover, drivers' responses can vary based on the specific features and setup of each technology. For instance, the AWARE system could detect vehicles moving at high speeds and activate alarms before an intrusion. However, due to its lower sound intensity, drivers typically recognized the alarm only when they were in close proximity to the unit, resulting in a delayed response. Combining the strengths of these technologies, such as installing them in multiple locations or having them operate simultaneously, might enhance their effectiveness in alerting drivers.

6. TASK 5: WORKERS' PERCEPTION AND RESPONSES TO WORK ZONE INTRUSION ALERT TECHNOLOGIES

Previous tasks primarily delved into the influence of intrusion alert technologies on drivers' cognitive functions and behaviors. This chapter aims to understand how these alert systems affect the cognitive processes and actions of the workers. Advanced wearable technologies were utilized to monitor workers' reactions and perceptions. It is worth noting that, during our study, workers continued their regular tasks surrounded by real environmental noises, including those from ongoing traffic and other construction activities. The insights obtained from this task will guide decision-making criteria concerning the alerts' efficacy for the workers.

6.1 Methods

6.1.1 Experimental Design and Data Collection

The primary goal of active work zone testing was to evaluate the effectiveness of four intrusion alert technologies in real-world construction scenarios. The study aimed to assess their impact on workers' situational awareness, attention allocation, and decision-making in risky environments. Controlled experiments provided insights, highlighting the need for further investigation into how intrusion alarms are perceived amidst background noise. Real work zones were chosen across Indiana's highway repair sites to gather user feedback and assess adoption.

Five suitable work zone types were selected based on factors like lane closures, speed limits, and work duration. A comprehensive research plan was developed just before active testing. Workers at each site received a briefing on the experiment during safety meetings. A participant from the crew was selected as the primary subject, equipped with wearable sensors (fNIRS, Empatica E4, and Tobii Pro eye tracker). Intrusion technologies were set up based on best practices observed in controlled testing (Chapters 4 and 5).

Participants were intentionally not informed of the functioning of each intrusion technology to capture their naturalistic responses. Manual activation of each technology was done by a research team member, allowing assessment of participants' situational awareness and their choice of escape routes upon hearing the intrusion alarm. Workers' feedback was collected through surveys and interviews after each technology test. Survey questions covered participant demographics, familiarity with intrusion technologies, alarm effectiveness, enhancement of work zone safety, perception of intrusion direction, lead time for finding escape routes, and alarm clarity amidst ambient noise (the draft of the survey is provided in Appendix A.3). An overview of the experiment is illustrated in Figure 6.1. Lastly, the participants were also asked to provide input, recommendations, and suggestions for future use of these intrusion technologies. Table 6.1 shows the schedule of active work zone testing.

6.1.2 Active Work Zones

6.1.2.1 Site 1: 5972 US-40, Greenfield, IN 46140

Project Description: This work zone involved asphalt repair work on the US-40 highway in Greenfield, Indiana. The roadway consisted of a four-lane roadway (two lanes in each direction) with narrow shoulders. One lane of the road was closed, and two lanes of the

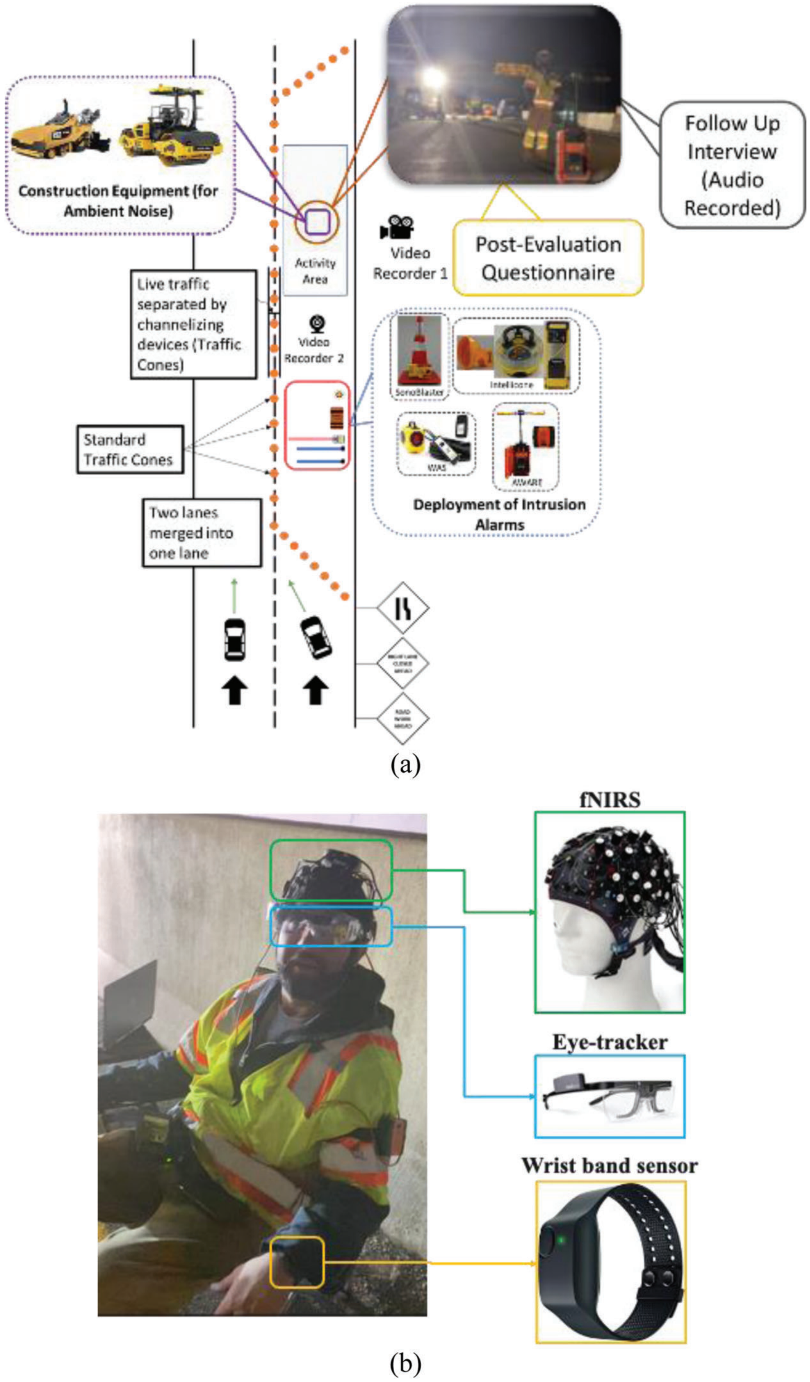


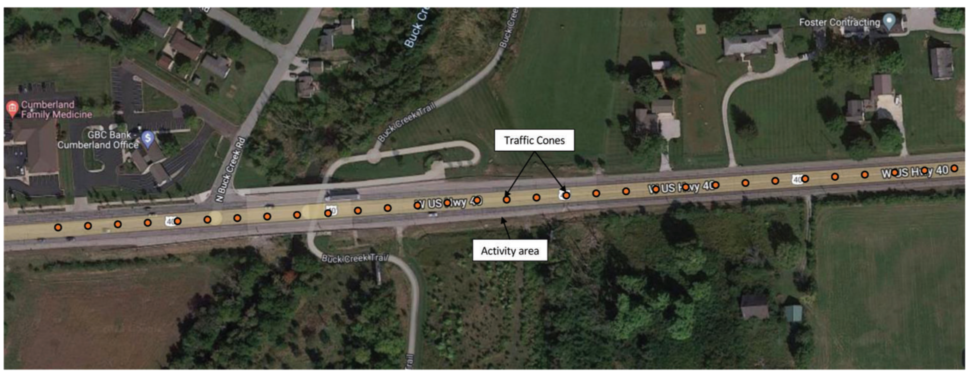
Figure 6.1 (a) Overview of the experimental design, and (b) primary participants with wearable sensors.

highway were merged into one lane with the help of channelizers (traffic cones). Hence, the approaching vehicles were made to reduce their speed and merge into one lane while driving through the work zone. The length of the lane closure was 400 feet in either direction of the activity area. In total, 12 ground crews and two equipment operators were working on the project. Heavy truck equipment, asphalt paver, and roller compactor were being used on this jobsite. The two technologies that were deployed were AWARE and Intellicone. Figure 6.2 shows the work zone layout, location, and closure setup, respectively.

Research Plan: At the beginning of the experiment, the research team briefly introduced the intrusion technologies to workers during the safety meeting. Participants were provided with the consent form to sign, and one primary subject who will wear all the wearable physiological sensors was identified. Upon arrival at the test location, the AWARE was set up at the entrance of the work zone, and the WorkTRAX

TABLE 6.1
Schedule of active work zone testing

Date	Location	Project Description	Work Zone Type	Applied Intrusion Technologies	Type of Data Collected
09/14/2022	5972 US-40, Greenfield, IN	Asphalt repair work	Mobile	AWARE, Intellicone	Physiological, survey, interview
09/14/2022	289-1 W US Hwy 40, Greenfield, IN	Asphalt repair work	Stationary	AWARE, Intellicone, SonoBlaster	Survey, interview
09/16/2022	US Hwy 421, Keystone at the Crossing, Indianapolis, IN	Patching and asphalt resurfacing	Stationary	AWARE, Intellicone, SonoBlaster	Physiological, survey, interview
10/04/2022	US-30, Plymouth, IN	Underground utility installation	Mobile	AWARE, Intellicone, SonoBlaster	Physiological, survey, interview
10/05/2022	Ripley St, Lake Station, IN	Bridge repair work	Stationary	AWARE, Intellicone, SonoBlaster	Physiological, survey, interview
10/06/2022	Allisonville Rd, Indianapolis, IN	Curb repair	Stationary	AWARE, Intellicone, SonoBlaster	Physiological, survey, interview
11/01/2022	US-36, Lynn, IN	Underground utility installation	Stationary	AWARE, Intellicone, SonoBlaster	Physiological, survey, interview



(a)

(b)

Figure 6.2 Site 1 (a) work zone layout, and (b) work zone closure.

units were given to four workers, including the primary subject. The AWARE sentry was set up with a 30-mph design speed to detect approaching vehicles exceeding the speed above this speed limit. The smart cones of the Intellicone were mounted on the standard traffic cones starting from the taper until the end of the activity area. The PSA of the Intellicone was set up near the activity area and near the shoulder of the roadway. A video recorder was set up near the activity area to record all participants' reactions upon activating the intrusion alarm. The project was being undertaken at two locations within the same work zone. The AWARE was activated on the first location, and the project was moved to the next location. On the second location, Intellicone was activated. After each activation, a short survey was distributed among the participants to document their feedback, and after the whole experiment, a short interview was conducted with the participants for their recommendations, suggestions, and concerns about these intrusion technologies. Each intrusion technology was activated within a specific time interval as shown in Figure 6.3.

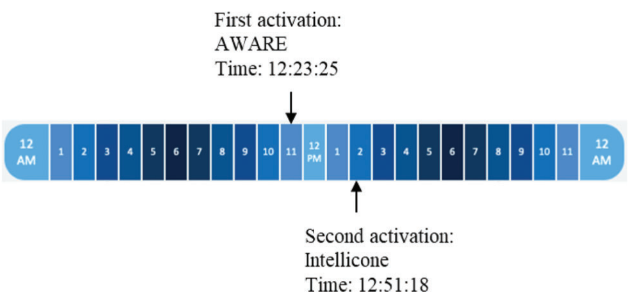
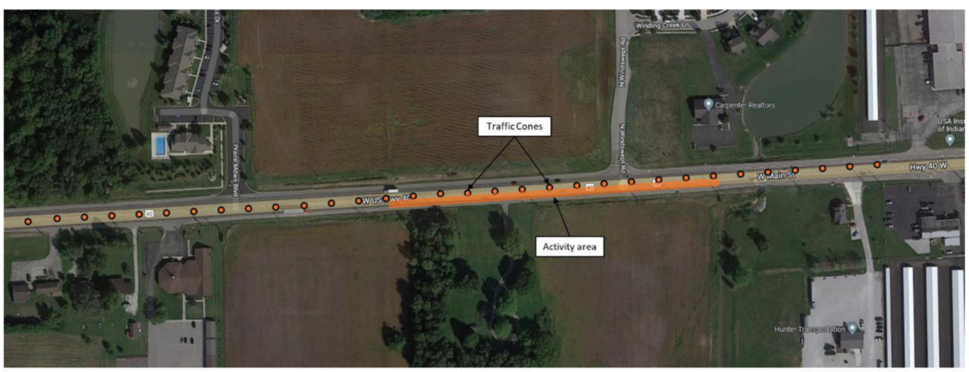


Figure 6.3 Activation time for intrusion alert technologies for Site 1.

6.1.2.2 Site 2: 289-1 W US Hwy 40, Greenfield, IN 46140

Project Description: This work zone involved asphalt repair work on 289-1 W US-40 highway in Greenfield, Indiana. The roadway consisted of a four-lane roadway (two lanes in each direction) with narrow shoulders. One lane of the road was closed, and two lanes of the roadway were merged into one lane with the help of channelizers (traffic cones). Hence, the approaching vehicles were made to reduce their speed and merge into one lane while driving through the work zone. In total, five ground crews and two equipment operators were working on the project. The three technologies that were deployed were AWARE, Intellicone, and SonoBlaster. Figure 6.4 show the work zone layout, location, and closure setup, respectively.

Research Plan: During the safety meeting before the experiment began, the study team gave the personnel a brief overview of the intrusion technologies. A consent form was given to participants. Upon arriving at the test site, the WorkTRAX units were installed with four workers, and the AWARE was placed at the entrance to the work zone. The AWARE sentry was configured with a design speed of 30 mph to detect approaching cars traveling faster than this speed limit. From the taper to the end of the activity area, the standard traffic cones were installed with the Intellicone smart cones, and a sentry laser was placed next to the workspace. The Intellicone PSA was set up close to the activity area and the road's shoulder. When the intrusion alarm went off, a video recorder was also placed close to the activity area to capture everyone's responses. After each activation, a short survey was distributed among the participants to document their feedback, and after the whole experiment, a short interview was conducted with the participants for their recommendations, suggestions, and concerns about these intrusion technologies. Each intrusion technology was activated within a certain time interval, as shown in Figure 6.5.



(a)

(b)

Figure 6.4 Site 2 (a) work zone layout, and (b) work zone closure.

