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Work Zone Alert Systems

Research Final Report from the University of Memphis | Sabysachee Mishra, Mihalis M. Golias and Diwas Thapa | April 1, 2021

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DISCLAIMER

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Work Zone Intrusion Alert (WZIA) technologies are emerging technologies that use sensors and alarms to detect and alert highway workers of vehicles intruding into a work zone perimeter. WZIA technologies are still evolving and there is no existing set of best practices for DOTs interested in implementing them. This project aimed to identify and evaluate existing WZIA technologies to provide recommendations on their implementation. To achieve this, recommendations on suitable use cases for three selected WZIA technologies were provided based on multicriteria analysis consisting of capital cost, performance accuracy, safety aspects, easiness of operation, and life cycle cost. Findings suggest that Intellicone can be highly beneficial if it is deployed on construction work zones on major highways, AWARE Sentry for flaggers is highly effective when used for flagging operation by flaggers, and Worker Alert System (WAS) is easy to deploy which makes it ideal for use in short-term work zones that are not too close to the traffic.</td></tr>
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Executive Summary

Work zone safety is a major concern for the Federal Highway Administration (FHWA), state departments of transportation (DOTs), the transportation industry, and the public. Work zones have significant impacts on traffic conditions and the safety of motorists and agency/contractor personnel. The growth of travel on the roadway system in the United States and recent adverse weather conditions have accelerated the deterioration of pavement, leading to constant pavement repairs and roadway rehabilitation. According to data from the Bureau of Transportation, Vehicles Miles Traveled (VMT) between 1982 and 2012 grew by 86% while the total available lane miles serving the growing transportation demand increased by only 7.4%. According to the FHWA's *Work Zone Injuries and Fatalities Facts and Statistics*, VMT through work zones has showed a similar growth pattern. This is particularly concerning to worker safety since motorists are often required to drive through a complex arrangement of signs, barrels, and lane alterations in the presence of workers.

Depending on how severe a work zone crash is, the associated fatalities, injuries, and property damage can lead to very high costs. This is in addition to costs associated with possible damage to high value goods being transported and longer travel delays. As a result, many states are paying special attention to work zone intrusions—crashes caused by civilian vehicles erroneously entering work zones, often due to drunk or distracted driving. There are several technologies designed to improve safety in short-term work zones such as adhesive rumble strips, intrusion alert systems, portable changeable message signs, portable speed monitoring displays, radar drones, vehicle-activated signs, CB radio alert systems, truck mounted attenuators, and mobile barriers. Of particular interest to the Tennessee Department of Transportation (TDOT) are Work Zone Intrusion Alert (WZIA) technologies. This class of safety devices is intended to recognize when a work zone intrusion is occurring, and to alert the driver and nearby workers of the intrusion so that they can respond appropriately. It is theorized that these alerts will allow workers more time to take cover or get out of the way and will allow drivers to stop more quickly or redirect their vehicles, mitigating the severity of injuries and damage caused by work zone intrusions.

WZIA technologies are a set of emerging technologies; few states have adopted their use, and no state has yet verified improved safety or cost-benefit analysis. Over the last two decades, DOTs and WZIA technology manufacturers have undergone a series of cyclic tests and re-designs: DOTs commission studies to test WZIAs, and manufacturers use the feedback from those tests to improve designs. Because this technology is still evolving, there is no existing set of best practices for DOTs interested in implementing WZIAs to mitigate work zone intrusions.

The main aim of this research was to provide recommendations for WZIA implementation and practices to TDOT by identifying and testing the most promising WZIA products. The objectives of the study were i) provide a comprehensive review of previous studies and best practices on WZIA technologies, ii) identify the characteristics of work zone crashes by work zone typologies, iii) identify technologies for evaluation, and iv) develop guidelines for implementing the identified WZIA technologies. First, a review of scholarly literature was carried out to identify potential technologies for evaluation. The identified technologies were tested under controlled conditions to assess their performance. Based on the results from controlled testing, the technologies were

then tested on live work zones to analyze workers' attitude towards them. Surveys administered to workers after live testing were used to rate the technologies based on five criteria. These were user friendliness, noticeability of alarms, low rate of false alerts, cost, and the ability to live-track work zone intrusions. Final recommendations on appropriate selection of technologies based on work zone typology are presented to aid decision making for their potential implementation across the state.

Three technologies were identified for evaluation. These were Intellicone, Advanced Warning And Risk Evasion (AWARE) Sentry system for flagging, and Worker Alert System (WAS). Overall, all three technologies were found to be effective in providing workers with timely alerts, although, Intellicone and WAS were more likely to result in false alarms. Based on the results from our testing, we recommend Intellicone for use in long-term stationary work zones, AWARE Sentry for use in flagging operations, and WAS for use in short-term and mobile work zones without lane encroachment. Currently, Intellicone is not commercially available in the US but it is used in highways work zones across the UK, and WAS can be readily bought in the US. Although, AWARE Sentry is ready for field testing, it is not produced on a commercial scale yet. Based on the characteristics of crashes on different work zone typologies, Intellicone could provide with the most benefits due to its low life cycle cost and scope of implementation (construction work zones on major highways), if it can operate effectively. Although expensive, AWARE Sentry demonstrated high accuracy in detecting intrusions. AWARE's lane intrusion detection system, that is currently under development, utilizes the same equipment as the Sentry and can be mounted on moving equipment, can be considered for testing after it is ready.

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Chapter 1 Introduction

1.1 Background

Safety in highway work zones is a major concern for the public and transportation agencies. Recently enacted acts, such as the Moving Ahead for Progress in the 21st Century Act (MAP-21) of 2012 and Fixing America's Surface Transportation (FAST) Act of 2015 have focused on making work zones safer. According to the Federal Highway Administration (FHWA), Vehicles Miles Traveled (VMT) between 2017-2037 is expected to increase by as much as 1.3% annually [5]. With the increase in VMT, the frequency of work zone crashes can also be expected to rise. For example, during the great recession, the reduction in VMT also reduced number of work zone crashes and fatalities as safer drivers travelled more than riskier drivers [6], [7]. Furthermore, with the rise in VMT, existing highway infrastructure are subjected to additional strain and therefore require rehabilitation and expansion to better serve the growing demand. This provides more opportunity for work zone crashes to occur. According to the Fatality Analysis Reporting System (FARS), about 1.7% of all highway crashes in 2019 occurred in work zones. Although this might not seem much, these crashes include about 26,964 injury crashes and 762 fatal crashes, which averages to about 74 injury crashes and 2 fatal crashes per day. If these highway crashes could be eliminated altogether, the resulting economic losses that could be averted would be significant [8].

Highway construction and maintenance projects often require workers to work near moving traffic. Although various safety measures are currently adopted for worker safety, existing measures might often be inadequate due to various human and environmental factors, such as inattentive driving, weather, and roadway conditions. For example, an inattentive motorist could disregard the safety measures in place, jeopardizing the safety of the workers and fellow travelers. Additionally, the chaotic and noisy nature of construction and maintenance activities in work zones can distract workers, impeding their ability to spot errant vehicles which could ultimately result in crashes [2].

To prevent economic losses and maintain safety in work zones, safety personnel and transportation agencies have considered using Work Zone Intrusion Alert (WZIA) technologies. These technologies detect errant vehicles and alert workers of an imminent crash. The ability of these systems to provide timely and accurate alerts can prevent injuries and saves lives in highway construction and maintenance projects. Additionally, these technologies can also be integrated with Intelligent Transportation System infrastructure to facilitate remote tracking of work zones and automate traffic management. Considering these benefits, evaluation of available technologies for potential implementation has been a focus of several DOTs. The purpose of this study was to test existing technologies and provide suitable recommendations to the Tennessee Department of Transportation (TDOT) for their adoption and implementation.

1.2. Study objectives and report organization

The primary goal of the project was to identify and test existing WZIA technologies to provide TDOT with recommendations on their selection based on work zone typology. The project goal was achieved by fulfilling the following objectives:

- Provide a comprehensive review of existing literature and best practices from other states.
- Select and utilize appropriate data sources to determine the characteristics of work zone typologies and their related rates of work zone intrusions.
- Analyze historical work zone crash data and recommend candidate technologies for on-site testing.
- Report on results from testing and provide recommendations on chosen technologies.
- Develop guidelines for implementing selected WZIA technologies in work zones across the state.

The rest of the report is organized as follows. Chapter 2 presents the literature review on WZIA technologies and past studies undertaken by DOTs across the country. In Chapter 3, a summary of work zone crashes is presented and needs for intervention are identified. Chapter 4 explains the methodology of the research and the results from experiments. More specifically, this section describes technology selection, experimental procedure and layout followed in testing, and results from testing and on-site surveys. Chapter 5 presents the concluding remarks and recommendations on technology selection and implementation.

Chapter 2 Literature Review

Based on the nature of detection, currently available WZIA technologies can be broadly divided into two categories; i) technologies using mechanical impact or pressure sensors, and ii) technologies using wireless sensing technology [3]. Technologies based on impact detection typically use barrier mounted sensors to detect impact from an errant vehicle while those based on pneumatic sensors detect intruding vehicles after they come in contact with a pneumatic sensor that is usually laid around the work zone perimeter. Wireless sensing technologies use wireless signals such as infrared or microwave to detect errant vehicles approaching the work zone perimeter. These technologies usually employ transmitter and receiver units. These transmitter units send wireless signals to the receivers which, when obstructed by an object, triggers alerts or alarms to warn workers nearby. Several WZIA technologies have been developed by manufacturers and tested by state DOTs and researchers over the years. However, most of them are based on the first prototypes that were developed under the Strategic Highway Research Program (SHRP). In the following section, we provide a review of previous research on these technologies.

2.1 Previous research on WZIA technologies

The first prototypes of safety devices for detecting work zone intrusions were developed and evaluated under SHRP Project H-108 and H-109 [9]. The devices were based on mechanical detection (pneumatic tube alarm) and wireless sensing technology utilizing ultrasonic waves and infrared light. Results from the evaluation carried out on the devices suggested that further refinement and research was necessary prior to their implementation. The same devices were also evaluated by the Kentucky Transportation Cabinet. Results from their evaluation further supported the findings from previous studies suggesting additional testing was necessary before the devices could be implemented on a large scale [10]. These devices underwent several improvements and were tested by various DOTs in the following years. Most of these DOTs, however, questioned the efficacy and worthiness of the devices. TABLE 2-1provides a summary of studies conducted by state DOTs on pneumatic, microwave and infrared based devices.