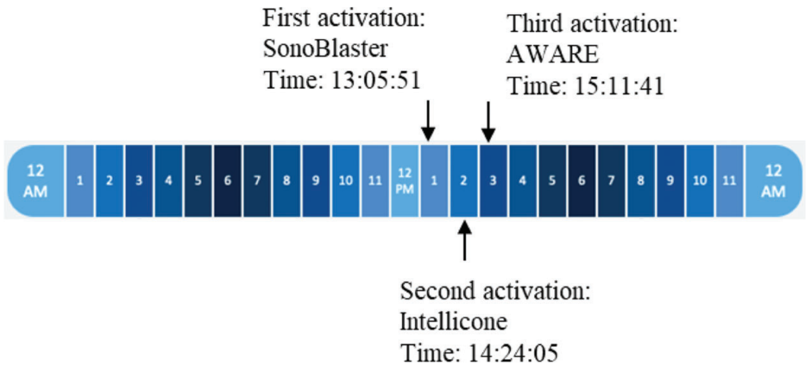
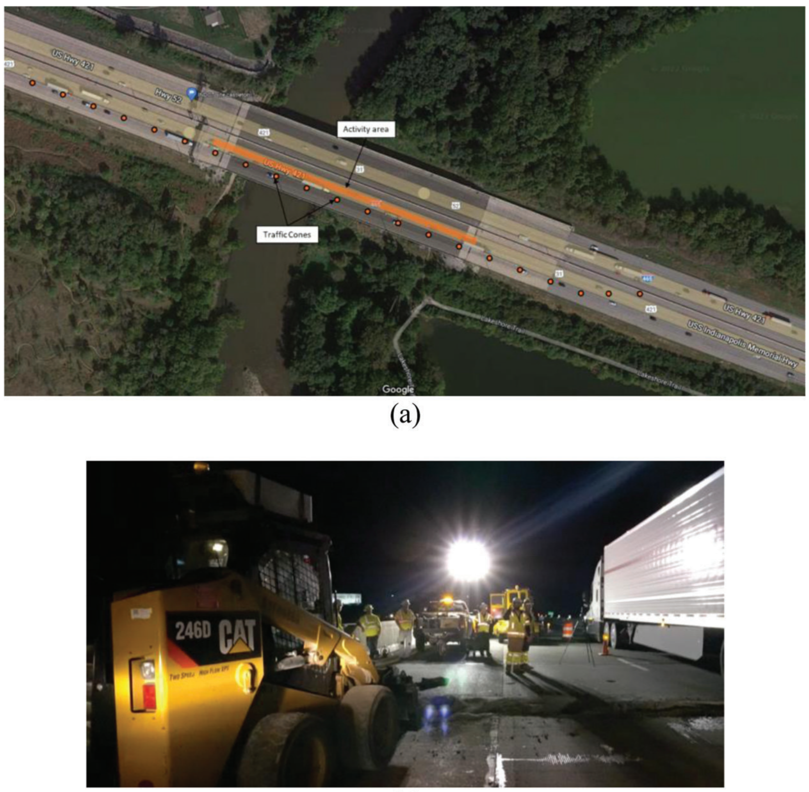


Figure 6.5 Activation time of intrusion alert technologies for Site 2.



(a)

(b)

Figure 6.6 Site 3 (a) work zone layout, and (b) work zone closure.

6.1.2.3 Site 3: US Hwy 421, Keystone at the Crossing, Indianapolis, IN 46240

Project Description: The third project was completed at the US Hwy 421 bridge over the White River at the crossing in Keystone, Indianapolis, IN. This work zone involved patching and asphalt resurfacing at the entry and departure of the bridge curb during nighttime. The road had a small shoulder and six lanes, with three lanes in each direction. Using channelizers, i.e., traffic cones, the highway's three lanes were combined into two lanes while one lane was closed. As a result, when vehicles traveled through the construction zone, oncoming traffic was instructed to slow down and merge into one lane. In total, five ground crews and two equipment operators were working on the project. A dozer, concrete truck, concrete cutter, and roller compactor were being used on this jobsite. The three technologies that were deployed were AWARE, Intellicone, and SonoBlaster. Figure 6.6 shows the work zone layout, location, and closure setup, respectively.

Research Plan: The study team briefed the staff on the intrusion technologies during the safety meeting before the experiment, and one primary subject, who will wear all the physiological sensors, was identified. Participants were given a consent document. As soon as they arrived at the test location, four workers installed the WorkTRAX units, and the AWARE was placed at the entrance to the work zone. To detect oncoming cars going faster than this speed limit, the AWARE sentry was set up with a design speed of 30 mph. The regular traffic cones were replaced with Intellicone smart cones from the taper to the end of the activity area, and a sentry laser was positioned adjacent to the workspace. A video recorder and a 360-degree camera were also put close to the activity area to record everyone's reactions when the intrusion alarm went off. A brief survey was circulated to participants following each activation to record their input, and following the completion of the experiment, a short interview was held with the participants to get their views, suggestions, and concerns regarding these intrusion technologies. Each intrusion technology was activated within a specific time interval, as shown in Figure 6.7.

6.1.2.4 Site 4: US-30, Plymouth, IN 46563

Project Description: The underground drainage pipe was being installed at US-30, Plymouth, in Indiana which involved cutting of the existing road, dredging the earth, and installing a new underground utility pipe. The roadway consisted of four-lane roadway (two lane on each direction) with moderately wide shoulders. Both two lanes of the road were closed, and the oncoming traffic was allowed to pass through one of the opposite adjacent lanes. The work zone was closed with the help of channelizers (traffic cones). This work zone was a complete closure which means no vehicles were made to enter the work zone. The length of the lane closure was 400 feet from the activity area. In total five ground crew members and one equipment operator (backhoe) were working on the project. The technologies that were deployed were AWARE, SonoBlaster and Intellicone. Figure 6.8 shows the work zone layout,

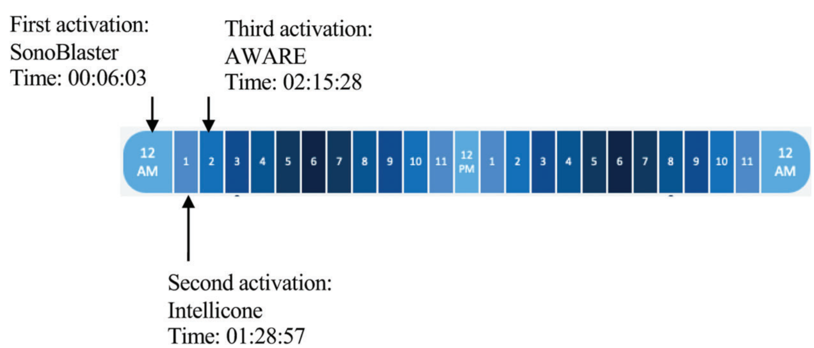
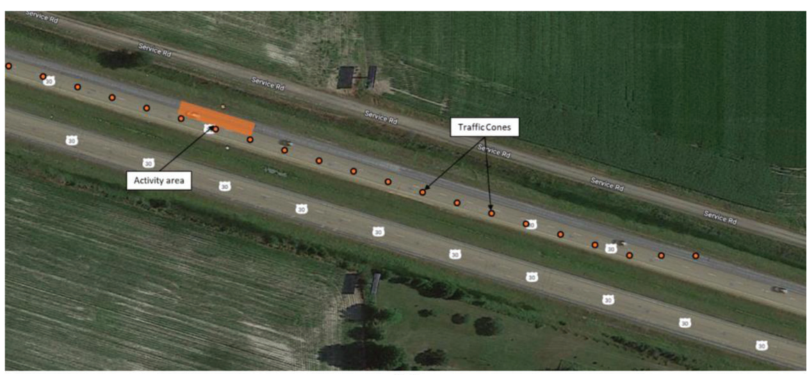


Figure 6.7 Activation time of intrusion alert technologies for Site 3.



(a)

(b)

Figure 6.8 Site 4 (a) work zone layout, and (b) work zone closure.

location, and closure setup respectively. This was a mobile work zone and Intellicone was activated on the first location and on the second location, SonoBlaster and AWARE were activated.

Research Plan: At the beginning of the experiment, the research team briefly introduced the intrusion technologies to workers during the safety meeting. Participants were provided with the consent form to sign, and one primary subject who will wear all the wearable physiological sensors was identified. Upon arrival at the test location, the AWARE was set up at the entrance of the work zone, and the WorkTRAX units were mounted with four workers, including the primary subject. The AWARE sentry was set up with a 30-mph design speed to detect the oncoming vehicles exceeding the speed above this speed limit. The smart cones of the Intellicone were mounted on the standard traffic cones starting from the taper until the end of the activity area. The PSA of the Intellicone was set up near the activity area and close to the workers. A video recorder, as well as a 360 camera, was set up near the activity area to record all reactions of the participants upon the activation of the intrusion alarm. After each activation, a short survey was distributed among the participants to document their feedback, and after the whole experiment, a short interview session was conducted with the participants for their recommendations, suggestions, and concerns about these intrusion technologies. Each intrusion technology was activated within a certain time interval, as shown in Figure 6.9.

6.1.2.5 Site 5: Ripley St, Lake Station, IN 46405

Project Description: The bridge repair work at Ripley St, Lake Station, IN involved scraping up the concrete surface and asphalt resurfacing. The road had two lanes in each direction and four lanes overall, with very little room for shoulders. With the use of channelizers i.e., traffic cones, the roadway's two lanes were completely closed, and the passing traffic was made to pass through one adjacent opposite lane. This work zone was a complete closure, and the length of the lane closure was 300 feet from the activity area where work was being performed. In total two ground crews and two equipment operators were working on the project. On this work zone, three intrusion technologies were deployed, i.e., AWARE, Intellicone, and SonoBlaster. The two technologies that were deployed were AWARE and Intellicone. Figure 6.10 shows the work zone layout, location, and closure setup, respectively.

Research Plan: The study team briefed the workers on the intrusion technologies at the beginning of the experiment during the safety meeting. A consent form was given to participants, and it was decided on one key subject who would wear every wearable physiological sensor. Upon arriving at the test site, the WorkTRAX units were installed with four workers, including the primary subject, and the AWARE was put up at the entrance to the work zone. The AWARE sentry was configured with a design speed of 30 mph to detect approaching cars traveling faster than this speed limit. From the beginning of the work zone on the roadway divider, the Intellicone smart cones were put on the regular traffic cones. The Intellicone PSA was set up on the shoulder and close to the activity area. A video recorder was placed close to the activity area to capture all participant responses to the intrusion alarm activation. A brief survey was sent out to participants following each activation to record their input, and following the completion of the experiment, a short interview was held with the participants to get their views, suggestions, and concerns regarding these intrusion technologies. According to Figure 6.11, each intrusion technology was turned on at a specific time during the experiment.

6.1.2.6 Site 6: Allisonville Rd, Indianapolis, IN 46250

Project Description: On this work zone, the work zone was set up using the channelizing devices (vertical panel channelizer) to completely close the entrance ramp to Allisonville road in Indianapolis, IN. In this work zone, construction work was being performed to repair the concrete curb on the intersection of Allisonville Road and the entrance ramp from US 52. The roadway consisted of eight lanes (four lanes in each direction) with wide shoulders. One lane of the road was closed, and the passing traffic was merged into three lanes with the help of channelizers (vertical panel channelizers). Hence, the approaching vehicles were made to reduce

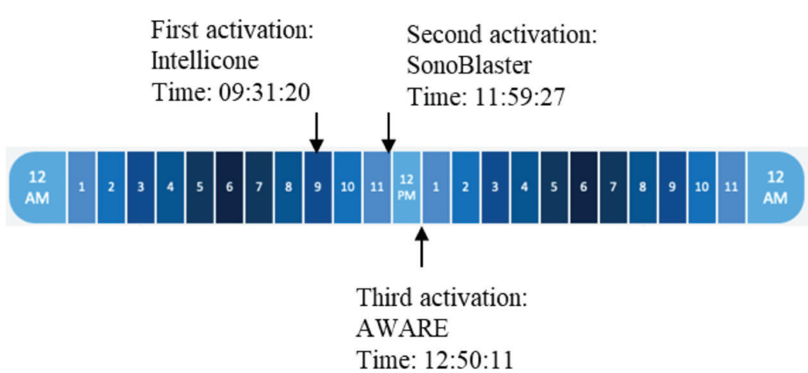
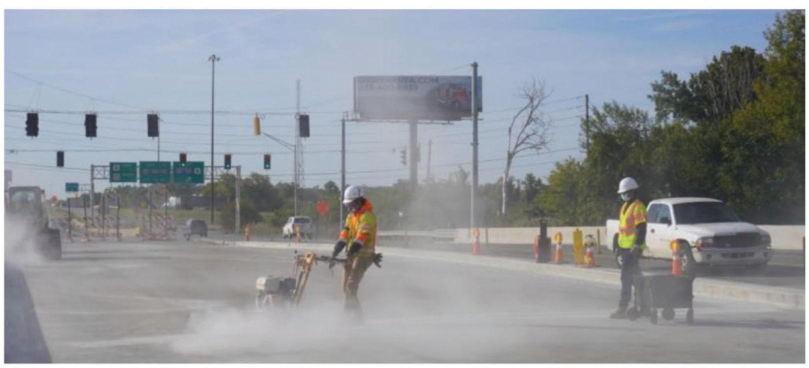


Figure 6.9 Activation time of intrusion alert technologies for Site 4.

(a)



(b)

Figure 6.10 Site 5 (a) work zone layout, and (b) work zone closure.

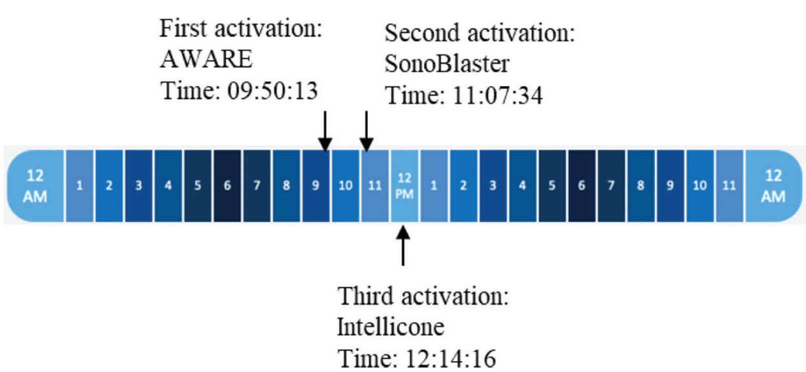


Figure 6.11 Activation time of intrusion alert technologies for Site 5.