In recent years, several modern intrusion detection and alert technologies have been developed by manufacturers and evaluated by DOTs and researchers. An impact or tilt-activated system called SonoBlaster was tested by the New Jersey DOT [4]. The system was designed to be attached to a traffic barricade surrounding the work zone perimeter. It produced a high-intensity sound when struck by an intruding vehicle. The sound was produced by an air horn using compressed CO_2. Researchers reported SonoBlaster to have unsatisfactory performance due to tedious setup, low durability, and frequent misfires during setup and storage. In 2012, the Minnesota DOT developed and tested a non-intrusive alert device to alert speeding drivers of upcoming work zones. The device was called Intelligent Drum Line (IDL) technology and employed a series of modified drums kept about 300 ft apart. These drums could detect the speed of approaching vehicles using radar, communicate this information to other drums and produce warning alerts to the driver when a certain threshold speed was crossed [11]. The warning alerts were also designed to be turned off automatically when the driver rectified their speed. The IDL technology was found to be effective by engineers and workers. However, there was a need to further develop the technology to make it crash proof. Two technologies, SonoBlaster and Intellicone, were tested for use in temporary work zones in Kansas [12]. Intellicone is an impact activated system that uses cone mountable sensor lamps to detect intrusion using built-in accelerometers and provides audiovisual alerts through a separate alarm unit. Results from the study suggested that workers were optimistic about the systems, although SonoBlaster setup was reportedly difficult and Intellicone alarms were not adequately loud for use in noisy environments. A wireless sensor network-based intrusion alarm was developed and tested for short-term work zones in 2016 [13]. The system used a barrier mountable sensor using ultrasonic waves and a modified wristwatch to detect vehicles and alert workers, respectively. Tests carried out suggested that the system was reliable and accurate although complete accuracy in detection was not observed during the experiments.

There are three notable technologies that have been tested by multiple studies. These are Intellicone, AWARE and Worker Alert System. AWARE is an advanced warning system which stands for Advanced Warning And Risk Evasion System. AWARE uses radar sensors to detect the speed of vehicles to identify a potential intrusion. Worker Alert System (WAS) is a pneumatic pressure-based technology that uses a pneumatic trip hose to detect vehicles entering a work zone perimeter. AWARE was extensively tested in 2016 by researchers at the Texas A&M Transportation Institute under controlled conditions [14], [15]. During their testing, AWARE was reported to work with complete accuracy, producing no false alarms throughout the test duration. A notable complaint reported by test participants has, however, been the resemblance of its alarm sirens to that of emergency and law enforcement vehicles. Similarly, researchers on behalf of Alabama DOT tested Intellicone, AWARE and WAS in a controlled test area to recommend use cases for the technologies [16]. The researchers recommended using Intellicone for stationary work zones and long tapers; AWARE for mobile work zones and long tapers; and WAS for short term work zones with short tapers. Sonoblaster, Intellicone, and WAS were also tested by researchers for Oregon DOT using controlled experiments and live work zones in 2017 [3]. Results from their study indicated that all three technologies were effective in alerting workers, although, the cost of technology (e.g., for Intellicone) could be a potential barrier for their adoption.

2.2 Research needs

WZIA technologies are a set of emerging technologies. Over the last two decades, DOTs and WZIA manufacturers have undergone a series of cyclic tests and re-designs, with DOTs commissioning studies to test WZIA technologies and manufacturers using the feedback from those tests to improve designs [4], [17], [18]. Past research suggests that these technologies need to address several deficiencies before they can be implemented. The majority of past research points out ineffectiveness, difficult setup and frequent false alarm as the primary causes for their rejection [19]. However, because this technology is still evolving and undergoing improvement and changes, additional research is necessary in determining their potential for being adopted. Also, no set of best practices for implementing WZIA technologies currently exists for DOTs interested in adopting them to mitigate work zone intrusions. Therefore, proposed research focuses on studying the literature to identify the most valuable WZIA products and provide a recommendation to TDOT for their implementation based on specific low cost, low rate of false alerts, ease of use, and ability to live-track work zone intrusions across the state.

TABLE 2-1

FINDINGS FROM TESTS CONDUCTED BY VARIOUS STATE DOTS ON SHRP INTRUSION ALERT SYSTEMS

Technology	DOT	Findings
Pneumatic	New Hampshire	False alarms frequently triggered by maintenance vehicles
	Pennsylvania	System not reliable in detecting intrusions
	Iowa	Time consuming to set up and move the system
	Alabama	System not able to provide workers enough time to react to an intrusion
Microwave	Iowa	Time consuming setup and difficulty moving the system after it has been set up
	Colorado	Ineffective due to strobe lights being not bright enough and sound alarms not being loud enough
	Alabama	Setup failure due to misalignment of the signals
	Pennsylvania	System unreliable as wind gusts from passing vehicles moved the system from their alignment, Frequent false alarms resulting in workers ignoring the alarms
	Washington	Difficulty operating the device and no troubleshooting guide available
Infrared	Colorado	Frequent false alarms due to interference to Citizen Band frequency
	New York	Frequent false alarm from workers moving in and out of work zone
	Missouri	Alarm too sensitive resulting in frequent false alarms
	Iowa	Difficult system setup due to misalignment of the components
	Vermont	Loud enough but difficult setting the components in narrow shoulders
	Pennsylvania	System inappropriate for mobile operation and frequent false alarms

Note: Collected from [19] and [20].

Chapter 3 Work zone data collection

A collection of previous work zone crashes and currently on-going projects were compiled using Enhanced-Tennessee Roadway Information Management System (E-TRIMS). The data was crucial for the project in two ways. First, it would allow researchers to find areas of intervention where work zone safety measures should be implemented first. Second, it provided an estimate of the scale at which WZIA technologies would have to be adopted.

3.1 Active projects

The Program, Project & Resource Management (PPRM) system was used to obtain information on currently active projects. The PPRM is comprised of information on project names, types, locations, progress, and budgets. Researchers identified 8,556 active projects throughout the state. TABLE 3-1 presents the number of active projects throughout the state in 2018.

TABLE 3-1

ACTIVE PROJECTS UNDER DIFFERENT PROGRAMS IN TENNESSEE (2018)

Program type	Number	Percentage of total
Bridge	1,805	21%
Road resurfacing and widening	1,447	17%
Maintenance	1,213	14%
Safety improvements	1,713	20%
Highway beautification	4	0.05%
Railways, Waterways and Others	2,357	27.5%
Total	**8,539**	**100%**

Note: Different project types were combined to form major categories to represented similar project types.

Figure 3-1. Active highway projects across Tennessee

Figure 3-1 shows the distribution of on-going highway projects across Tennessee. Highways near major cities like Memphis, Nashville, Chattanooga, and Knoxville have more active projects. Therefore, highway work zones are mostly concentrated near major cities.

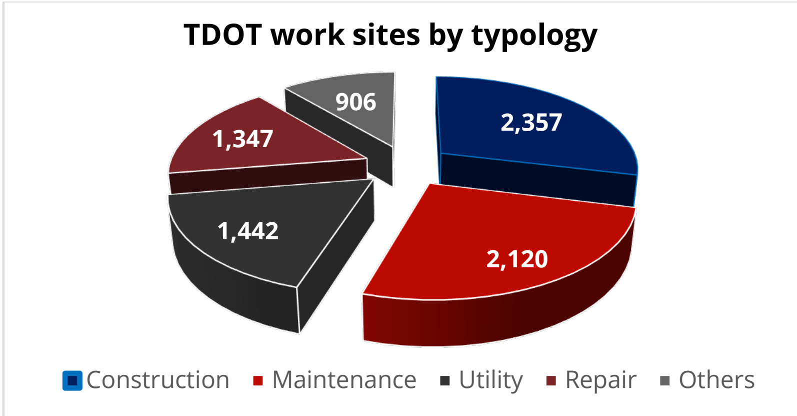


Figure 3-2. Work sites by type of work

The Manual of Uniform Traffic Control Devices (MUTCD), 2009 suggests the use of traffic control devices based on work zone duration and movement of work [21]. The manual categorizes work zones into five groups based on work duration and movement. These are as follows, i) long-term stationary, ii) intermediate-term stationary, iii) short-term stationary, iv) short duration, and v) mobile. The type of work (construction, maintenance, utility, and repair) is closely related to this classification. For example, maintenance and utility operations are often short-term and mobile lasting less than a day and requiring intermittent or continuous movement of work. On the other hand, construction operations are often stationary and long-term lasting more than a day. Due to this reason, lane closures for construction work zones are often maintained over a longer period. Figure 3-2 presents the share of different types of work in highway projects between 2002-2016. Most of the projects undertaken during the duration were construction projects (29%) followed by maintenance projects (26%), utility projects (18%) and repair projects (16%).

3.2 Work zone fatalities

Work zone crash data for analysis was collected from E-TRIMS. E-TRIMS provides a database of all recorded highway crashes in Tennessee along with details on its location, roadway characteristics, weather conditions, type of work, type of crash, etc. In this analysis, all work zone related incidents from 2002-2019 were analyzed. Figure 3-3 presents the location of all reported work zone crashes during the period. Based on the figure, it is evident that the frequency of crashes is greater around the main cities Memphis, Clarksville, Nashville, Murfreesboro, Chattanooga, and Knoxville. Also, more crashes are observed on interstates and major highways.

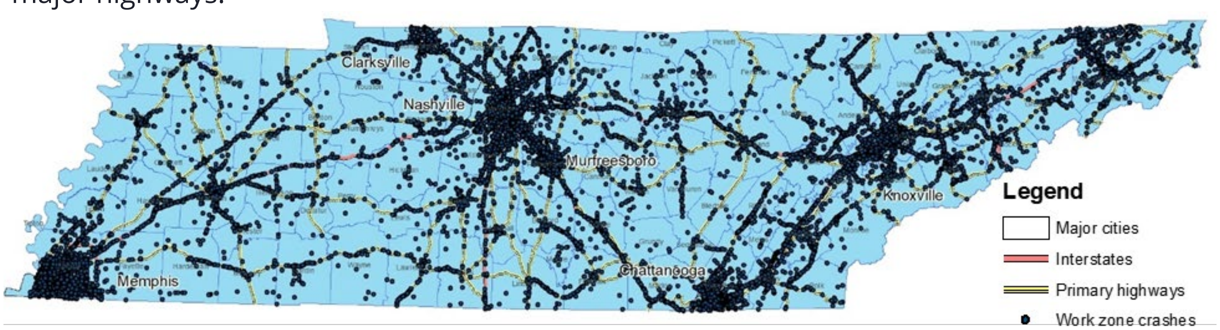


Figure 3-3. Location of all reported work zone crashes between 2002-2019

3.2.1 Fatalities by work zone type

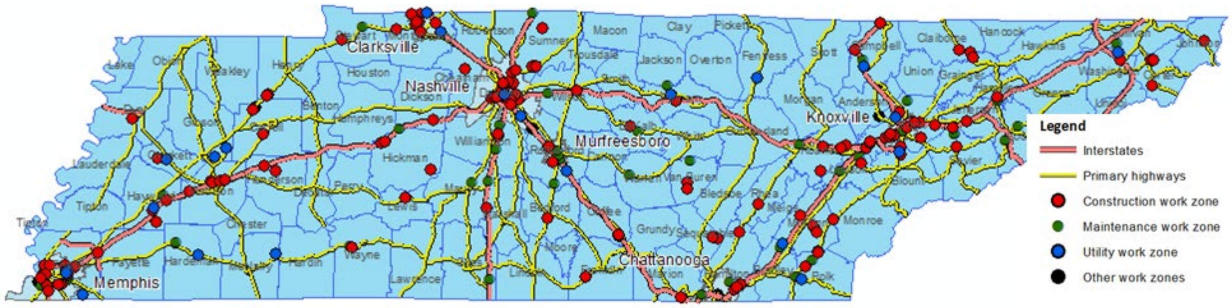


Figure 3-4. Location of fatal work zone crashes by work zone typology

All fatal work zones crashes recorded between 2002-2019 are categorized by work zone typology and presented in Figure 3-4 and TABLE 3-2. Fatal crashes are notably more frequent near Memphis, Clarksville, Nashville, and Knoxville. Also, construction work zones on interstates show comparably larger number of fatalities than maintenance and utility work zones. As shown in TABLE 3-2, most fatalities during the analysis period occurred in construction work zones followed by maintenance work zones. More than 85% of all work zone crash fatalities can be attributed to construction and maintenance work.

TABLE 3-2

FATALITIES BY WORK ZONE TYPOLOGY (2002-2019)

Year	Construction	Maintenance	Utility	Others
2002-2006	100	5	4	3
2006-2010	24	10	2	2
2010-2014	8	14	9	1
2014-2018	4	15	7	0
2018-2019	2	0	0	0
Total	138	44	22	6
% of total	65.71%	20.95%	10.48%	2.86%

3.2.2 Fatalities by roadway type

According to the collected data, most work zone fatal crashes have occurred on major highways. Of 210 fatalities, 91 of them have been on interstates and 106 on state highways. This suggested that safety interventions should first be focused on major highways. Figure 3-5 shows the frequency of fatal work zone crashes by roadway type and work zone typology.

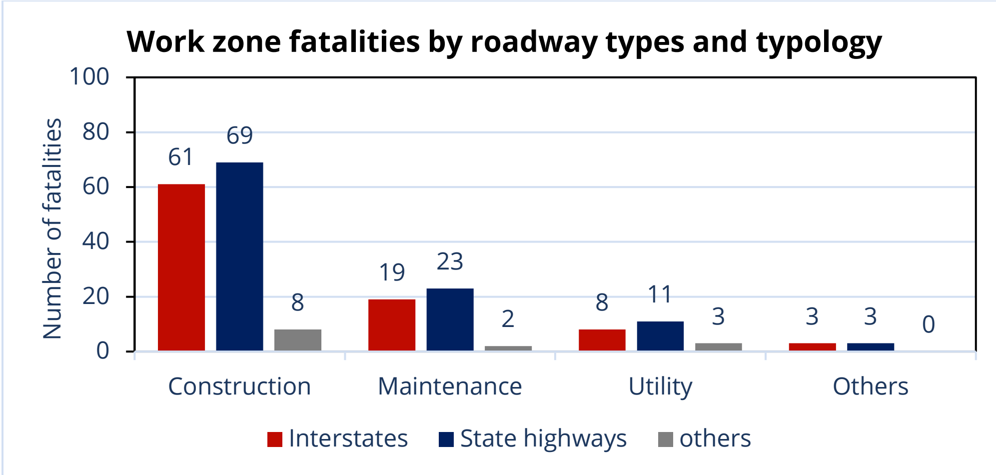


Figure 3-5. Fatal work zone crashes by roadway type and work zone typology

3.2.3 Fatalities by crash location

A considerable proportion of work zone fatalities have occurred along roadways, followed by intersections. This could be a result or relatively considerable number of work zone activities on roadways compared to intersections, bridges, ramps, and underpasses.

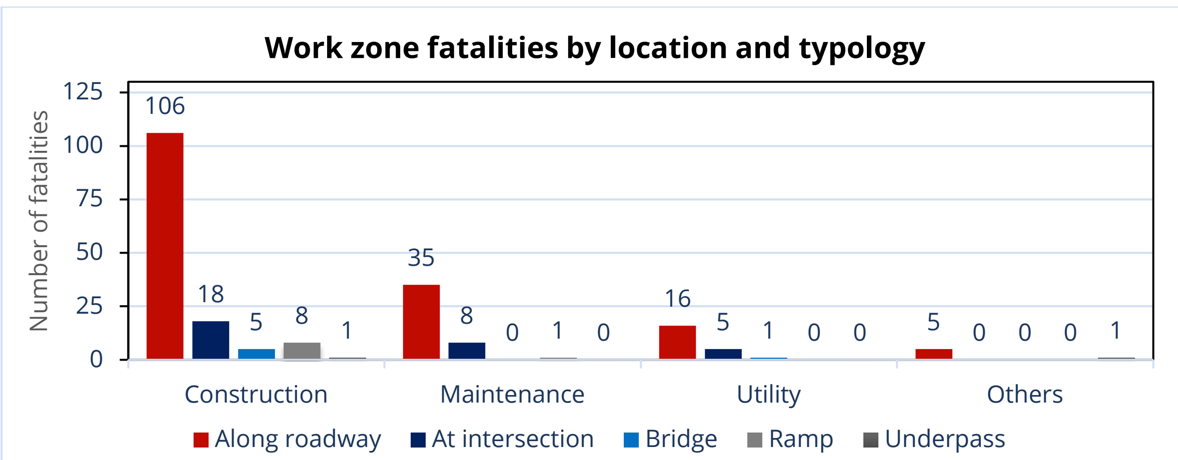


Figure 3-6. Fatal work zone crashes by location and work zone typology

3.3 Findings

The PPRM data for highway projects suggest that the frequency of active projects is higher in and around major cities. Similarly, more work zone crashes, and fatalities have been observed near major cities and on major highways. Despite of near similar number of highway construction and maintenance projects, more fatalities have occurred on construction work zones. These observations can be attributed to several causes. Highway infrastructures near densely populated areas need frequent maintenance and repairs. Second, greater number of fatalities on major highways can be attributed to higher travel speeds [22], [23]. Based on the crash data, safety interventions should be focused on construction work zones near densely populated areas and on major highways to reduce work zone fatalities.

Chapter 4 Methodology

The overall methodology of the study has been divided into six categories as follows.

- Selection of technologies
- Controlled testing of selected technologies
- Live testing of selected technologies
- Evaluation of the technologies' live tracking abilities
- Evaluation of the technologies' life cycle cost
- Multicriteria evaluation of the technologies

The first step in the study was to identify and select appropriate technologies for evaluation. An extensive review of the literature was undertaken to identify potential technologies. Three technologies were then chosen. Manufacturers of each chosen technology were also contacted to ensure technology availability for testing and future procurement. The chosen technologies were acquired from the manufacturers and evaluated using field tests. The field tests were first conducted under controlled conditions followed tests under live conditions. In controlled testing, the technologies were tested under pre-defined experimental configurations to evaluate their performance. In live testing, the technologies were tested on real work zones and feedback was collected from workers to better understand their applicability on work zones. Following live testing, the technologies were evaluated based on multiple criteria using feedback collected from the workers using on-site surveys. Multi criteria effectiveness was used to evaluate overall applicability of the technologies based on alarm noticeability, alarm accuracy, user friendliness, likelihood of adoption based on cost, and live tracking abilities.

4.1 Selection of technologies

A systematic review of the literature and web search on WZIA products identified technologies shown in Figure 4-1. Three technologies were selected based on availability for testing and future procurement. These were Intellicone, AWARE and Worker Alert System. A description of these technologies follows.

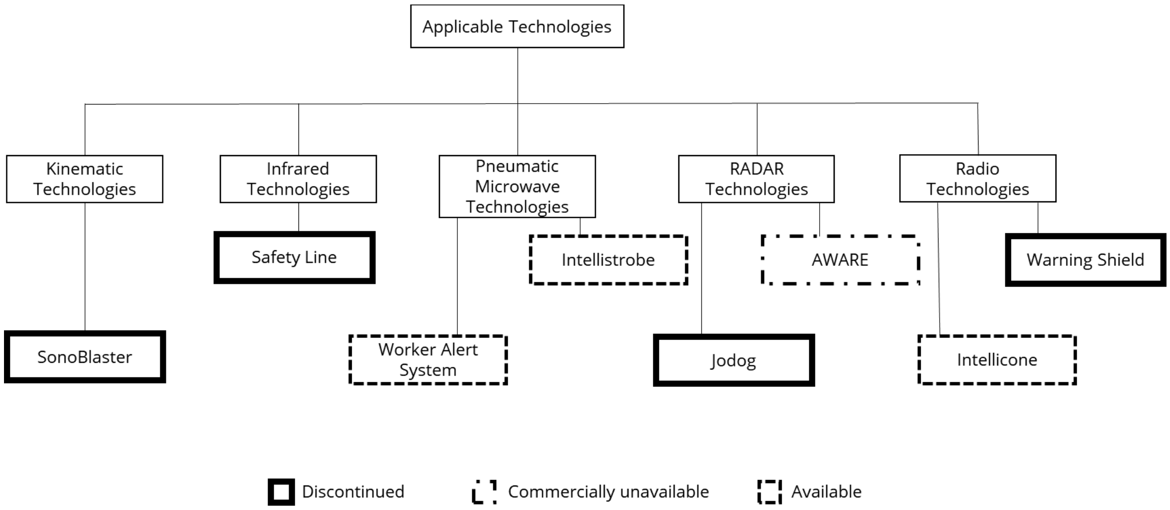


Figure 4-1. Identified WZIA technologies

4.1.1 Intellicone

Intellicone is an impact activated system that uses two components, traffic cone mountable sensor and Portable Site Alarms (PSA). These components are shown in Figure 4-2. The sensor uses LED lamps with built-in accelerometers to detect motion from vehicular impact on traffic cones. The LEDs are designed to be lit when the sensor is armed and ready for use. Additionally, the LEDs also help to draw a driver's attention and highlight the work zone perimeter specially in poor lighting conditions. The sensors are powered by a user replaceable heavy-duty battery, which can be easily swapped manually without the use any tools. The PSA contains built-in LEDs, speakers, and a non-removeable battery that can be charged using an AC adapter that comes included with the PSA. In a typical arrangement, the sensors are mounted on traffic cones around a work zone perimeter, and the PSA is kept close to the workers. When an intrusion is detected by the sensors, wireless radio signals are communicated to the PSA. The PSA produces flashing lights in addition to a high-pitched alarm to alert workers of the intrusion. The sensors can communicate intrusions to the PSA in two ways. When the PSA is within wireless transmission range of the sensor, the sensors can transmit radio alerts directly to PSA. However, when the PSA is out of a sensor's transmission range, the signals are transmitted from one sensor to another until it reaches the nearest PSA.