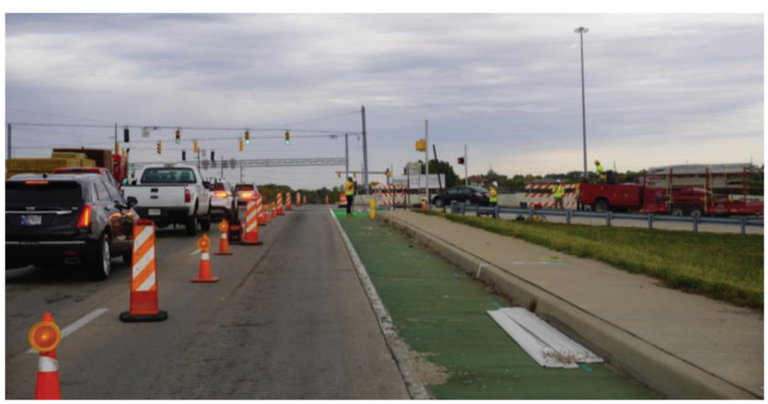
their speed and merge into one lane while driving through the work zone. In total, four ground crews were working on the project. The intrusion technologies that were deployed were AWARE, Intellicone, and SonoBlaster. Figure 6.12 shows the work zone layout, location, and closure setup, respectively.

Research Plan: At the beginning of the experiment, the research team provided a short introduction to the intrusion technologies to workers during the safety meeting. Participants were provided with the consent form to sign, and one primary subject who will wear all the wearable physiological sensors was identified. Upon arrival at the test location, the AWARE was set up at the entrance of the work zone with a 30-mph design speed to detect the oncoming vehicles exceeding the speed above this speed limit. The smart cones of the Intellicone were mounted on the standard traffic cones starting from the taper until the end of the activity area. The PSA of the Intellicone was set up near the activity area and on Allisonville road. A video recorder and a 360 camera were set up near the activity area to record all participants' reactions upon the activation of the intrusion alarm. After each activation, a short survey was distributed among the participants to document their feedback, and after the whole experiment, a short interview was conducted with the participants for their recommendations, suggestions, and concerns about these intrusion technologies. Each intrusion technology was activated within a certain time interval as shown in Figure 6.13.

6.1.2.7 Site 7: US-36, Lynn, IN 47355

Project Description: At US-36, Lynn in Indiana, a new underground utility pipe was being laid, which required cutting the current road, dredging the ground, and installing the pipe. The street had two lanes, one in each direction, with broad shoulders. With the aid of channelizers, the work zone was closed off by shutting both highway lanes using the traffic cones. No vehicles could access this work zone because it was completely closed off. The distance of the lane closure from the activity area was 150 feet. Three ground crew workers and one backhoe operator were working on the project in total. AWARE, SonoBlaster, and Intellicone were the technologies that were used in this work zone. Figure 6.14 shows the work zone layout, location, and closure setup, respectively. All three intrusion technologies, i.e., Intellicone, SonoBlaster, and AWARE, were activated in the same location as this was a stationary work zone.

(a)



(b)

Figure 6.12 Site 6 (a) work zone layout, and (b) work zone closure.

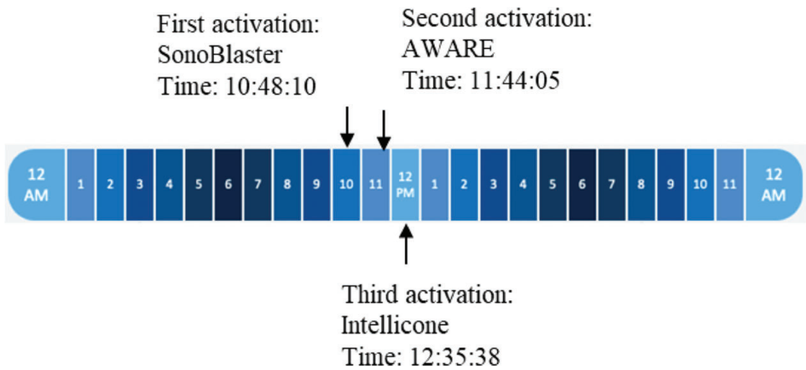


Figure 6.13 Activation time of intrusion alert technologies for Site 6.

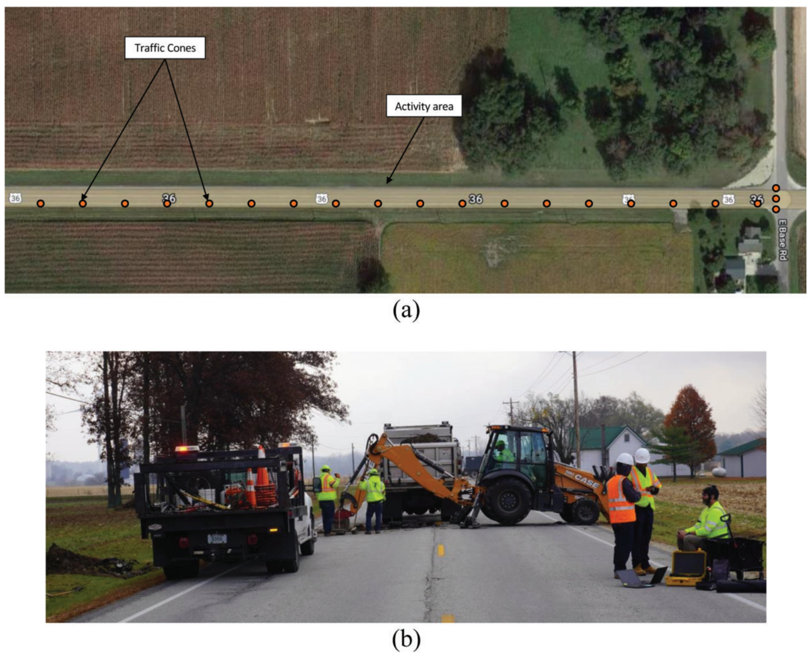


Figure 6.14 Site 7 (a) work zone layout, and (b) work zone closure.

Research Plan: At the beginning of the experiment, the research team briefly introduced the intrusion technologies to workers during the safety meeting. Participants were provided with the consent form to sign, and one primary subject who will wear all the wearable physiological sensors was identified. Upon arrival at the test location, the AWARE and the WorkTRAX units were set up with a 30-mph design speed to detect the oncoming vehicles exceeding the speed above this speed limit. As there was no active commuter traffic due to full closure, to activate the AWARE Sentry, one of the research team members drove the sedan toward the AWARE sentry to activate the intrusion alarm for the AWARE trial. The smart cones of the Intellicone were mounted on the standard traffic cones starting from the taper until the end of the activity area. The PSA of the Intellicone was set up near the activity area and near the shoulder of the roadway. A video recorder was set up near the activity area to record all participants' reactions upon activating the intrusion alarm. After each activation, a short survey was distributed among the participants to document their feedback. After the whole experiment, a short interview was conducted with the participants for their recommendations, suggestions, and concerns about these intrusion technologies. Each intrusion technology was activated within a specific time interval as shown in Figure 6.15.

6.1.3 Data Analysis

The workers' subjective perceptions of each intrusion alert technology were evaluated using survey data. The survey questionnaire consisted of eight questions that covered different evaluation criteria, such as familiarity, distinguishable sound, and a sense of urgency. Participants were instructed to provide a score ranging from 1 (strongly disagree) to 5 (strongly agree) for each

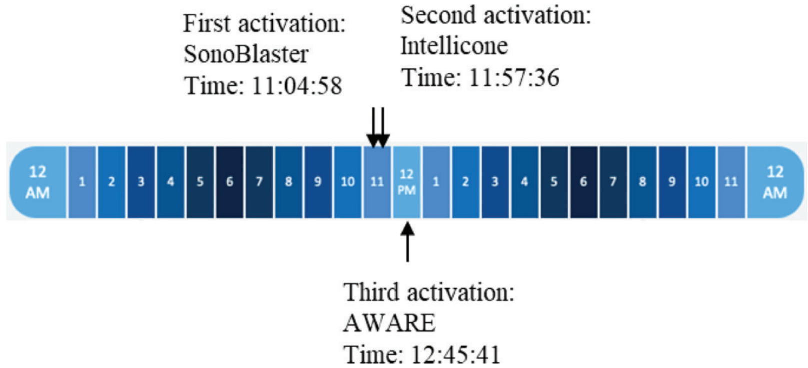


Figure 6.15 Activation time of intrusion alert technologies for Site 7.

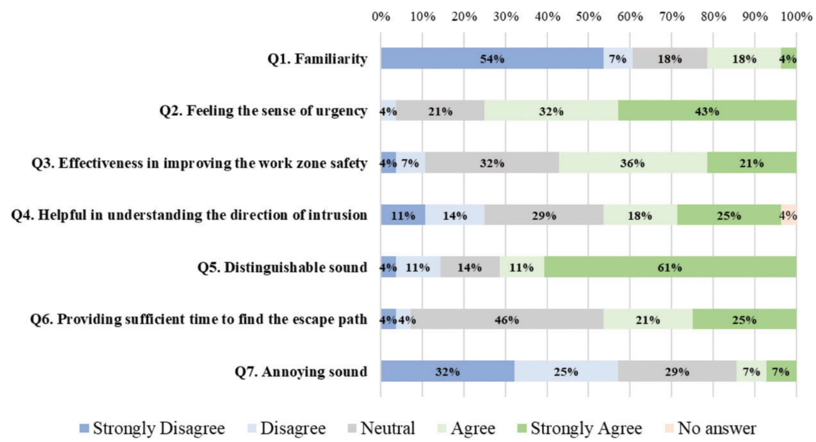


Figure 6.16 Summary of survey results for AWARE.

question. Subsequently, the psychophysiological responses of the workers were studied by monitoring the trends in the Electrodermal Activity (EDA) signal and hemodynamic responses. To minimize the influence of external factors, the analysis primarily focused on the short duration immediately before and after the activation of alarms. A consistent noise removal and feature extraction process was applied to enhance the quality of data, following the methodology outlined in Section 5.1.2. Lastly, video recordings of each alarm activation were used to analyze the reactions and behaviors of the workers in response to the warning alarms. This analysis encompassed not only the direction of the workers' visual attention towards the intrusion alert technologies after perceiving the alarm but also whether they interrupted their ongoing tasks and left their work zones based on their perceived situations.

6.2 Results

6.2.1 AWARE

6.2.1.1 Workers' subjective feedback. The analysis of workers' feedback related to AWARE is presented in Figure 6.16, and the associated interpretation is described as follows.

- Q.1 Only 22% of workers indicated familiarity with the AWARE system.
- Q.2 Seventy-five percent of workers reported feeling a sense of urgency when the alarm was triggered.
- Q.3 Fifty-seven percent of workers believed the AWARE system would effectively improve work zone safety, while 32% were unsure of its effectiveness.
- Q.4 Twenty-five percent of workers felt the AWARE system did not assist in determining the direction of an intrusion at all. Meanwhile, 29% were unsure about its helpfulness in this aspect.
- Q.5 Seventy-two percent of workers could distinguish the alarm sound of the AWARE system. However, some also noted that its sound was reminiscent of an emergency vehicle's alarm.
- Q.6 Forty-six percent of workers were unsure if the triggered alarm provided enough time to identify an escape route.
- Q.7 Fifty-seven percent of workers felt that the AWARE system's alarm sound was not annoying.

6.2.1.2 Workers' hemodynamic responses. Workers' brain cortical activation was recorded and analyzed using the fNIRS method when different intrusion technologies were in place. Since the focus was on evaluating the effectiveness of each intrusion technology in terms of the auditory stimuli, the following results show workers' auditory perception after hearing the associated audio alarm. Figure 6.17 shows the trend

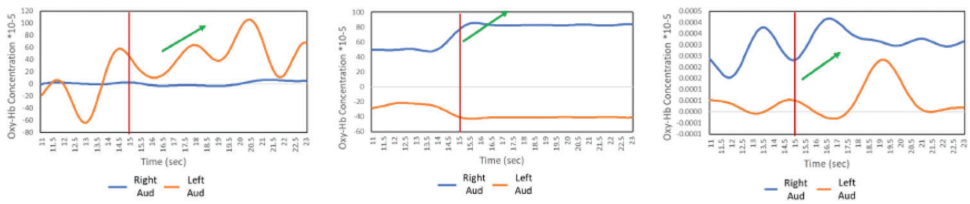


Figure 6.17 Changes in hemodynamic responses of primary participants in response to AWARE.

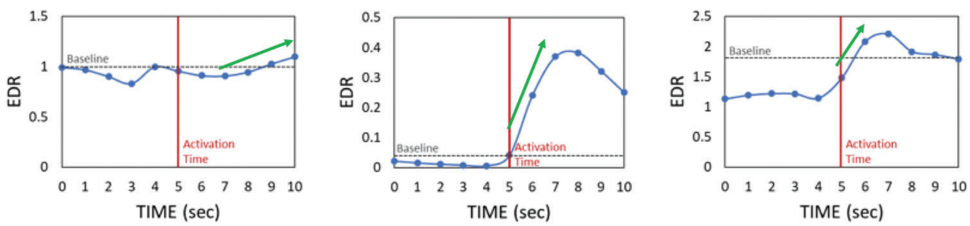


Figure 6.18 Changes in electrodermal responses of primary participants in response to AWARE.