(a) Traffic cone mounted sensor

(b) Portable Site Alarm showing layout of functional buttons and alarm speaker

Figure 4-2. Intellicone components

Intellicone, although not available in the US, is used on highway projects across the UK. The technology supports live-tracking abilities using the Internet of Things (IoT) platform through *Geozones*. *Geozones* are used to create a digital layer of work zones that enables Intellicone devices components to communicate with each other and to be tracked remotely [24]. Since *Geozones* can be extended over any geographical area, this feature enables wireless communication between two PSAs regardless of the distance between them. This allows Intellicone to be used in lane closures that extend over long distances.

4.1.2 Advanced Warning and Risk Evasion (AWARE)

AWARE is a radar-based advanced warning system capable of detecting intrusions using speed of the oncoming vehicle. Two versions of the system are currently under development. The first is a lane intrusion system capable of detecting work zone intrusions, and the second is called the Sentry that is primarily designed for use by flaggers. Both systems use the same components. A key difference between the two is that the lane intrusion system can be mounted on moving vehicles and equipment whereas the Sentry is housed in a hard case that is kept fixed at a location. Only the Sentry was available to the researchers at the time of the testing. The Sentry is comprised of two components; a sensor/alarm housing unit consisting of a radar sensor called Raven, LEDs, and an alarm speaker, and personal alarms called Worktrax. These are shown in Figure 4-3. Four Worktraxs are included with each Sentry. Worktrax alarms can be either strapped onto a worker's arm or carried in pockets. The sensor/alarm housing unit has in-built batteries that can be charged using an AC adapter included in the unit. The Worktrax alarms are charged automatically when placed inside the housing unit. The Sentry can be programmed to use desired configurations in detecting errant vehicles. This is done using a smartphone application that is provided by the manufacturer. The application connects to the Sentry using a Bluetooth connection. The application can be used to configure the relative position and orientation of the Sentry with respect to the road and set the threshold speed limit for detecting intrusions. The recommended setup for the Sentry is to place it in a shoulder along with a flagger trained to operate it. When a vehicle approaches the work zone at a speed higher than the configured speed limit, the vehicle is marked as an intruder and alerts are produced. Alerts in the main housing units are produced by flashing LEDs and a siren from the sound speaker. Additionally, the Worktraxs produce a vibratory and high-pitched chirping sound.

(a) Sensor/alarm assembly

(b) Worktrax personal alarm

Figure 4-3. AWARE components

AWARE produces three distinct types of alerts based on the speed of the errant vehicle. The first type of alert is only produced by the Worktraxs, the second type activates LED warning lights on the Sentry, while the third produces a loud siren on the Sentry. When an errant vehicle is detected, the Raven first calculates the Stopping Sight Distance (SSD) for the vehicle using the equation:

$$SSD = 1.47Vt + 1.075\frac{V^2}{a} \text{ for different values of } t \tag{1}$$

Where:
SSD = Stopping Sight Distance
V = Speed of errant vehicle
t = time
a = 11.2 ft/s^2.

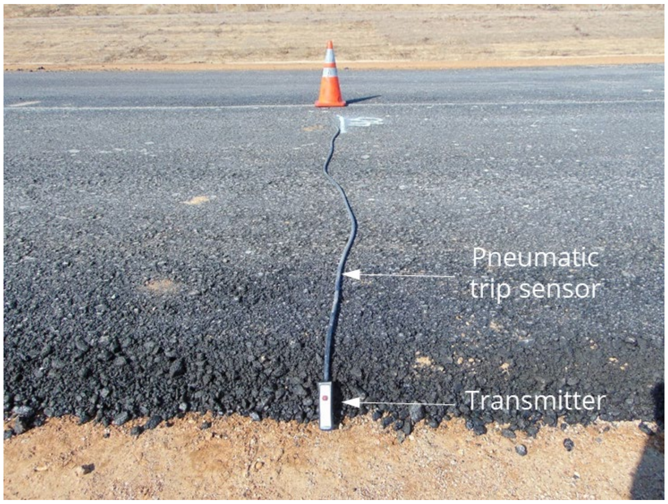
The Sentry then produces three different alerts based on the value of SSD as follows. If the approaching vehicle is within the SSD calculated using *t*=6 seconds, it activates alerts only on Worktrax. When the vehicle is within the SSD calculated using *t*=4.5 seconds, the warning lights are activated primarily to alert the drivers. If the driver fails to rectify the approach speed and is within the SSD for *t*=2.5 seconds, alerts are produced on Worktrax and the Sentry. The reference values for different speeds are provided in TABLE 4-1.

TABLE 4-1
DISTANCE FOR DIFFERENT ALERT TYPES ON THE SENTRY IN FEET

Speed (mph)	Alert type		
	Worktrax (*t* = 6 s)	Lights (*t* = 4.5 s)	Worktrax+Lights+Siren (*t* = 2.5 s)
30	117	95	66
35	142	116	82
40	169	139	100
45	197	164	120
50	227	190	141
55	258	218	164
60	292	247	189
65	326	278	215
70	363	311	243
75	400	345	272

4.1.3 Worker Alert System (WAS)

The Traffic Guard Worker Alert System is a pneumatic sensor-based technology comprised of three components: a pneumatic trip hose sensor with a signal transmitter, a Portable Alarm Case (PAC) housing a sound speaker alarm and LEDs, and Personal Safety Devices (PSD) for workers. These components are shown in Figure 4-4. The pneumatic sensor and PSD are powered by standard AA and AAA batteries, respectively. The PAC uses replaceable batteries that can be charged using an AC power adapter that come included with the PAC. The standard length of the pneumatic sensor available for purchase is 12 ft and 18 ft. The sensor hose is designed to detect pressure after it has been runover by an intruding vehicle. The PSDs can either be carried on a pocket or strapped onto the arm. PSDs are also provided with a reset button that facilitates alarm reset in case false alarms are triggered. In the field, the sensor is typically laid across the lane closure at the end of the transition taper where the intruding vehicle is most likely to run over it. The PAC is placed in the work area, close to workers. When pressure from an intruding vehicle is detected, the signal transmitter attached to the sensor hose sends alerts to the PAC and PSD within its range. The PAC produces flashing lights and sound alarm to alert the workers while the PSD produces a vibratory alert.



(a) Pneumatic sensor hose

(b) Portable Alarm Case (PAC) showing LED and position of the alarm speaker

(c) Personal Safety Device (PSD) with the remote reset button

Figure 4-4. WAS components

TABLE 4-2 presents a summary of notable characteristics of Intellicone, AWARE, and WAS, including the manufacturer recommended deployment strategies.

TABLE 4-2

NOTABLE CHARACTERISTICS OF THE CHOSEN TECHNOLOGIES

Characteristics	Intellicone	AWARE	WAS
Manufacturer	Highway Resource Solutions Ltd.	CRH America Materials, Inc.	Astro Optics LLC but sold by TAPCO Inc.
Country of manufacturing	United Kingdom	United States	United States
System components	• Cone mounted sensor lamps, and • Site alarm	• Sensor/alarm unit consisting of radar-based sensor, flashing LEDs and alarm speaker, and • Worktrax personal alarms	• Pneumatic trip hose sensor, • site alarm, and • personal alarms called PSD
Alert mechanism	Motion detection from vehicular impact on the traffic cones	Radar based vehicle tracking	Pressure exerted by vehicle running over the trip hose
Type of alert	Sound and flashing lights	• Sound and flashing LED on the sensor unit, and • vibratory and sound alert on personal alarms	• Sound and flashing lights on site alarm, and • vibratory alert on personal alarms
Deployment	• Sensors mounted on traffic cones placed around the work zone perimeter, and • site alarm close to the workers	• Main unit placed on the shoulder outside the transition taper facing the oncoming traffic, and • personal alarms carried by the worker	• Pneumatic sensor laid across the closed lane in transition area, • site alarm within the work area, and • personal alarms carried by the workers
Approximate cost (USD)*	$15-$35 for a set on a lease basis	$15,000	$575 for sensor and PAC; $170 for each PSD
Website	https://www.highwayresource.co.uk/smart-closure	NA	https://www.tapconet.com/product/worker-alert-system

*Note

- According to the manufacturers, the pricing of Intellicone elsewhere is based on the lease duration. Typically, sets of sensors and PSAs are provided to the consumers on a lease basis. During the lease period, all essential repair and maintenance on the systems is undertaken by the manufacturers without additional costs. A rough estimate provided by the manufacturers was between $15-$35 per day for a set of sensors and PSA.
- According to the manufacturers, the best estimate for the Sentry is approximately $15,000 per unit. They note that this estimate is expected to decrease after it is produced and sold at a larger scale.
- The cost of WAS is derived from TAPCO's web store: https://www.tapconet.com/product/worker-alert-system.

4.2 Controlled testing of selected technologies

The three technologies were tested in two phases: controlled testing and live testing. The goal of the first phase of testing was to evaluate performance of the technologies by emulating controlled work zone intrusions. This required a test location that was off limits to regular traffic and pedestrians. After careful consideration, site of an on-going road expansion project on TN-14 was chosen for controlled testing. The test site was an asphalt base with about 2000 ft of two-lane road. The road was approximately 25 ft wide with 6 ft shoulders on both sides. The location of the test site is shown in Figure 4-5.

Figure 4-5. Location of the test site used for controlled tests. The test site is highlighted in red. (Source: Google Maps)

Controlled tests on the technologies were carried out over a period of four days. To ensure comparability of results, experiments were undertaken on identical environmental conditions. Any experiment undertaken on a certain day was conducted on all three technologies on the same day. TABLE 4-3provides the test schedule for controlled testing.

TABLE 4-3

CONTROLLED TESTING SCHEDULE

Date	Time	Experiments conducted
13/11/2019	10 am-4 pm	1. Duration and intensity of sound alarm 2. Transmission range of system components
14/11/2019	10 am-4 pm	3. Alarm activation (False alarms) 4. Worker reaction to alerts
15/11/2019	11 am-2 pm	5. Alarm sound in presence of equipment
27/11/2019	12 pm-4pm	6. Additional testing on worker reaction

A detailed description of the experiment and results is presented in the following sub-sections.