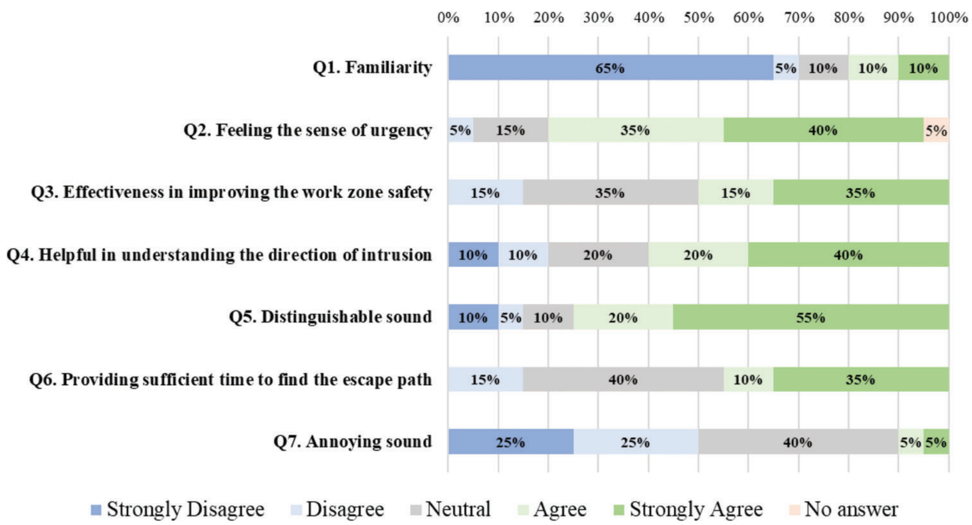


Figure 6.19 Summary of survey results for SonoBlaster.

for three workers' auditory activation of the right and left sides of the brain when AWARE was in place. The red vertical lines illustrate the activation time. It is critical to examine the changes in auditory cortices activation signals for primary participants to assess the effectiveness of each technology's auditory alarm in capturing worker's attention. Most of the workers demonstrated an increasing trend in their auditory activation after hearing the siren generated by AWARE. These results indicated that workers generally could hear the alarm sound of AWARE system, demonstrating that the alarm was loud enough. However, the question is whether this siren successfully conveyed a sense of urgency to workers to find the proper escape path.

6.2.1.3 Workers' risk perception. Physiological reactions (EDR) of primary workers are depicted in Figure 6.18. Most workers had signal increases after the alarm activation. However, it was also observed that workers had varied perception duration. Accordingly, two workers showed instant increases, while one illustrated a latency of approximately 2 seconds before their EDRs began to rise, i.e., a delay in risk perception. These results showed that workers perceived a certain level of risk from the activated alarm.

6.2.2 SonoBlaster

6.2.2.1 Workers' subjective feedback. The analysis of workers' feedback related to SonoBlaster is shown in Figure 6.19, and the associated interpretation is described below.

- Q.1 Only 20% of workers indicated familiarity with the SonoBlaster.
- Q.2 Seventy-five percent of workers reported feeling a sense of urgency when the alarm was triggered.

Q.3 Fifty percent of workers believed the SonoBlaster would effectively improve work zone safety, while 35% were unsure of its effectiveness.
Q.4 Twenty percent of workers felt the SonoBlaster did not assist in determining the direction of an intrusion. Meanwhile, 20% were unsure about its helpfulness in this aspect.
Q.5 Seventy-five percent of workers could distinguish the alarm sound of the SonoBlaster. However, some also noted that its sound was reminiscent of the air brakes on semi-trucks.
Q.6 Forty-five percent of workers were unsure if the triggered alarm provided enough time to identify an escape route.
Q.7 Fifty percent of workers felt that the SonoBlaster's alarm sound was not annoying.

6.2.2.2 Workers' hemodynamic responses. Figure 6.20 shows the trend for workers' auditory activation of the right and left sides of the brain while using the Sono Blaster technology. As shown, increasing trends can be seen in most workers' auditory activation after hearing the siren generated by SonoBlaster. These results showed that workers generally could hear the alarm sound of SonoBlaster. However, the question is whether this siren successfully conveyed a sense of urgency to workers to find the proper escape path.

6.2.2.3 Workers' risk perception. Figure 6.21 shows the primary workers' physiological concerning the activation of warning alarms. As illustrated, immediate reactions to the triggered alarm were observed across the workers, indicating prompt risk perceptions. Furthermore, while one worker exhibited a marginal elevation in the EDR signal, others illustrated a significant spike following the alarm's activation. These results indicated that workers perceived a certain level of risk from the activated alarm.

6.2.3 Intellicone

6.2.3.1 Workers' subjective feedback. The analysis of workers' feedback related to Intellicone is illustrated in Figure 6.22, and the associated interpretation is described below.

Q.1 Only 20% of workers indicated familiarity with the Intellicone system.
Q.2 Sixty-five percent of workers reported feeling a sense of urgency when the alarm was triggered.
Q.3 Fifty percent of workers believed the Intellicone system would effectively improve work zone safety, while 30% were unsure of its effectiveness.
Q.4 Twenty-five percent of workers felt the Intellicone system did not assist in determining the direction of an intrusion. Meanwhile, 15% were unsure about its helpfulness in this aspect.
Q.5 Sixty-five percent of workers could distinguish the alarm soud of the Intellicone.
Q.6 Twenty-five percent of workers were unsure if the triggered alarm provided enough time to identify an escape route. Meanwhile, 20% believed that the system was not helpful in this aspect.
Q.7 Sixty-five percent of workers felt that the Intellicone's alarm sound was not annoying.

6.2.3.2 Workers' hemodynamic responses. Figure 6.23 shows the trend for workers' auditory activation of the right and left sides of the brain. Increasing trends can be seen in all workers' auditory activation after hearing the siren. This shows the siren generated by Intellicone was effective enough to be heard by workers. However, the question is whether this siren successfully conveyed a sense of urgency to workers to find the proper escape path.

6.2.3.3 Workers' risk perception. The physiological responses of primary workers are exhibited in Figure 6.24. Most workers showed gradual increases after the activation of the alarm. Furthermore, these results indicated that workers perceived a certain level of risk from the activated alarm.

6.2.4 Workers' Reaction to the Warning Alarm

It must be noted that the reaction of workers to the alarms after hearing and perceiving the risk can be different due to many factors, e.g., their risk tolerance, the alarm distinctiveness, and their engagement in the experiments. Workers' reactions to the warning alarms were assessed by examining video recordings. As illustrated in Table 6.2, workers were able to notice the activation of alerts and directed their visual attention toward the sources of the sound. While more than 80% of workers looked towards the sound sources when the AWARE system and SonoBlaster were activated, only 60% did so when the Intellicone was activated. However, irrespective of the technology used, workers did not consistently exhibit safe behavior in response to the triggered alarms. Specifically, workers often paused their activities, surveyed their surroundings, and continued their tasks. This behavior implies they were uncertain about how to engage correctly with the intrusion alert systems. Considering the unfamiliar-

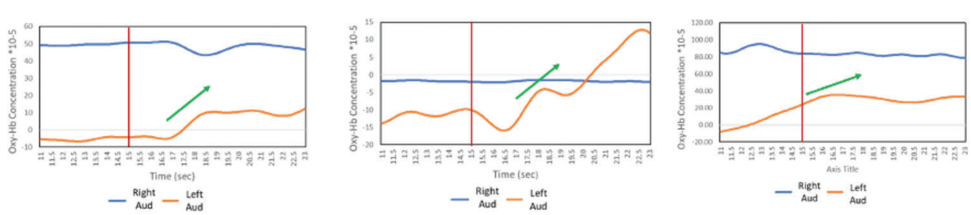


Figure 6.20 Changes in hemodynamic responses of primary participants in response to SonoBlaster.

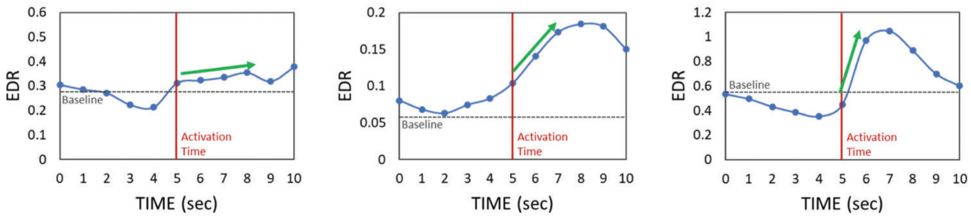


Figure 6.21 Changes in electrodermal responses of primary participants in response to SonoBlaster.

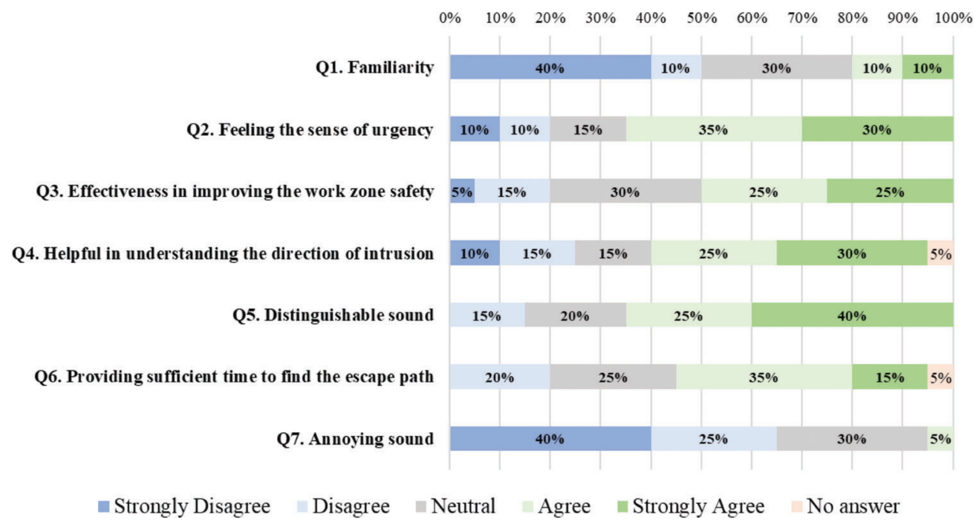


Figure 6.22 The summary of survey results for Intellicone.

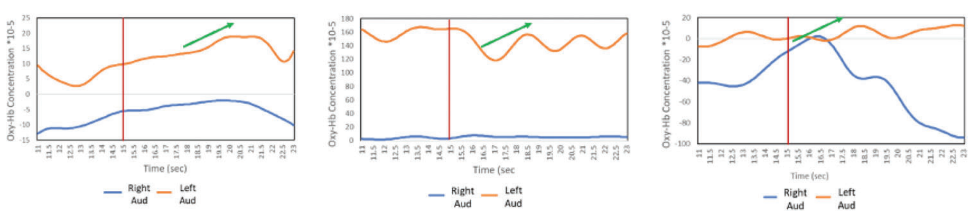


Figure 6.23 Changes in hemodynamic responses of primary participants in response to Intellicone.

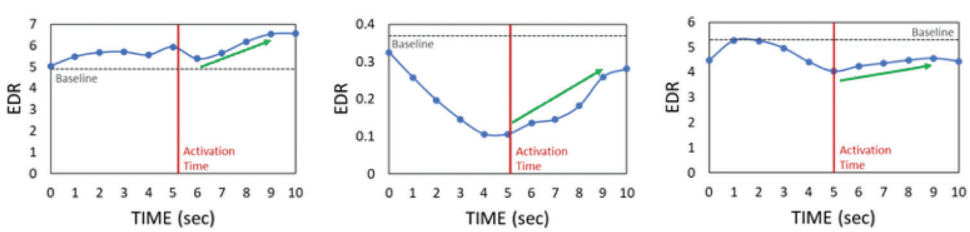


Figure 6.24 Changes in electrodermal responses of primary participants in response to Intellicone.

TABLE 6.2
Effectiveness of intrusion alert technologies in grabbing workers' visual attention

Criteria	AWARE	SonoBlaster	Intellicone
No. of workers exposed to the alarms	28	20	20
No. of workers who directed their attention toward the alarm source	25	16	12
Percentage of workers who directed their attention toward alarm source	89%	80%	60%

ity of workers with these technological advances, this observation suggests that additional training regarding the alert systems might be necessary to ensure workers develop situational awareness skills by properly distributing their attention spatially and learning how to appropriately interact with the intrusion technologies before placing them.

6.2.5 Functional Limitations of Intrusion Alert Technology Based on Field Observation

During the on-site tests, several functional limitations were observed. For instance, the haptic feedback of AWARE's WorkTrax device was deemed insufficient, especially when workers were engaged in heavy construction tasks, rendering it ineffective in alerting them to intrusions. Regarding the Intellicone, its highly sensitive smart cones were prone to activation due to vibrations from road-cutting activities, resulting in unwarranted PSA unit triggers and false positives. However, this issue is resolved in the new version of the smart cones after sharing these results with the manufacturer. Additionally, occasional connectivity issues were noted with the AWARE system, and the accompanying software application struggled to consistently modify system settings. Lastly, it was also observed that all alerts were not effective for operators, while ground workers could recognize the alarms.

6.3 Conclusion

This study employed various approaches, incorporating data from surveys and interviews, wearable technologies, and video recordings, to comprehensively evaluate the effect of intrusion alert systems on workers' responses within work zone incidents. The survey results revealed that workers were generally able to differentiate the alarm sound emanating from the intrusion alert technologies. Consequently, this differentiation contributed to their heightened sense of urgency. However, there were also challenges in distinguishing sounds from devices like SonoBlaster and AWARE, indicating a potential area for enhancement in sound distinctiveness.

Aligned with the outcomes derived from subjective assessments, the analysis of psychophysiological signals exhibited a noticeable increase immediately following the activation of alarms. This observed increase indicated that workers not only heard the warning alarms but also perceived the associated risks they signified. However, it is noteworthy that the observation of workers' reactions yielded a distinctive insight. Despite the activation of the alert sound and their awareness, the majority of workers exhibited a tendency to persist with their ongoing tasks rather than evacuating the work zone.

These insights underscore the importance of training initiatives to teach construction workers to interpret auditory and visual cues accurately, understand their implications, and determine the most effective evacuation routes. Simultaneously, there is an evident need for manufacturers to refine their systems, ensuring they address identified limitations and optimize their effectiveness.

It should be noted that this study, being an initial investigation at the jobsite, primarily focused on assessing whether workers could hear the alarm and perceive the associated risk in an ongoing construction environment. Consequently, all technologies were manually triggered instead of being activated by an actual intrusion, prioritizing worker safety. However, the absence of a real intrusion might have influenced the workers' escape behavior. Therefore, it is recommended to further investigate workers' reactions to the triggered alarms, including examining the relationship between their reaction time and varying vehicle speeds. Such an investigation would provide deeper insights into the effectiveness of these technologies.

7. DECISION-MAKING FRAMEWORK FOR OPTIMAL TECHNOLOGY SELECTION

Based on the insights from previous analyses, we have developed a decision-making framework to assist transportation safety professionals and key decision-makers in choosing the most appropriate work zone intrusion alert technologies. Illustrated in Figure 7.1, this framework encompasses several stages: defining evaluation criteria, gathering subjective and objective assessments, determining weighting factors, and conducting a benefit-cost analysis (BCA). Initially, 11 principal attributes linked to the intrusion alert technology were determined from the findings of earlier tasks. After this, an objective rating for each attribute was deduced for every technology based on test outcomes. Concurrently, INDOT safety professionals were enlisted to provide ratings for these attributes, considering both overall effectiveness and the safety perspective. This is crucial as the significance of each attribute can differ based on varying objectives. These collected ratings were then harnessed to determine weighting factors, which signify both the importance of each attribute and its performance. In the BCA, these weighting factors related to the safety aspect were employed to outline the potential safety benefits of the intrusion alert technology. Finally, a metrics-driven decision-making tool was crafted, factoring in the overall effectiveness of the weighting factors and the results of the BCA. The subsequent sections will deliver a more detailed explanation of each stage.

7.1 Step 1: Development of Evaluation Criteria

The attributes that determine the preference for each intrusion alarm were collated from extensive tests, manufacturers' details, and reviews of past studies. Eleven pivotal criteria were underscored, focusing on the functionality, performance, and cost of the alert technologies. These criteria are paramount for comprehensive consideration before any investment and deployment commitments. Table 7.1 provides details of

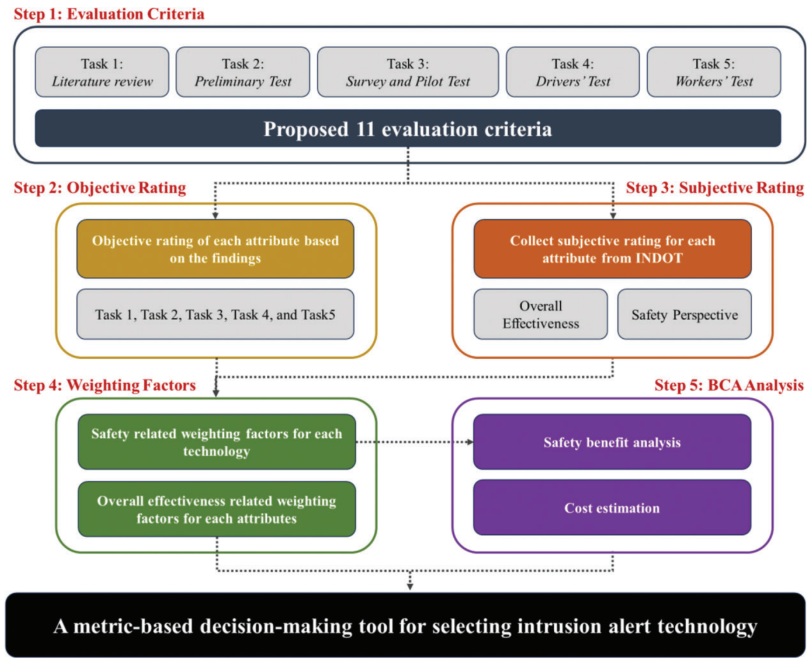


Figure 7.1 Overview of decision-making framework.

these evaluation criteria, illustrating their ideal characteristics and the phase in which each was recognized. The criteria encompass ease of deployment, transportation and storage simplicity, work zone coverage, alarm accuracy, alarm noticeability considering sound level, type and distinctiveness, overall effectiveness, cost implications, and the availability of relevant incident data.

7.2 Step 2: Rating Based on the Observed Testing Results

For choosing the optimal intrusion technology/combination of intrusion technologies to meet specific work zone needs, it's imperative to undertake a thorough evaluation based on the ideal characteristics these technologies exhibit. Given the distinct performance of the four intrusion technologies, a metrics-driven decision-making framework becomes essential. Table 7.2 offers a comprehensive analysis, showcasing the preferred intrusion technology according to evaluation criteria and their intrinsic characteristics.

Then, based on the evaluation criteria and preferences established through observation (Table 7.2), the ratings for the attributes of each technology were determined. Table 7.3 provides an overview of the ratings for each intrusion technology. In this table, the most favored technology for each criterion is designated with a rating of 4, whereas the least favored receives a rating of 1. Additionally, any criteria deemed "not applicable" were assigned a rating of 0.

7.3 Step 3: Rating Based on the Obtained Inputs from INDOT Safety Professionals

While every attribute is pertinent in selecting the right intrusion alert technology, the significance of each criterion can change based on specific priority, such as a safety perspective or overall effectiveness. Recognizing this variability, the research team disseminated surveys to INDOT safety professionals, prompting them to rate each attribute on a scale from 1 (lowest) to 5 (highest), both from a *safety* viewpoint and regarding *overall effectiveness*. The average of these responses was then harnessed to compute the weightage for each attribute based on its rating. Table 7.4 displays the average ratings sourced from the professionals and the corresponding weightage. The method for determining the weightage was derived using Equation 7.1.

$$W_n = \left[\frac{R_2}{\sum_{i=1}^{N_{Rating}} i} \right] \quad \text{(Eq. 7.1)}$$

Where,
W_n = Weight of the attribute based on rating.
n = Number of criteria.
N_{Rating} = Highest value in Likert rating.
R_2 = Rating of the attribute.

7.4 Step 4: Calculation of Weighting Factors

7.4.1 Weighting Factors of Each Attribute Concerning Overall Effectiveness

In order to derive realistic weighting factors for each attribute of intrusion alert technologies, both the ratings from Table 7.3 and the weights from Table 7.4 were utilized. For the computational procedure, the rating of each attribute for every technology was multiplied by its corresponding weightage concerning

TABLE 7.1
Proposed evaluation criteria and ideal characteristics for selecting intrusion alert technologies

Evaluation Criterion	Description	Ideal Characteristic	Phase–Within This Research Project
Deployment	Efforts required to set up the technology to be ready for use	Easy, and takes less time	Pilot-controlled testing, literature review
Work Zone Coverage	An area that can be covered once deployed	Provide maximum work zone coverage	Pilot-controlled testing, literature review
Transportation and Storage	Transportation and storage before/after use	Ease in conveying, removal after use, and storing	Preliminary, pilot-controlled testing, literature review
Sound Loudness	The loudness of the alarm	Louder alarms are preferred	Preliminary, pilot-controlled testing
Sound Distinctiveness	The uniqueness of the alarm sound among highway traffic noise	Noticeable in the presence of traffic and construction background noise	Evaluation survey, Preliminary testing
Frequency of False Alarms	Rate of false positives and false negatives	Very few or no false alarm	Literature review, pilot-controlled testing
Effectiveness in Alerting the Drivers	Effectively warn the driver about the potential risk	Create a sense of urgency in drivers to react by braking	Driver testing
Cost of the Technology	The overall cost of technology	Minimum cost while providing greater work zone coverage	Literature review, manufacturers' website/info
Timely Communication with Supervisor and Incident Database for Future Assessment	Availability of incident database for further investigation, and communicating the incident data for first responses and field operation	Tracking and storing the incident data, communicating the incident occurrence data in real-time with first respondents and officials for better response, creating a reliable database for future analysis and learning	Preliminary, pilot-controlled testing, literature review, driver testing
Alert Type	Variety of alert types (visual, audio, haptic/vibration)	Multiple alarm types are preferred	Preliminary, pilot-controlled testing
Effectiveness in Alerting the Workers	Effectively warn the worker about the intrusion	Create a sense of urgency in workers to find proper escape path	Active work zone testing

overall effectiveness. Subsequently, these derived values were normalized to fit within a range of 0 to 1 to determine the final weighting factor. This normalization accounted for variations in each attribute because the minimum and maximum values could shift based on the presence of a 0 (indicating "not applicable"). Table 7.5 illustrates the summary of the final weighting factors. These values will be utilized in decision-making to help professionals make informed decisions.

7.4.2 Weighting Factors of Each Intrusion Alert Technology Concerning Safety Perspective

Regarding the weighting factors related to safety, the overall factor for each technology was determined instead of individual attribute values. This approach ensures that the results represent each technology's cumulative anticipated safety performance. These cumulative values will be instrumental in the safety benefit analysis of the following sections. To compute this, the rating for each attribute of a given technology was multiplied by its respective weightage from a safety standpoint. After this, cumulative values were normalized to fit within a 0 to 1 range, resulting in the final safety-related weighting factor. Table 7.6 provides the safety-focused weighting factor for every technology.

7.5 Step 5: Benefit-Cost Analysis

7.5.1 Safety Benefit Analysis

Studies have highlighted the significant influence of cost and anticipated benefits in selecting and accepting intrusion alert technology. Considering this, a benefit-cost analysis was conducted, adhering to the USDOT's BCA (benefit-cost analysis) guidance (USDOT, 2023). This analysis aimed to assess the potential merits of implementing intrusion alert technologies, specifically reducing fatalities and injuries in work zones. Consequently, the expected safety benefits were calculated utilizing the following Equation 7.2.

$$\begin{aligned} \textit{Safety Benefits} &= \textit{Baseline Risk} \times \textit{Risk Reduction} \\ &\quad \times \textit{Expected Consequences} \end{aligned} \qquad \text{(Eq. 7.2)}$$

In order to determine the safety benefit, it is essential to estimate a baseline risk, which represents the existing conditions, as a reference point for measuring the risk reduction achieved by the project. To ensure precise results for the Indiana Department of Transportation (INDOT), the analysis focused on the work zone conditions in the state. Historical work zone accident data from 2016 to 2020 in Indiana were summarized in Table 7.7. However, it must noted that the final decision support platform can be modified using any

TABLE 7.2
Multi-criteria evaluation matrix to select the most effective intrusion technology

Evaluation Criterion	SonoBlaster	AWARE	Intellicone	WAS
Deployment	Takes time to set up and mount units to traffic cones. Once attached, then very easy to deploy and replace cartridges	Very straightforward deployment, easy to set up and get connected to servers	Takes time to insert batteries in smart cones. Easy to get connected to servers (As the number of cones increases, more time it will take to setup)	Simple to deploy hoses and alarm units in a work zone
Work Zone Coverage	Not applicable	It can be extended up to 510 feet (Between Sentry and PSDs)	Unlimited coverage with more smart cones	Up to 400 feet (Between alarm unit and pressure sensor)
Transportation and Storage	Very difficult to transport as traffic cones cannot be stacked on each other.	Very easy to transport and store	Requires larger space to store and transport due to many smart cones. Batteries are needed to be removed after each use.	Hoses get entangled if placed together. Batteries need to be removed while transporting.
Sound Loudness	Loudest (~85 dB)	Second loudest (~81 dB)	Low sound level (~69 dB)	Moderately loud (~75 dB)
Sound Distinctiveness	Similar to vehicle horn or braking sound, and not as effective as expected in the presence of background traffic noise	Can easily be confused with an emergency vehicle's siren	Unique 3-tone sound that can easily cut through background traffic noise	A short pulsing siren alarm can be recognized in the presence of background noise.
Frequency of False Alarms	High false positives and false negatives rates. More false negatives in cold weather.	Very low false-positives or false-negatives rate.	Moderate false positives rate due to sensitivity of smart cones	Very high false negative rate
Effectiveness in Alerting the Drivers	Very effective due to its loud sound alarm. When impacted, if the sound alarm is close to drivers and can be heard clearly	Can be heard only when drivers are passing near the AWARE unit	Effective to being heard by drivers due to its unique tone and the unique option of having more PSA units.	Not effective at all, even if the sound alarm unit is oriented toward drivers
Cost of the chronology	$1,140.62	$15,000 (leasing option is available)	$45–$100 per day on a lease basis	$1,937.50
Timely Communication with Supervisor and Incident Database for Future Assessment	Not applicable	Recording and storing the incident data, communicating the incident occurrence data in real-time with first respondents and officials for better response, creating a reliable database for future analysis and learning	Storing the incident data, communicating the incident occurrence data in real-time with first respondents and officials for better response, creating a reliable database for future analysis and learning	Not applicable
Alert Type	Audio alert only	Audio alert, visual alert, and haptic alert	Audio alert, visual alert	Audio alert, visual alert, and haptic alert
Effectiveness in Alerting the Workers	Very effective due to its loud sound alarm	Effective to be heard by workers due to sound loudness	Moderately effective due to its unique tone and low sound level	Not applicable

Note:
Most preferable is in green.
Preferable is in orange.
Somewhat preferable is in purple.
Least preferable is in blue.

TABLE 7.3
Rating of each intrusion technology determined through observed testing results

Evaluation Criterion	SonoBlaster	AWARE	Intellicone	WAS
Deployment	2	4	1	3
Work Zone Coverage	0	3	4	2
Transportation and Storage	1	4	2	3
Sound Loudness	4	3	1	2
Sound Distinctiveness	2	1	4	3
Frequency of False Alarms	2	4	3	1
Effectiveness in Alerting the Drivers	4	2	3	1
Cost of the Technology	4	1	2	3
Timely Communication with Supervisor and Incident Database for Future Assessment	0	4	3	0
Alert Type	1	4	2	3
Effectiveness in Alerting the Workers	4	3	2	0

TABLE 7.4
Rating of each attribute obtained from INDOT safety professionals

	Overall Effectiveness		Safety Perspective	
Attributes	**Rating (1: Lowest and 5: Highest)**	**Weightage Based on Rating**	**Rating (1: Lowest and 5: Highest)**	**Weightage Based on Rating**
Deployment	4	0.267	4	0.267
Work Zone Coverage	4	0.267	4	0.267
Transportation and Storage	3	0.200	2	0.133
Sound Loudness	4	0.267	4	0.267
Sound Distinctiveness	5	0.333	4	0.267
Frequency of False Alarms	4	0.267	4	0.267
Effectiveness in Alerting the Drivers	3	0.200	3	0.200
Cost of the Technology	3	0.200	2	0.133
Timely Communication with Supervisor and Incident Database for Future Assessment	3	0.200	2	0.133
Alert Type	4	0.267	3	0.200
Effectiveness in Alerting the Workers	5	0.333	5	0.333

TABLE 7.5
Weighting factors for each attribute developed based on the testing results and INDOT professionals' input

Evaluation Criterion	SonoBlaster	AWARE	Intellicone	WAS
Deployment	0.37	0.79	0.16	0.58
Work Zone Coverage	0.00	0.60	0.80	0.40
Transportation and Storage	0.11	0.58	0.26	0.42
Sound Loudness	0.79	0.58	0.16	0.37
Sound Distinctiveness	0.47	0.21	1.00	0.74
Frequency of False Alarms	0.37	0.79	0.58	0.16
Effectiveness in Alerting the Drivers	0.58	0.26	0.42	0.11
Cost of the Technology	0.58	0.11	0.26	0.42
Timely Communication with Supervisor and Incident Database for Future Assessment	0.00	0.60	0.45	0.00
Alert Type	0.16	0.79	0.37	0.58
Effectiveness in Alerting the Workers	1.00	0.75	0.50	0.00

other database. Based on the data, it was determined that, on average, there were 20 fatal collisions and 779.4 non-fatal collisions annually. These values were utilized as the baseline risk for the safety benefit analysis. To determine the expected consequence, the rates of fatalities and injuries per collision were extracted from the data, resulting in rates of 1.11 fatalities and 1.53 injuries per collision. Then, these rates were multiplied by the associated values of reduced fatalities ($11,800,000) and injuries ($213,900) provided by the USDOT's BCA guidance. This calculation allowed for the estimation of the safety benefits associated with different risk reduction rates, as illustrated in Table 7.8. The calculated safety benefits were then utilized in the subsequent benefit-cost analysis to assess the overall merits of implementing intrusion alert technologies. For this study, the safety benefit associated with the reduction rate of 10% was used in BCA.