4.2.1 Duration and intensity of sound alarm

Duration and intensity of sound alerts are crucial factors in determining noticeability of sound alarms. The intensity of sound alert perceived by the workers was measured at different distances from the alarms using a sound meter. The distance was varied between 0 ft and 300 ft at 50 ft intervals. Due to the test site's proximity to traffic nearby, ambient sound on the test site was measured prior to the tests and found to be 45 dB. Therefore, alarm sound intensities were measured only up to 300 ft to ensure that there was no interference from the ambient noise. At each interval, three readings for sound intensity and duration were recorded. Sound intensity of the alerts was measured on four perpendicular directions to the alarm. This was done to test if orientation of the alarms had considerable influence on the intensity of alerts produced. Previous studies have found that the intensity of alert is affected by the orientation of the alarm [12]. This is particularly relevant considering the placement of alarm speakers in the alarm units of the chosen technologies. Specifically, the placement of alarm speakers in Intellicone is symmetrical as it has three alarm speakers placed at about 120° to one another. The placement of speakers in AWARE and WAS, however, is asymmetrical since they are mounted only on one side of their respective alarm cases (see Figure 4-6 for details).

All experimental trials for Intellicone were carried out after mounting the PSA on a 28" traffic cone while no particular arrangement was necessary for AWARE. For WAS, the experiments were carried out with the PAC placed on the ground. To test for directionality in alarms, the sound intensities were measured on four perpendicular directions marked as shown in Figure 4-6.

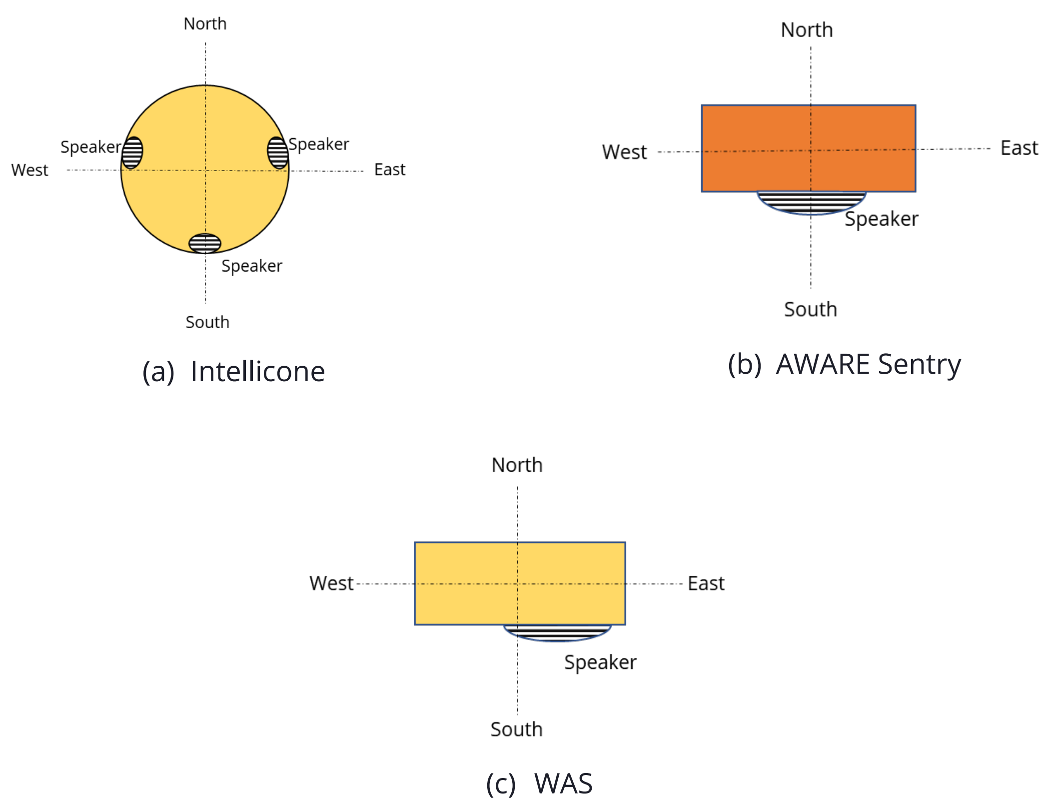


Figure 4-6. Relational directions used in measuring sound intensities of the technologies shown in top view. Placement of alarm speakers within the alarm units is also shown.

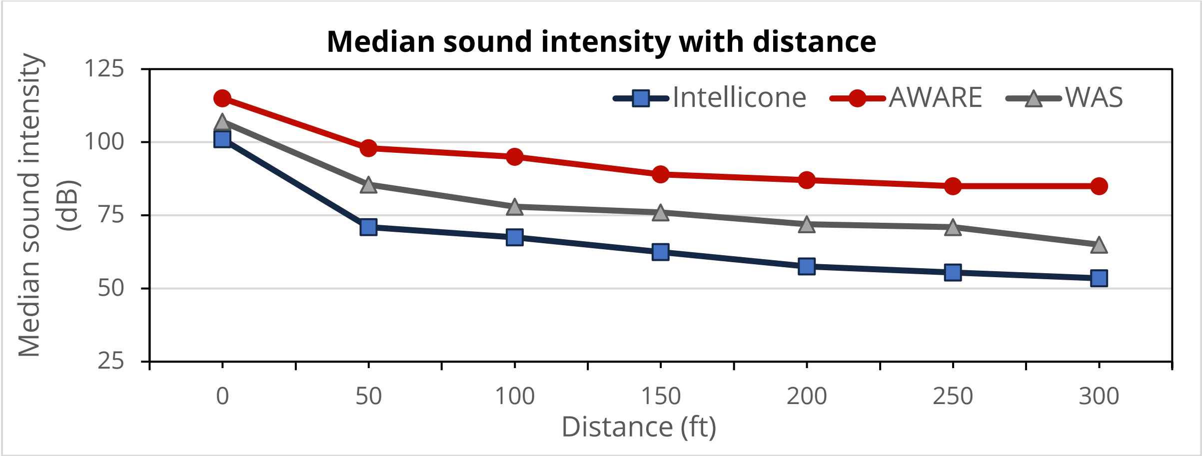
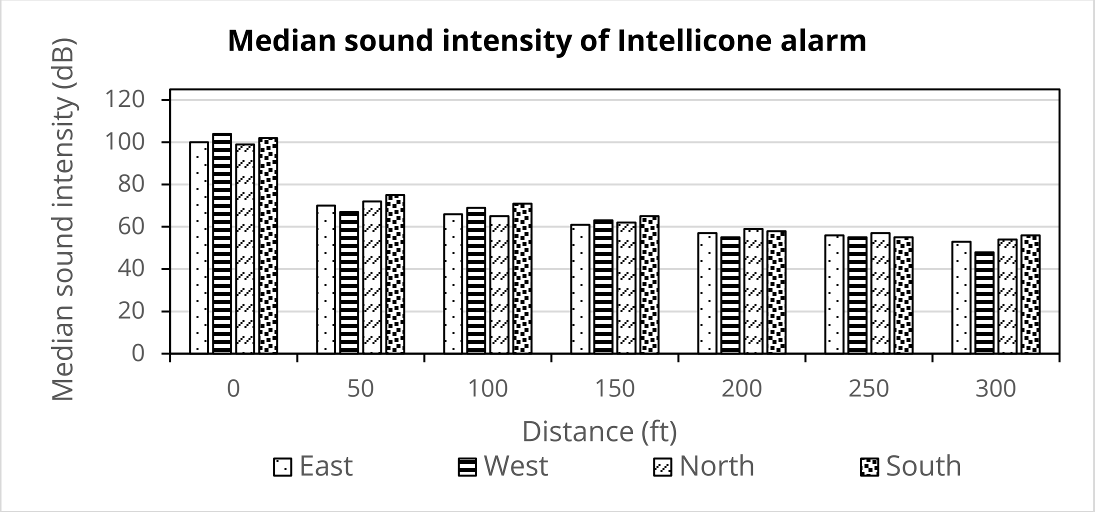
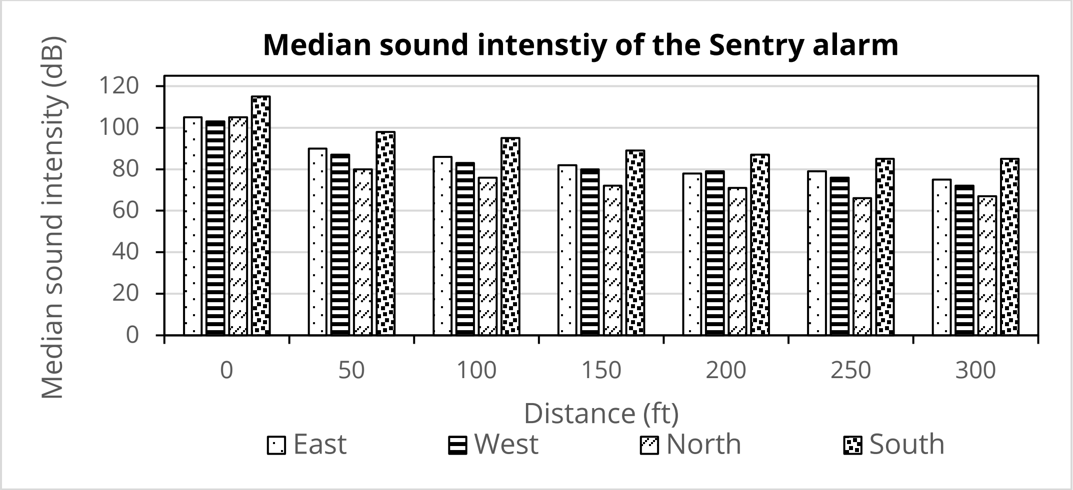


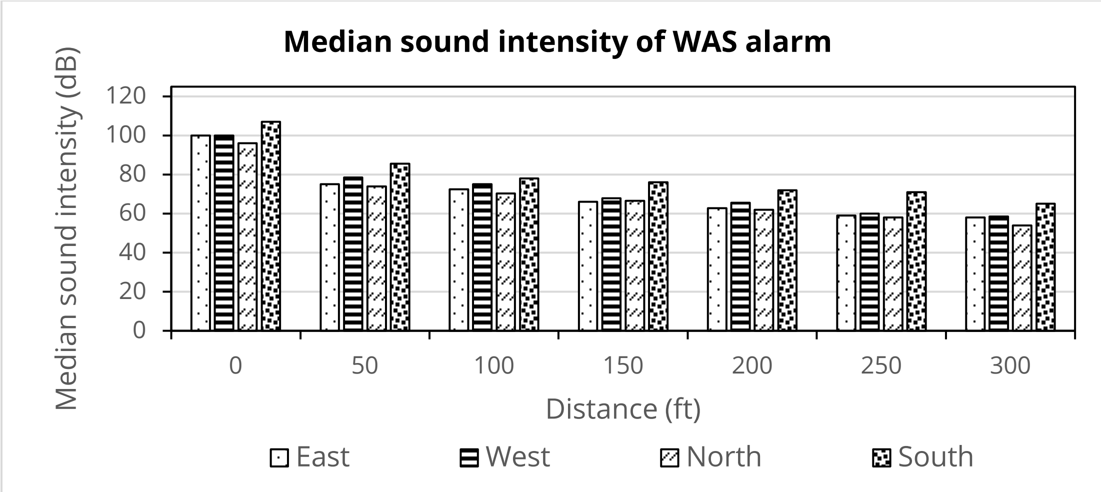
Figure 4-7. Variation in the sound intensity of alerts with distance



(a) Variation of intensity with distance and direction: Intellicone



(b) Variation of intensity with distance and direction: AWARE Sentry



(c) Variation of intensity with distance and direction: WAS

Figure 4-8. Results from tests measuring the intensity of alerts on different directions

At 0 ft, the intensity of sound produced by all three systems was found to be comparable and between 100-120 dB as shown in Figure 4-7. However, the difference in intensity was more prominent as the distance increased. At 300 ft, the highest sound intensity was measured for AWARE followed by WAS, and Intellicone. Figure 4-8 shows the intensity of alarms observed in four perpendicular directions. As expected, both AWARE and WAS showed notable directionality in sound alarms. Greater sound intensity was observed for AWARE and WAS with the speakers facing the sound meter (South direction). On the other hand, sound intensity of alarms produced by Intellicone was found to be more or less consistent on all directions.

The duration of the sound alarms was found to be consistent for all three alarms as indicated by their low standard deviations in TABLE 4-4. Intellicone was found to have the longest alarm, lasting 20 seconds, followed by AWARE (5 seconds) and WAS (4.7 seconds).

TABLE 4-4

DURATION OF SOUND ALERTS

WZIA technology	Mean duration (seconds)	Std. Dev. (seconds)
Intellicone	20	0.59
AWARE	5	0.62
WAS	4.7	0.22

Note: Number of observations=84

4.2.2 Transmission range

The transmission range between technology components is the maximum distance or range over which they can communicate. Transmission range is a limiting factor when deploying a technology since it determines the work zone area that can be covered by a technology. Furthermore, work zone coverage is a key factor that needs to be considered when choosing systems since WZIA technologies might be rendered useless when used in work zones that are longer than its transmission range. The goal of this experiment was to determine the transmission range for various components of chosen technologies as follows. An important thing to note here is that the transmission range here is determined between the sensor (transmitter) and alarm units (receiver).

i. Intellicone: Transmission range between
    a. a sensor and PSA.
ii. AWARE: Transmission range between
    a. the Sentry and Worktrax carried by the workers.
iii. WAS: Transmission range between
    a. the pneumatic sensor and PAC, and
    b. the pneumatic sensor and PSD carried by the workers.

In the experimental setup, the sensor units for the technology being tested was fixed at a point. The alarm unit was then placed at 50 ft intervals from the sensor unit. The communication between the sensor and alarm units were then tested by attempting to trigger alerts in the alarm using the sensor. For example, for Intellicone, the transmission distance between a sensor and a PSA was determined by fixing the sensor and moving the PSA away from the sensor at 50 ft intervals 50ft, 100ft, 150ft and so on (see Figure 4-9). At each of these intervals, three attempts were then made to activate the alerts by knocking down the sensors. If all three attempts were successful the transmission was assumed to be complete (or 100%), otherwise the transmission was assumed to be incomplete. The distance beyond which incomplete transmission was observed was considered as the transmission range [12]. A similar procedure was followed for AWARE and WAS components.

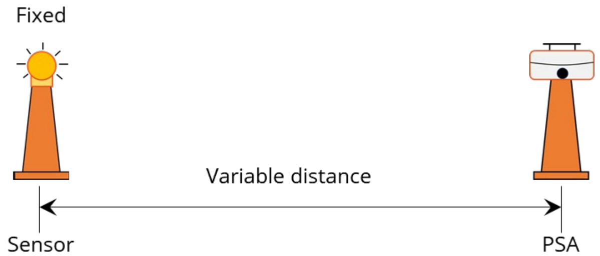
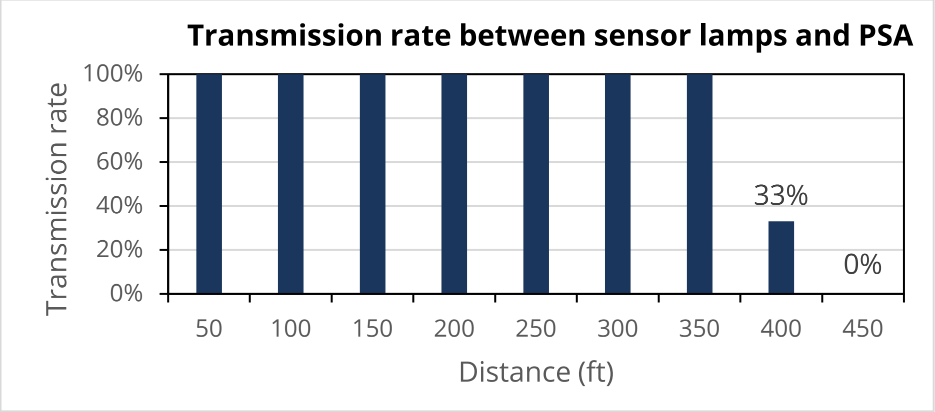
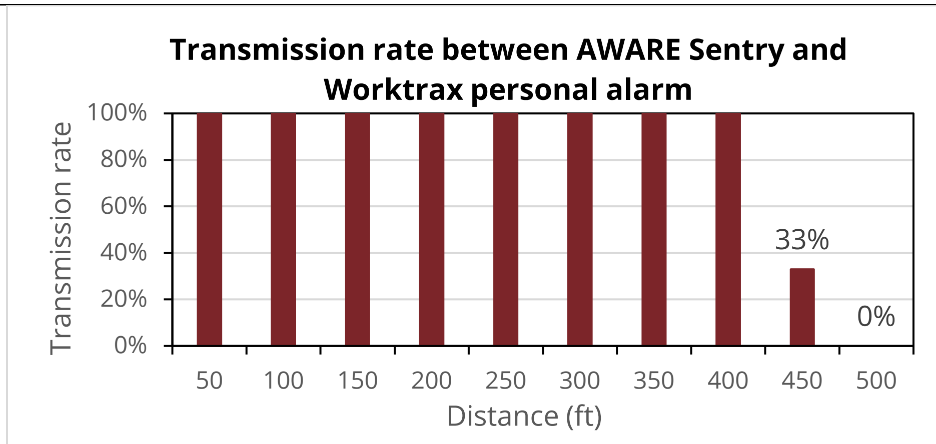


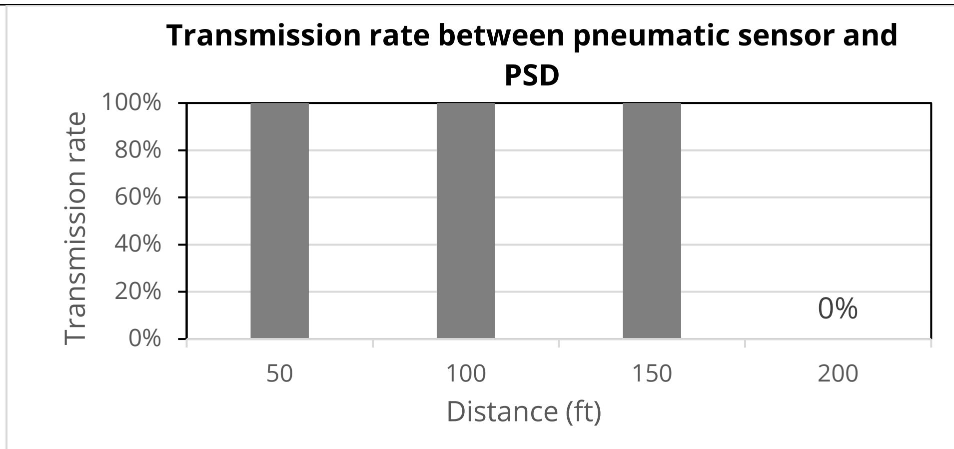
Figure 4-9. Experimental setup for determining transmission range of Intellicone



(a) Transmission range between Intellicone sensor and PSA



(b) Transmission between AWARE Sentry and Worktrax alarms



(c) Transmission between pneumatic sensor and PSD for WAS

Figure 4-10. Transmission range of different technology components

4.2.3 Alarm activation and worker response

Previous research has found that frequent false alerts result in workers ignoring the alarms which reduces the effectiveness of WZIA technologies [4]. A worker's timely response is another crucial factor needed to avoid a crash after an intrusion has occurred. In case of delayed alerts from WZIA technologies, workers might not have adequate time to perceive and react to an intrusion which can ultimately result in a crash. Therefore, accurate detection and prompt alerts needs to be carefully considered to determine the efficacy of WZIA technologies. In this experiment, the chosen technologies' ability to detect intrusions was determined through controlled intrusions where test vehicles traveling at different test speeds emulated work zone intrusions. Consequently, the time taken by the workers to respond to the alerts produced by alarm units following the intrusions was recorded and evaluated to determine the effectiveness of the chosen technologies.

4.2.3.1 Intellicone

The rate of successful alarm activation for Intellicone was determined using crash tests in which a test vehicle emulating work zone intrusions was driven into the traffic cones mounted with the sensors. A lane closure was set up, as shown in Figure 4-11, where traffic cones in the transition taper were mounted with sensors. Two PSAs were placed on shoulder, one close to sensors and the other close to a worker, 100 ft away from the first PSA. The distance between the two PSAs were fixed whereas the distance between the second PSA and the worker was varied between 100 ft and 150 ft.

Prior to the experiment, the worker was instructed to react to the sound of the alarm and ignore the sound of the vehicle crashing into the traffic cones. A pickup truck was used as the test vehicle and intrusions were emulated for speeds of 30 mph, 45 mph and 60mph. At each experimental trial, activation of alarms and the worker's response time was noted. It is noteworthy that worker response time here is the time between the vehicle entering the work zone perimeter and the worker reacting to the alarm.