7.5.2 Cost Estimation

To conduct the benefit-cost analysis, a hypothetical work zone closure for a 12-foot-wide lane was considered (Figure 7.2). The calculation of capital cost and annual operation and maintenance cost was based on the work zone layout and the work zone traffic control guidelines provided by the Indiana Department of Transportation. However, it must be noted that in the developed decision support platform, the layout (lane closure and channelizing required) can be modified for any project. In the default layout, firstly, the total number of traffic cones required was determined by referring to the INDOT work zone layout. This analysis resulted in a total of 21 cones, with 16 cones allocated for the merging taper area and 5 cones for the buffer and workspace. Next, the number of units needed to cover the designated work zone was estimated based on previous performance test results. The estimation results and their associated capital and operation costs for each technology are summarized in Table 7.9. Pertaining to maintenance cost, this study adopted the assumptions outlined in the report from the Tennessee Department of Transportation (DOT) and information from manufacturers (Mishra et al., 2021). The estimated costs were then used in the subsequent benefit-cost analysis to assess the overall merits of implementing intrusion alert technologies.

TABLE 7.6
Weighting factors for each technology that was developed based on the testing results and INDOT professionals' input

Intrusion Alert Technology	Weighting Factor (Safety Perspective)
SonoBlaster	0.39
AWARE	0.50
Intellicone	0.41
WAS	0.31

7.5.3 Calculation of Benefit-Cost Ratio (BCR)

Drawing from the values identified in the previous steps, the benefit-cost ratio is then calculated to display the correlation between the comparative costs and benefits of deploying intrusion alert technology, all denominated in monetary terms. Table 7.10 offers a detailed breakdown of each value used in this assessment. When determining the cost-associated value, we sourced the peak number of work zones operated concurrently by INDOT from their historical work zone data 2017–2023. The motivation for using this specific value stemmed from accident data, which revealed the aggregate number of fatalities and injuries originating from all work zones within Indiana. Consequently, for a comprehensive cost evaluation, it was imperative to consider that every work zone would be equipped with intrusion alert technology. Historical data spotlighted that in June 2018, Indiana hosted 3,735 work zones (only in June), marking the highest count within the chosen time frame. Delving deeper into this data, June 11 of the same year witnessed 314 active work zones, representing the peak for daily work zones in the state during the period under consideration. As a result, 314 work zones were selected to represent the work zones that would be simultaneously safeguarded by intrusion alert technology. These zones encapsulate various road construction endeavors, spanning pavement works, vegetation management, traffic markings, and repairs. Furthermore, it is essential to highlight that the BCR analysis in our study operated on the assumption that every work zone

TABLE 7.7
Work zone fatalities and injuries that occurred between 2016 and 2020 in Indiana

Year	Work Zone Fatal Collision	Work Zone Fatalities	Work Zone Non-Fatal Collision	Work Zone Non-Fatal Injuries
2016	15	15	804	1,237
2017	24	27	924	1,469
2018	17	18	793	1,194
2019	25	29	806	1,192
2020	19	22	570	857
Average	20	22.2	779.4	1,189.8
Fatality per Collision	–	1.11	–	–
Injury per Collision	–	–	–	1.53

TABLE 7.8
Safety benefits with various risk reduction rates

	Risk Reduction Rates				
Percentage	**10%**	**20%**	**30%**	**40%**	**50%**
Fatality Benefit ($/year)	26,196,000	52,392,000	78,588,000	104,784,000	130,980,000
Injury Benefit ($/year)	25,494,099	50,988,198	76,482,297	101,976,397	127,470,496
Total Safety Benefit ($/year)	51,690,099	103,380,198	155,070,297	206,760,397	258,450,496

	Risk Reduction Rates				
Percentage	**60%**	**70%**	**80%**	**90%**	**100%**
Fatality Benefit ($/year)	157,176,000	183,372,000	209,568,000	235,764,000	261,960,000
Injury Benefit ($/year)	152,964,595	178,458,695	203,952,794	229,446,893	254,940,993
Total Safety Benefit ($/year)	310,140,595	361,830,695	413,520,794	465,210,893	516,900,993

Note:
Fatality benefit: 20 collision/year × risk reduction rate × (1.11 fatalities/collision × $11,800,000).
Injury benefit: 779 collision/year × risk reduction rate × (1.53 injuries/collision × $213,900).
Total safety benefit: fatality benefit + injury benefit.

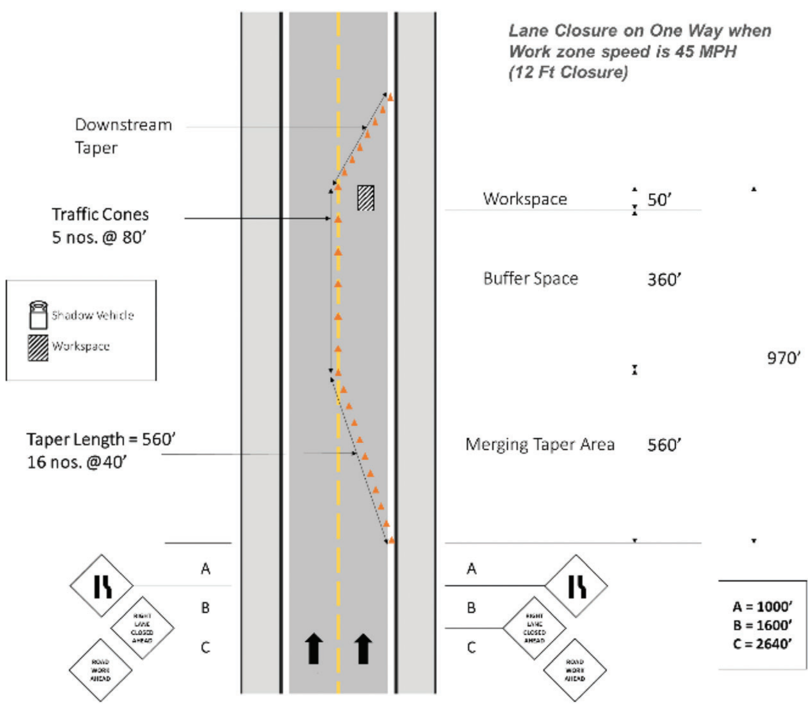


Figure 7.2 The hypothetical work zone closure for BCA analysis.

would be equipped with a uniform number of units, derived from a theorized work zone layout.

Table 7.11 presents a summary of the BCR (Benefit-Cost Ratio) analysis. As depicted, every technology boasts a BCR value exceeding 1, signifying that the anticipated benefits surpass the investment costs. Notably, SonoBlaster and WAS stand out with a significantly higher BCR value, which is attributable to their relatively lower initial costs than other technologies. This result underscores that the outcomes of a benefit-cost analysis (BCA) should not be the sole criterion for selecting an appropriate technology.

Consequently, within this report, the BCA findings were incorporated as just one component of the

TABLE 7.9
Cost estimation for each intrusion alert technology

Components	Number of Units	Unit Cost ($)	Total Cost	Comments
		AWARE		
		Capital		
AWARE System	2	$15,000.00	$30,000.00	–
Worktrax Alarms	8	–	–	Four sensors included with the main system
Total	–	–	$30,000.00	
		Annual Maintenance Cost		
Worktrax Alarms	8	$150.00	$1,200.00	All Worktraxs' replaced
Total	–	–	$1,200.00	–
		Intellicone		
		Capital		
PSA	2	$2,640.00	$5,280.00	–
Sentry Laser	1	$1,950.00	$1,950.00	–
Smart Cones	21	$100.00	$2,100.00	–
Batteries	21	$2.50	$52.50	–
Total	–	–	$9,382.50	–
		Annual Maintenance Cost		
Online Platform	1	$2,436.5	$2,436.50	–
Batteries	231	2.5	$577.50	Each battery lasts for 1 month (11 months * 21 = 231)
Total	–	–	$3,014.00	–
		SonoBlaster		
		Capital		
Alarm Unit	21	$98.95	$2,077.95	–
C02 Cartridge	21	$2.30	$48.30	–
Total	–	–	$2,126.25	–
		Annual Maintenance Cost		
CO2 Cartridge	100	2.3	$230.00	–
Total	–	–	$230.00	–
		WAS		
		Capital		
Pneumatic Sensor PAC	2	$550.00	$1,100.00	–
PSD	8	$150.00	$1,200.00	–
Total	–	–	$2,300.00	–
		Annual Maintenance Cost		
PSD	8	150	$1,200.00	All PSDs replaced
Total	–	–	$1,200.00	–

TABLE 7.10
Description of each term used in BCR analysis

Terms	Description
Total Capital Cost (TCC)	Capital cost for a single work zone (Table 7.9) × number of work zones concurrently covered by each intrusion alert technology
Safety Benefit (SB)	Safety benefit related to a 10% reduction rate (Table 7.8)
Total O&M Cost (TOMC)	O&M cost for a single work zone (Table 7.9) × number of work zone concurrently covered by intrusion alert technology
Benefit	Safety Benefit – Total O&M cost
Weighted Benefit (WB)	Benefit × Weighting factors concerning safety perspective (Table 7.6)
Net Present Value (NPV)	Weighted Benefit – Total Capital Cost
Benefit-Cost Ratio (BCR)	Weighted Benefit / Total Capital Cost

TABLE 7.11
Summary of benefit-cost ratio analysis

Technology	TCC ($)	SB ($)	TOMC ($)	Benefit ($)	WB ($)	NPV ($)	BCR
AWARE	9,420,000.00	51,690,099.00	376,800.00	51,313,299.00	25,889,891.77	16,469,891.77	2.75
Intellicone	2,946,105.00	51,690,099.00	946,396.00	50,743,703.00	20,989,440.79	18,043,335.79	7.12
WAS	722,200.00	51,690,099.00	376,800.00	51,313,299.00	15,860,474.24	15,138,274.24	21.96
SonoBlaster	667,642.50	51,690,099.00	72,220.00	51,617,879.00	19,943,271.43	19,275,628.93	29.87

Figure 7.3 Overview of the developed dashboard.

comprehensive decision-making tool. Furthermore, since all the technologies have BCR values above 1, any of them would be a viable choice from a benefit-cost perspective. Additionally, it is worth noting that a reduction rate of 10% was employed in this analysis. Thus, benefits would correspondingly rise if the reduction rate were to increase, leading to an even more favorable BCR value. The BCR ranking was incorporated into Table 7.5 to create the final decision matrix. This matrix serves as the foundational framework for the suggested decision-making tool.

7.6 A Metric-Based Decision-Making Platform

The concluding phase of this task was centered around combining the discoveries from Sections 7.1 to 7.5 to construct an interactive decision-making platform. This dashboard aggregates all project outcomes, providing INDOT and contractors with the clarity needed to carefully select the proper work zone intrusion alert technologies. Illustrated in Figure 7.3, this dashboard was developed utilizing Excel Macros and VBA.

The dashboard serves as a tailored solution for INDOT, streamlining the selection process of the optimal intrusion alert technology suitable for varying scenarios. This intuitive platform ensures users can access consolidated data efficiently, which, in turn, facilitates informed decision-making. The dashboard comprises two primary sections: “Final Rank” and “Customization.” Users can effortlessly specify rank and rate for individual attributes contingent on project specifics, after which the ranking system autonomously determines the most preferred intrusion alert technologies. It is worth noting that the dashboard’s default settings are rooted in INDOT’s data. If users wish to adjust foundational values based on unique conditions, the “Customization” feature allows for seamless integration of new inputs in a structured manner. The detailed information and guide for the dashboard can be found in Appendix B.

8. CONCLUSION

The comprehensive exploration of intrusion alert technologies, as detailed in this report, shines a spotlight on the evolving dynamics of work zone safety. Our holistic approach, spanning literature reviews to wearable technology assessments, reveals the advancements in this field and the existing gaps that call for immediate attention.

One of the most significant findings is the pressing need to fine-tune these alert systems to function optimally in varied real-world scenarios. Most current evaluations have taken place under controlled environments, often sidelining the nuanced challenges that real-world conditions present. Sound distinction, for example, is pivotal. While specific devices like the SonoBlaster are loud, their efficacy diminishes if the alarm sound has inconsistent duration and is not distinctive enough to alert workers and drivers to the noise of a typical work zone.

This leads to a significant practical implication—while technology is making strides in enhancing work zone safety, human behavior remains a variable that is challenging to predict and influence. The study highlighted that even when workers hear and recognize these alarms, their immediate response is not always to find a proper escape path—indicating a gap between technology's intent and user behavior. Training workers to react appropriately to alarms, understanding the severity of potential risks, and choosing the safest escape routes emerge as a top priority. From a driver's perspective, while these technologies aim to induce urgency and caution, the findings from various field tests suggest that the current systems fall short. Weak visual cues, coupled with alarms that often blend into environmental noise (e.g., some workers noted that the alarm sound of the AWARE system was reminiscent of an emergency vehicle's alarm), render the systems ineffective in fully altering driver behavior.