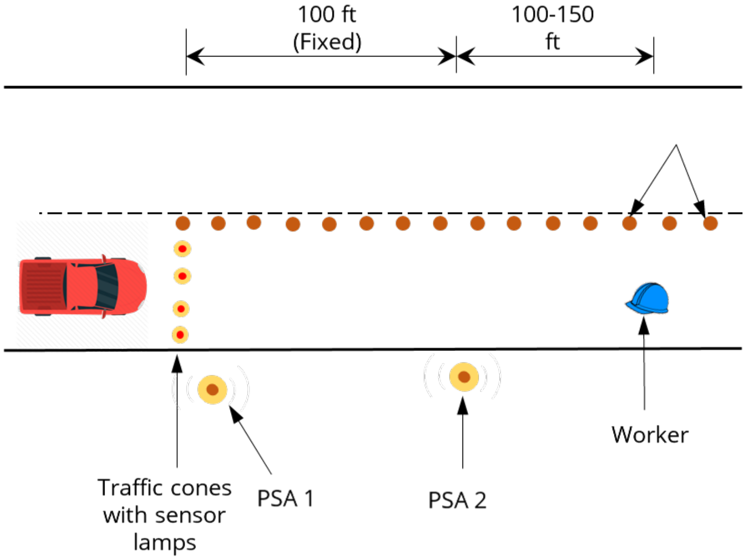


Figure 4-11. Experimental setup for testing alarm activation and worker response

Figure 4-12. Crash testing of Intellicone sensors

TABLE 4-5

RATE OF SUCCESSFUL ACTIVATION

Test speed (mph)	PSA 2 to worker distance (ft)	Success rate	Comments
30	100	66%	Only two of three attempts resulted in an alert
	150	66%	Only two of three attempts resulted in an alert
45	100	66%	Only two of three attempts resulted in an alert
	150	33%	Only one of three attempts resulted in an alert
60	100	0%	No alerts on all three attempts
	150	0%	No alerts on all three attempts

TABLE 4-5 presents the summary of successful activations observed during the experiment. For test speed of 30 mph, the sensor detected the intrusion successfully only two thirds of the time. The overall accuracy decreased even more at 45 mph. At test speed of 60 mph, the alerts failed to activate on all occasions indicating that at higher speeds the technology was less reliable.

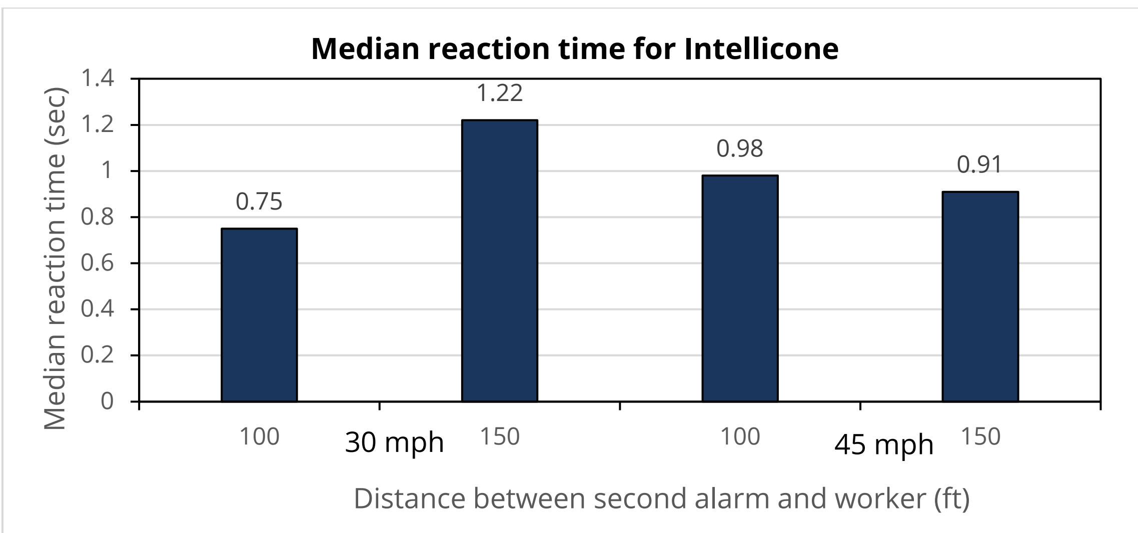


Figure 4-13. Observed worker reaction time for Intellicone

Shown in Figure 4-13 are the worker's response time. In general, the worker's response time was found to be less than 1 second. However, in some experimental trials the alerts were triggered considerably late. For example, at a test speed of 30 mph, the worker's response time at a distance of 150 ft was significantly higher than in the rest of the experiment trials. This was due to delayed activation of alerts. Furthermore, during one trial run, the alarms activated after the test vehicle had passed the worker. This suggested that there was an inconsistent latency between intruison detection and alert activation.

4.2.3.2 AWARE Sentry

Primarily designed for flagging, the Sentry detects errant vehicles using a threshold speed limit. Based on this, the researchers identified potential use scenarios to evaluate its accuracy in detecting intrusions. Three scenarios were identified for analysis which are discussed in the following subsections. Note that some of these tests were derived from a prior study [14].

4.2.3.2.1 Scenario 1: Vehicle violating the queue

The Sentry can be used to detect vehicles violating a queue formed in flagging operations using the threshold speed limit. In this experiment, the Sentry's accuracy was determined by first setting the speed limit on the Sentry and driving test vehicles towards it at different speeds to check for alert activation. Three vehicles were queued as shown in Figure 4-14 with the test vehicle placed between 100-150 ft from the Sentry. For the first set of experiments, a test vehicle was driven at 10 mph from behind the queue with the speed limit set to 15 mph on the Sentry to test for false positive alerts. In the second experiment, the same test vehicle was driven at 20 mph with the speed limit set to 15 mph to check for false negative alerts. The two experiments were then repeated with the speed limit set to 20 mph and the test vehicle travelling at 15 mph and 25 mph, respectively. The activations of the alerts were then noted.

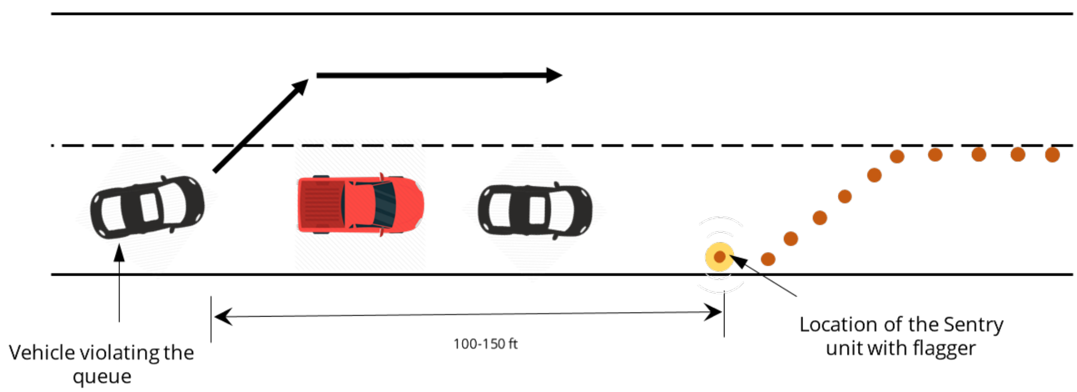


Figure 4-14. Experimental arrangement for testing AWARE Sentry: Scenario 1

TABLE 4-6

RATE OF SUCCESSFUL ACTIVATION OF THE SENTRY AND WORKTRAX: SCENARIO 1

Sentry to vehicle distance (ft)	Speed limit on the Sentry (mph)	Speed of test vehicle (mph)	Sentry alarm	Worktrax alarm	Comments
100	15	10	0%	0%	No alarms on all three trials
		20	100%	100%	Alarms on all three trials
	20	15	0%	0%	No alarms on all three trials
		25	100%	100%	Alarms on all three trials
150	15	10	0%	0%	No alarms on all three trials
		20	100%	100%	Alarms on all three trials
	20	15	0%	0%	No alarms on all three trials
		25	100%	100%	Alarms on all three trials

TABLE 4-6 shows the rate of alarm activation. Note that in the table, 0% refers to no alerts triggered during experimental trials. This was the desired results experiments in which the test speed was less than the threshold speed limit. As shown by the table, no false alarms were observed throughout the experiment.

4.2.3.2.2 Scenario 2: Vehicle passing by the Sentry at high speed

Scenario 2 tested the accuracy of alarms when vehicles passed by the Sentry at high speeds. The key distinction between the first and second scenarios was that for the first scenario, vehicles approached the Sentry from behind the queue. For this scenario, the Sentry was setup on the shoulder with the speed limit on the Sentry set to 10 mph. A worker equipped with a Worktrax personal alarm was placed within the work zone and a test vehicle driving at speed higher than 10 mph was driven towards the worker (see Figure 4-15). Any consequent alarm activations were then recorded. The experiment was conducted for test speeds of 30 mph, 45 mph and 60 mph. The Sentry was able to produce accurate alerts on all experimental trials as shown in TABLE 4-7.

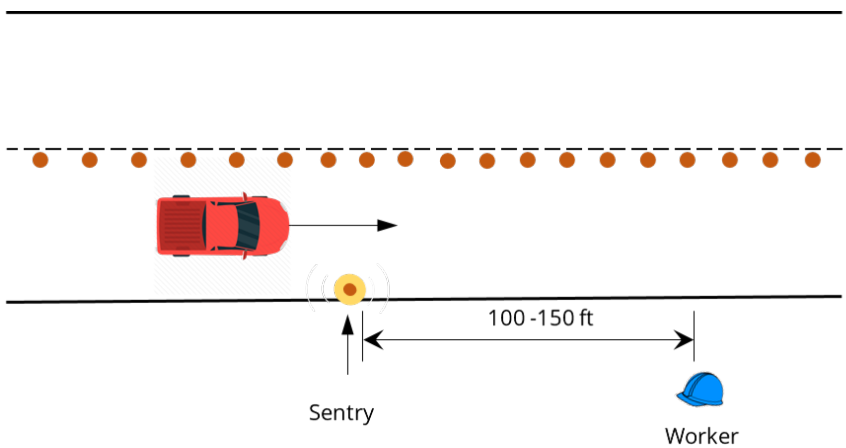


Figure 4-15. Experimental arrangement for testing AWARE Sentry: Scenario 2

TABLE 4-7

RATE OF SUCCESSFUL ACTIVATION OF THE SENTRY AND WORKTRAX: SCENARIO 2

Sentry to worker distance (ft)	Speed (mph)	Alert on Sentry	Alert on Worktrax	Comments
100	30	100%	100%	Alarms on all three trials
	45	100%	100%	Alarms on all three trials
	60	100%	100%	Alarms on all three trials
150	30	100%	100%	Alarms on all three trials
	45	100%	100%	Alarms on all three trials
	60	100%	100%	Alarms on all three trials

4.2.3.2.3 Scenario 3: Vehicle changing lanes to the lane with the Sentry

The goal of scenario 3 was to test the Sentry's ability to recognize abrupt intrusions. In this scenario, the test vehicle was initially driven on the lane adjacent to the Sentry and then abruptly moved to the lane with the Sentry as shown in Figure 4-16. As with Scenario 2, the Sentry was setup with a 10-mph speed limit and test vehicles were driven at a higher speed. Alarm activations were then recorded for each experimental trial for test speeds of 30 mph, 45 mph and 60 mph. Results from the experiment is shown in TABLE 4-8. As with previous scenarios, the Sentry was able to produce accurate alerts.