Furthermore, our investigations underline that no singular technology is a universal solution. The efficacy of these systems varies with specific work zone environments and conditions, reinforcing the need for a flexible decision-making matrix that accommodates these variables. The creation of an interactive dashboard, rooted in the findings from this study, addresses this necessity, ensuring that INDOT and contractors can make informed decisions tailored to each project's unique demands.

Fundamentally, the practical thrust of this report underscores a two-pronged approach for the future: refine and innovate the technological aspects of intrusion alert systems and invest in behavioral training for both workers and drivers. While technology provides the tools, the synergy between technology and human understanding will truly redefine safety standards in work zones.

8.1 Limitations of This Research

This research, while comprehensive in its approach, presents several notable constraints. To begin with, our initial trials of these technologies took place within a simulated off-road work zone, set against the backdrop of mild traffic noise, devoid of the more pronounced sounds associated with heavy machinery. Furthermore, the simulated environment mirrored INDOT's archetype of a straight work zone. This specificity may constrain the extrapolation of our results to more dynamic settings such as mobile or curved work zones. However, the field testing of workers could provide very insightful findings. This study adopted a singular approach in terms of technology evaluation, testing each technology independently without exploring potential synergies that might arise from their combined use. Moreover, existing research underscores the potential variability in driver reaction times influenced by age. However, our study could not explore this facet in depth, attributed to the narrow age spectrum of our participants.

8.2 Recommendation for Future Research

While the efficacy of intrusion technologies is evident, a deeper dive through expansive field testing across diverse traffic densities, operation modalities, and work zone configurations could sharpen our understanding. As the landscape of work-zone safety evolves, integrating emerging technologies is a focal point for road operators. However, current technology applications exhibit notable constraints. Firstly, the disparate nature of these systems—from intrusion technologies to TMAs, wearables, and signage—means they function individually, lacking the capacity for intercommunication. Secondly, the absence of a holistic, integrated solution tailored to current traffic scenarios further accentuates the need for advancement. Envisioning the future, immense potential lies in harnessing an integrated IoT-driven work zone framework. Such a system, fusing smart channelization tools with intrusion technologies and worker-centric wearables, is promising to enhance safety across mobile and stationary work zones.

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APPENDICES

Appendix A. Survey Questionnaire

Appendix B. A Metric Based Decision-Making Tool

APPENDIX A. SURVEY QUESTIONNAIRE

A.1 Online Evaluation Survey Report

- **Demographic Information:**

1. Please select an organization from the following list you are working with.
    - o Department of Transportation (DOT)
    - o American Society of State Highway and Transportation Officials (AASHTO)
    - o Institute of Transportation Engineers (ITE)
    - o National Highway Traffic Safety Administration (NHTSA)
    - o Federal Highway Administration (FHWA)
    - o Construction Company
    - o Other
      Please Specify: _____________

2. Which of the following best describes your job title in the organization?
    - o Supervisor
    - o Executive Manager
    - o Equipment Operator
    - o Engineer
    - o Construction Foreman
    - o Construction Worker
    - o Other
      Please Specify: ____________

3. How many years of experience do you have in Highway Construction/Operation/Maintenance, etc.?
    - o 0 to 5 years
    - o 5 to 10 years
    - o 10 to 15 years
    - o 15 to 20 years
    - o 20 to 25 years
    - o More than 25 years

4. In which state is your job located?

Drop down List

- **Technologies Used:**

1. Which of the following technologies have you used before in your role to improve the work zone safety in Highway Construction/Operation/Maintenance? (Please select all that apply)
    - ☐ SonoBlaster
    - ☐ Traffic Guard Worker Alert System (WAS)
    - ☐ Advance Warning and Risk Evasion (AWARE)
    - ☐ Intellicone
    - ☐ None of these

- Effectiveness of the Technology:

Answer the following questions with respect to perceive the degree to which it was successful to avoid accidents due to intrusion of vehicles in the work zone.

1. **<u>Before</u>** using this technology, what was your <u>expected effectiveness</u> of it to improve the work zone safety?
   - o Very Effective
   - o Effective
   - o Moderately Effective
   - o Slightly Effective
   - o Not Effective at all

2. **<u>After</u>** using this technology, how would you rate its effectiveness to improve work zone safety?
   - o Very effective
   - o Effective
   - o Moderately effective
   - o Slightly effective
   - o Not effective at all

3. On which type of road alignment do you think this technology works well? (Please select all that apply)
   - ☐ On a straight road alignment
   - ☐ On a right curve road alignment
   - ☐ On a left curve road alignment
   - ☐ None

4. For what type/s of operation duration would you like to recommend this technology? (Please select all that apply)
   - ☐ Short duration highway work zones operation
   - ☐ Moderate duration highway work zones operation
   - ☐ Long duration highway work zones operation
   - ☐ None
   - ☐ Other _________

- **Pre-Deployment of the Technology:**

Please rate the following items on a scale of 1 to 5, 1 being Extremely higher and 5 being Extremely lower.

	Extremely Higher	Higher	Moderate	Lower	Extremely Lower	Don't Know
	1	2	3	4	5	
Time taken to fully set up the system	O	O	O	O	O	O
Time taken to fully retrieve the system (i.e., to dispose it back to storage)	O	O	O	O	O	O

- **Deployment of the Technology:**

Please rate the following items on a scale of 1 to 5, 1 being very difficult and 5 being very easy.

	Very Difficult	Difficult	Moderate	Easy	Very Easy	Don't Know
	1	2	3	4	5	
Deployment on long term lane and shoulder closure (Heavy traffic highways)	O	O	O	O	O	O
Deployment on short term lane and shoulder closure (Light traffic highways)	O	O	O	O	O	O
Deployment on narrowed Lanes (Highways with low-speed limit)	O	O	O	O	O	O

- **Practicality and Reliability of the Technology:**

Please rate the following items on a scale of 1 to 5, 1 being very poor and 5 being excellent.

	Very Poor	Poor	Fair	Good	Excellen t	Don't Know
	1	2	3	4	5	
Usefulness of features and functions (e.g., triggering the system on/off, system app, connectivity, etc.)	O	O	O	O	O	O
Security (anti-theft measures) and maintenance of the technology	O	O	O	O	O	O
Battery Life	O	O	O	O	O	O

- **Alert System of the Technology:**

Please rate the following items on a scale of 1 to 5, 1 being very poor and 5 being excellent.

	Very Poor	Poor	Fair	Good	Excellent	Don't Know
	1	2	3	4	5	
Control over the duration of the alarm	O	O	O	O	O	O
Determining the direction of intrusion	O	O	O	O	O	O
Effectiveness of sound alarm level in alerting construction workers	O	O	O	O	O	O
Effectiveness of Visual Alarm in alerting Construction Workers	O	O	O	O	O	O
Distinctiveness of sound alarm in the presence of construction operation sound	O	O	O	O	O	O
Providing adequate worker alert/reaction time (lead time)	O	O	O	O	O	O
Providing adequate work zone coverage	O	O	O	O	O	O
Effectiveness of Personal Safety Devices (PSD) in triggering the alarm	O	O	O	O	O	O
Improvement in worker productivity after employing the AWARE	O	O	O	O	O	O

- Please select the issues that you encountered with this intrusion technology.
  (Please select all that apply)
  - ☐ False-Positive (No intrusion but Alarm activation)
  - ☐ False-Negative (Intrusion but No Alarm Activation)
  - ☐ Activation of alarm during setup
  - ☐ Alarm activation but ineffective to alert workers
  - ☐ None
  - ☐ Other
    Please Specify: _____________

- Any other features/characteristics that you would like to recommend enhancing the effectiveness of this intrusion technology?

Comment Box

- **Durability:**

Please rate the following items on a scale of 1 to 5, 1 being very poor and 5 being excellent.

	Very Poor	Poor	Fair	Good	Excellent	Don't Know
	1	2	3	4	5	
Ability to withstand wear and tear	O	O	O	O	O	O
Resistance toward environmental Impact (e.g., Rain, Snow, Wind, Sunlight)	O	O	O	O	O	O

- Do you have any additional comments/thoughts to share with us that has not been covered in this survey?

Comment Box

A.2 Survey and Interview Questionnaire Utilized in Drivers' Test

Name: Technology:

SECTION I: QUESTIONNAIRE

Please rate the following questions on a scale from 1 – 5, 1 being very low and 5 being very high:

	Very low 1	**Low 2**	**Moderate 3**	**High 4**	**Very High 5**	**Not Applicable**	**Don't know**
Q.1. How familiar were you with this technology before testing?	☐	☐	☐	☐	☐	☐	☐
Q.2. How would you rate its effectiveness in alerting the drivers? (Sound intensity, providing sufficient reaction time)	☐	☐	☐	☐	☐	☐	☐
Q.3. To what extent did you feel a sense of urgency after hearing the alarm?	☐	☐	☐	☐	☐	☐	☐
Q.4. If you feel the alarm sound was annoying, please rate the annoyance level.	☐	☐	☐	☐	☐	☐	☐
Q.5. To what extent did the visual alarm grab your attention while intruding into the work zone?	☐	☐	☐	☐	☐	☐	☐
Q.6. Rate the alarm based on its distinctiveness compared to other emergency alarms.	☐	☐	☐	☐	☐	☐	☐
Q.7. To what extent do you feel this alarm is effective in alerting distracted drivers?	☐	☐	☐	☐	☐	☐	☐
Q.8. To what extent do you feel this alarm is effective in alerting the workers?	☐	☐	☐	☐	☐	☐	☐

Q.9. Based on today's experience with intrusion alarms, in what situation do you think the intrusion alarm can be more effective? (Please select all that apply)

- ☐ Day time with high traffic volume
- ☐ Day time with low traffic volume
- ☐ Night time with high traffic volume
- ☐ Night time with low traffic volume
- ☐ Other _____________

Q.10. Do you have any other comments/recommendations to enhance the effectiveness of this technology?

____

____

SECTION II: POST EVALUATION INTERVIEW AUDIO-RECORDED

Q.1. Which intrusion technology is the most effective in alerting drivers while intruding the work zone? Why?

____

____

Q.2. Which technology contributed the most to creating a sense of urgency? Why?

____

____

Q.3. What is your opinion/concerns on the feasibility of using these intrusion alarms in an actual work zone? Please explain in brief.

____

____

Q.4. Based on your experience today, which combination of the alerting system might work better: Audio only, Visual only, or Audio-Visual? Why?

____

____

A.3 Survey and interview questionnaire utilized in workers' test

- **Post-evaluation Survey**

Name: ____________________ Age: ____________________

Date: __________ Gender: __________ Technology Name: __________

Job Title: __________ Years of experience in construction: __________

Please rate the following information on a scale of 1 – 5, with 5 being "strongly agree" and 1 being "strongly disagree".

Statement	Strongly Disagree 1	2	3	4	Strongly Agree 5
You were familiar with this technology before testing.	1	2	3	4	5
The alarm caused you to feel a sense of urgency after its activation.	1	2	3	4	5
This technology was effective in improving the work zone safety.	1	2	3	4	5
This system was helpful in figuring out the direction of intrusion.	1	2	3	4	5
In the presence of ambient noise environment, the alarm sound was distinguishable.	1	2	3	4	5
The alarm allowed sufficient lead time to find the escape path.	1	2	3	4	5
The sound of the alarm felt annoying while working.	1	2	3	4	5
The flashing lights of the alarm were effective to grab your attention.	1	2	3	4	5

For what type/s of operation duration would you like to recommend this technology?

(Please select all that apply)

- ☐ Short duration highway work zones operation
- ☐ Moderate duration highway work zones operation
- ☐ Long duration highway work zones operation
- ☐ None
- ☐ Other __________

- **Interview Questions**

Q.1. Do you have any other comments/recommendations to enhance the effectiveness of this technology?

____

____

Q.2. How frequently would you like to see this technology be adopted in highway construction work zones? Why?

____

____

Q.3. Do you think this technology influences your productivity knowing it is deployed in a work zone? Why?

____

____

APPENDIX B. A METRIC BASED DECISION- MAKING TOOL

- Main Menu

The main menu consists of four parts: (a) Technology Selection, (b) Customization, (c) Historical Database, and (d) BCA Database-Figure B.*1*.

Figure B.1 Main menu.

- Specify users' priority and importance of each attribute for their work zone

When users click the "Technology Selection" button in the main menu, they will be redirected to a page where they can provide inputs based on their work zone-specific needs. As illustrated in Figure B.*2*, this page features two columns that require users to rank and rate various attributes. In the first column, users are asked to prioritize each attribute based on the specific characteristics of their work zone. The second column requires users to rate the importance of each attribute. After filling out all the necessary information, users can click the "Submit" button, which will then take them to the next page displaying the results.

Menu

Step 1: Specify Your Priority and Rate the Importance of Each Attribute for Your Work Zones

Submit

Reset

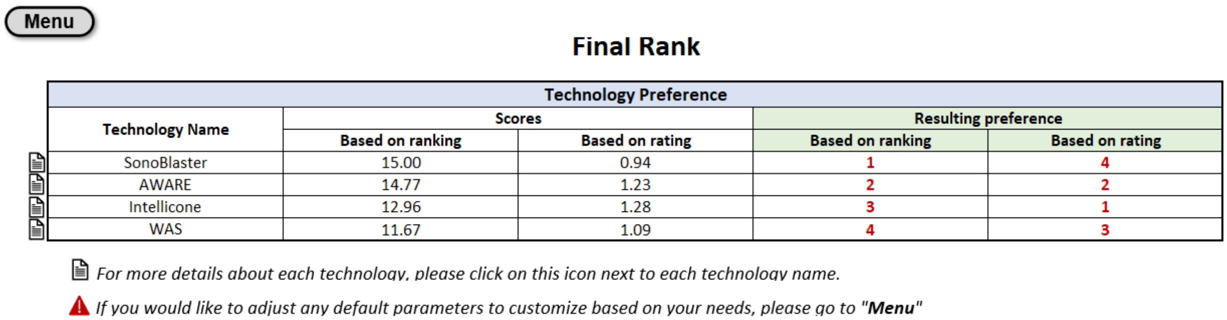
Please click the "Submit" button once you are finished

	Attributes	Ranking (1: Highest priority - 12: Lowest priority)	Rating (1: Lowest importance - 5: Highest importance)	Weightage based on ranking	Weightage based on rating
a.	**Deployment** (Easy, straightforward, and less time-consuming to deploy technology)			0.167	0.000
b.	**Work zone coverage** (Area that can be covered once deployed)			0.167	0.000
c.	**Transportation and storage before/after use**			0.167	0.000
d.	**Sound loudness**			0.167	0.000
e.	**Sound distinctiveness** (Uniqueness of the alarm sound among highway traffic noise)			0.167	0.000
f.	**Frequency of false alarms** (Rate of false positives and false negatives)			0.167	0.000
g.	**Effectiveness in alerting the drivers** (Effectively warn the driver in case they intrude the work zone)			0.167	0.000
h.	**Cost**			0.167	0.000
i.	**Timely communication with supervisor and incident database for future assessment**			0.167	0.000
j.	**Various alert type** (Visual, audio, and haptic/vibration)			0.167	0.000
k.	**Effectiveness in alerting the workers** (Effectively warn the workers in case work zone intrusion occur)			0.167	0.000
L.	**Benefit-Cost Ratio**			0.167	0.000

Figure B.2 Technology selection page.

- Final Rank

The application automatically calculates a ranking of technologies suitable for the work zone based on users' input. As shown in Figure B.*3*, the results are evaluated separately based on the ranking and rating data that users provided in the previous stage. Additionally, users can click the document-shaped icon next to the technology name if they want to learn more about each technology in detail. This will redirect them to a new page to access more detailed information. It is important to note that these results are calculated using Indiana DOT's inputs and historical data. Therefore, if users wish to apply their data, which may differ from the default dataset, they can initiate this by clicking the "Customization" button in the main menu.


Menu

Final Rank

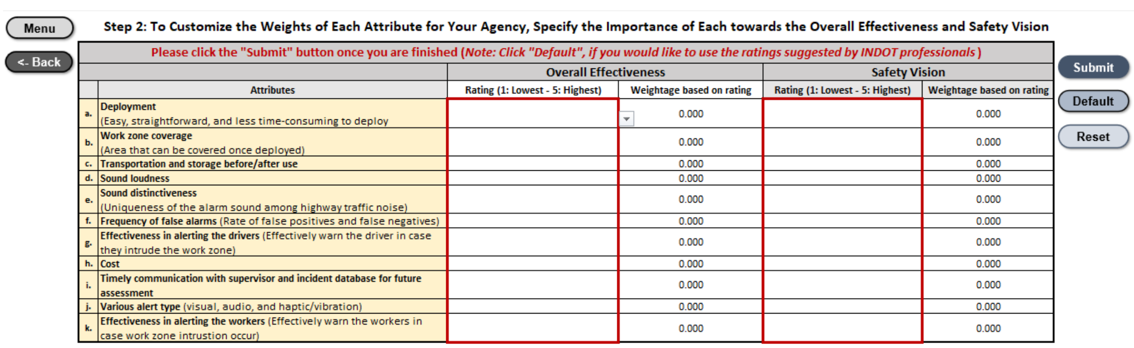
Technology Name	Scores: Based on ranking	Scores: Based on rating	Resulting preference: Based on ranking	Resulting preference: Based on rating
SonoBlaster	15.00	0.94	1	4
AWARE	14.77	1.23	2	2
Intellicone	12.96	1.28	3	1
WAS	11.67	1.09	4	3

For more details about each technology, please click on this icon next to each technology name.

*If you would like to adjust any default parameters to customize based on your needs, please go to "**Menu**"*

Figure B.3 Final Rank.

- Customization
  - Step 1: Specify users' priority and importance of each attribute for their work zone
  - Step 2: Customize the weights of each attribute for users


Menu

<- Back

Step 2: To Customize the Weights of Each Attribute for Your Agency, Specify the Importance of Each towards the Overall Effectiveness and Safety Vision

Please click the "Submit" button once you are finished (*Note: Click "Default", if you would like to use the ratings suggested by INDOT professionals*)

	Attributes	Overall Effectiveness: Rating (1: Lowest - 5: Highest)	Overall Effectiveness: Weightage based on rating	Safety Vision: Rating (1: Lowest - 5: Highest)	Safety Vision: Weightage based on rating
a.	**Deployment** (Easy, straightforward, and less time-consuming to deploy		0.000		0.000
b.	**Work zone coverage** (Area that can be covered once deployed)		0.000		0.000
c.	**Transportation and storage before/after use**		0.000		0.000
d.	**Sound loudness**		0.000		0.000
e.	**Sound distinctiveness** (Uniqueness of the alarm sound among highway traffic noise)		0.000		0.000
f.	**Frequency of false alarms** (Rate of false positives and false negatives)		0.000		0.000
g.	**Effectiveness in alerting the drivers** (Effectively warn the driver in case they intrude the work zone)		0.000		0.000
h.	**Cost**		0.000		0.000
i.	**Timely communication with supervisor and incident database for future assessment**		0.000		0.000
j.	**Various alert type** (visual, audio, and haptic/vibration)		0.000		0.000
k.	**Effectiveness in alerting the workers** (Effectively warn the workers in case work zone intrustion occur)		0.000		0.000

Submit

Default

Reset

Figure B.4 Customizing the weights of each attribute.

As illustrated in Figure B.*4*, users can specify the importance of each attribute in relation to their agency's overall goals for effectiveness and safety, thereby customizing the weighting factors. If users wish to use the inputs from INDOT Safety Professionals, they can click the "Default" button.

  - Step 3: Insert work zone data

As depicted in Figure B.*5*, users are required to input data related to their work zones. In Part A, they are prompted to enter annual data on fatalities and injuries that have occurred in the work zone. Additionally, they can specify the maximum number of

work zones where they wish to deploy the new technology. Finally, they are asked to indicate the expected risk reduction rate after deploying the new technology.
In Part B, users must first input the typical number of lane closures and the speed limit for their work zones. Next, they need to provide the average length of a work zone. Upon receiving all the inputs, the application will automatically calculate the total length of the work zone and the associated number of traffic cones needed to determine the quantity of technology required for the user's work zone. After completing all these steps, users can click the "Submit" button to view the final results, calculated based on their specific conditions.

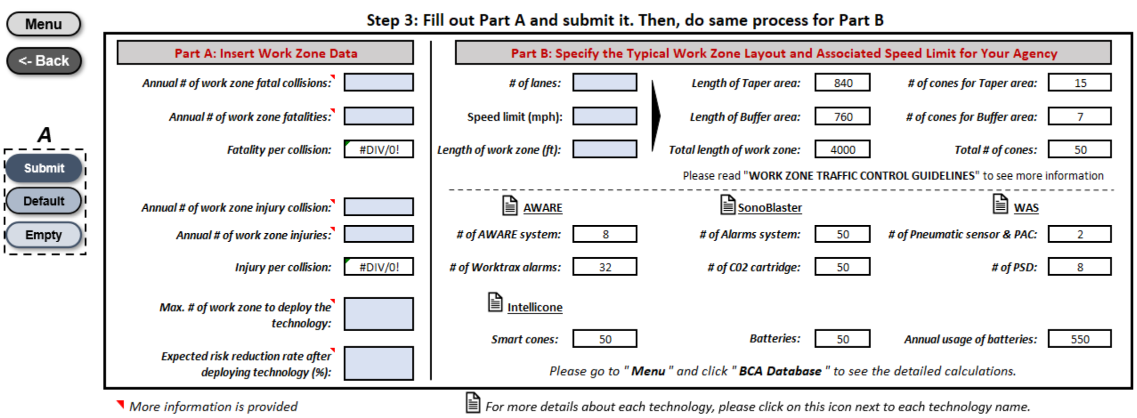


Figure B.5 Workzone related data.

- Supplementary Information (Technology details)

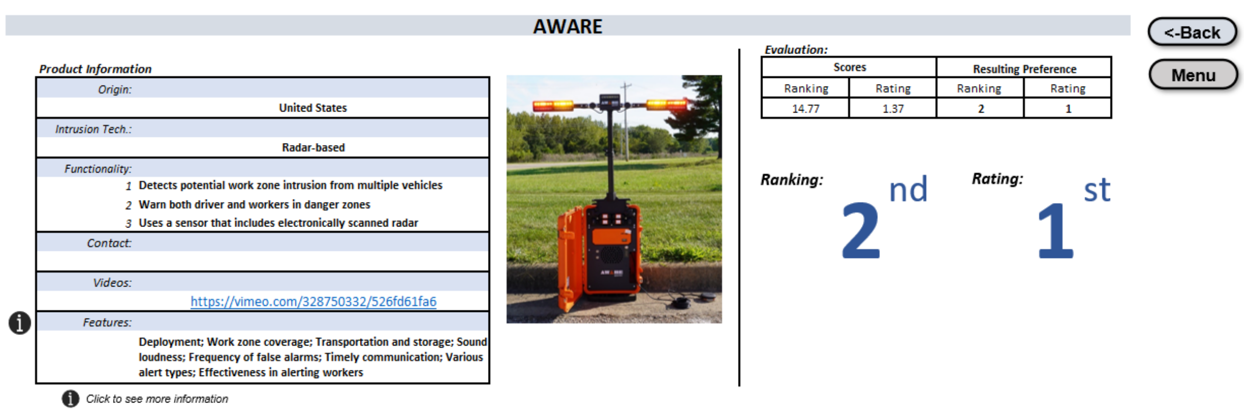


Figure B.6 Product information for AWARE system.

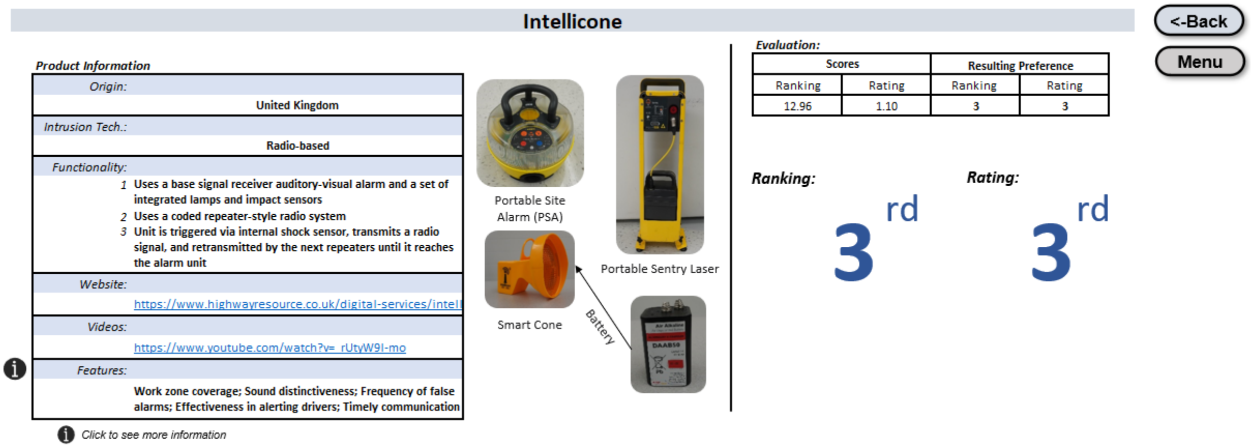


Figure B.7 Product information for Intellicone system.

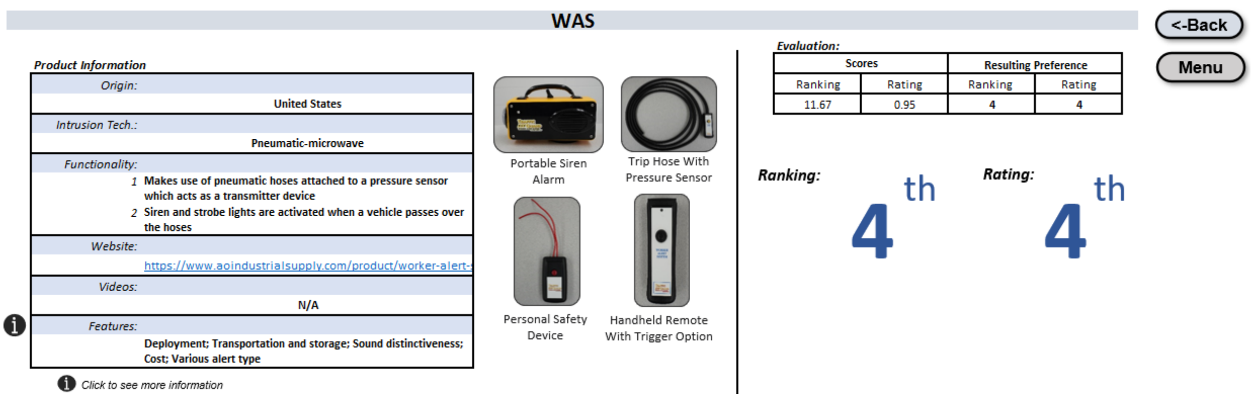


Figure B.8 Product information for WAS system.

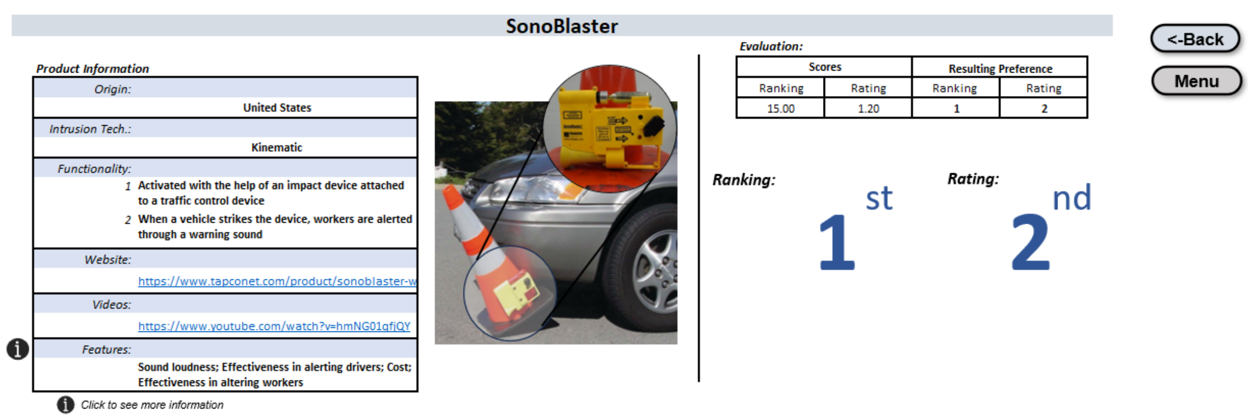


Figure B.9 Product information for SonoBlaster.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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