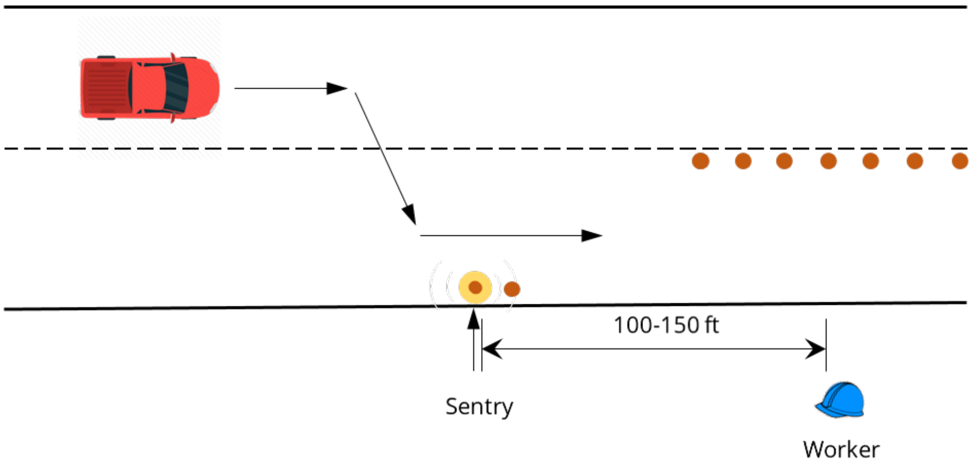


Figure 4-16. Experimental arrangement for testing AWARE Sentry: Scenario 3

TABLE 4-8

RATE OF SUCCESSFUL ACTIVATION OF THE SENTRY AND WORKTRAX: SCENARIO 3

Sentry to worker distance (ft)	Speed (mph)	Alarm on Sentry	Alarm on Worktrax	Comments
100	30	100%	100%	Alert on all three trials
	45	100%	100%	Alert on all three trials
	60	100%	100%	Alert on all three trials
150	30	100%	100%	Alert on all three trials
	45	100%	100%	Alert on all three trials
	60	100%	100%	Alert on all three trials

In WZIA technologies such as Intellicone, worker reaction time is a practical measure of a technology's ability to alert workers promptly. However, the Sentry is an advanced warning system, therefore, detection range of the system was evaluated as a substitute measure for worker reaction time in determining efficacy of the system. To determine detection range, a test vehicle was driven towards the Sentry at different test speeds. The exact location at which the sound alerts were activated on the Sentry was marked for each speed and the distance of the marked point from the Sentry was measured. Test speeds of 30 mph, 45 mph and 60 mph were considered. Results from the tests are shown in Figure 4-17. As expected, the observed detection range for the test speeds was found to be comparable to AASTHO SSD (equation (1) with t=2.5 seconds).

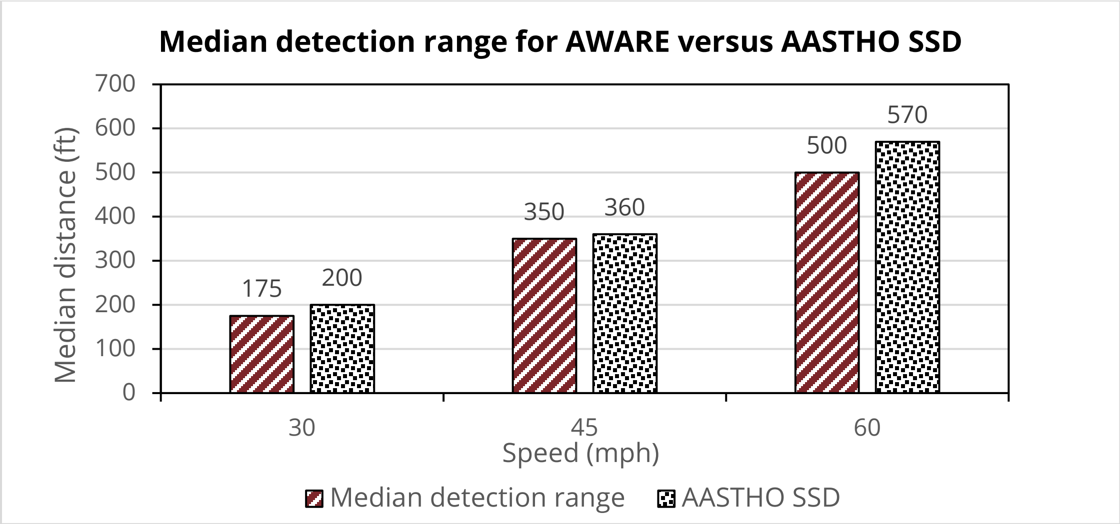


Figure 4-17. Detection range for the Sentry compared with AASTHO SSD

4.2.3.3 WAS

The experimental procedure for evaluating the accuracy and work reaction for WAS was similar to that of Intellicone. As with Intellicone, a test vehicle was driven into a work zone set up with WAS to emulate intrusions. The field setup for the experiment is presented in Figure 4-18. The pneumatic sensor hose was laid across the lane closure with the PAC next to it. A worker carrying a PSD was placed at 100 ft from the sensor and instructed to react to alert on the PSD. The experiment was conducted using test speeds of 30 mph and 45 mph. Alarm activation and worker reaction were then recorded for the test speeds. The experiment was repeated with the worker placed 150 ft away from the sensor. A dump truck was used as the test vehicle for the experiments (Figure 4-19) to ascertain the durability of the sensor in the presence of a heavier vehicle.

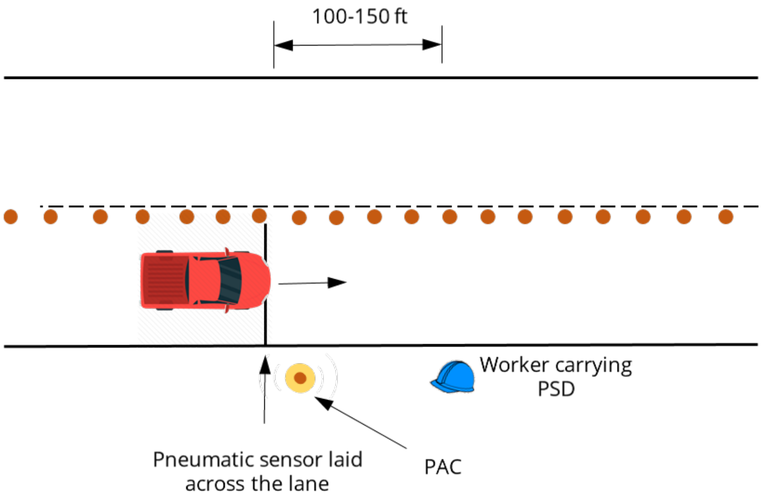


Figure 4-18. Experimental arrangement for testing WAS

Figure 4-19. Test vehicle running over the pneumatic sensor

TABLE 4-9

RATE OF SUCCESSFUL PSD ACTIVATIONS

Test Speed (mph)	Distance between sensor and PSD (ft)	Success rate	Comments
30	100	100%	Alert on all three trials
	150	66%	Only two of three attempts resulted in alarms
45	100	66%	Only two of three attempts resulted in alarms
	150	33%	Only one of three attempts resulted in an alarm

Result from the experiments on alarm activation are represented in TABLE 4-9. The experiment suggested that the transmission of signals from the pneumatic sensor to PSD was unreliable beyond 100 ft. When the distance between the two was greater than 100 ft, the accuracy of alerts was reduced.

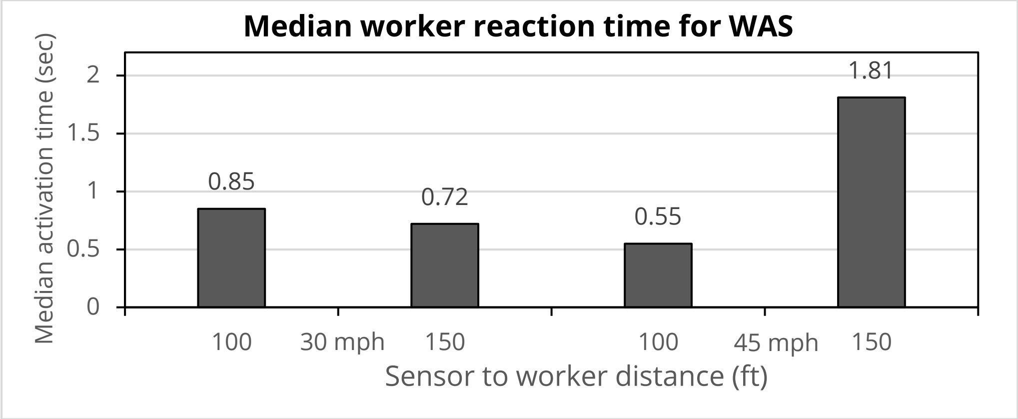


Figure 4-20. Observed worker reaction time

Worker reaction results are shown in Figure 4-20. Results show that the transmission between the pneumatic sensor and the PSD was unreliable when the two were more than 100 ft apart. For example, for a test speed of 45 mph at 150 ft, the median worker's reaction was measured to be about 1.81 seconds. This was considerably higher than the worker's reaction time on other experiments. This suggests that WAS was prone to significant transmission delay at times.

4.2.4 Sound intensity in presence of equipment

Workers in work zones often need to work around noisy equipment which results in distractions. Noise from equipment and operating machines might also prevent sound alarms from being heard. The goal of this experiment was to measure the sound intensity of intrusion alarms in the presence of equipment using a sound meter. Two possible scenarios were considered in the experiment which are discussed in detail in the following subsections. The experiments were conducted using an idling backhoe to mimic an equipment operating within the work zone. The experimental setup was identical for the alarm units of all WZIA technologies being tested. The experimental procedure followed were derived from a previous study [3].

4.2.4.1 Scenario 1: Worker is between the alarm and equipment

In this scenario, the idling backhoe was fixed permanently at a point. With the sound meter temporarily fixed 50 ft away from the backhoe, the alarms were moved at 50 ft increments away from the sound meter. At each incremental distance, the sound intensity of alarms was measured up to 450 ft. The same procedure was repeated after moving and fixing the sound meter at 50 ft intervals away from the backhoe. Figure 4-21 presents the experimental procedure.

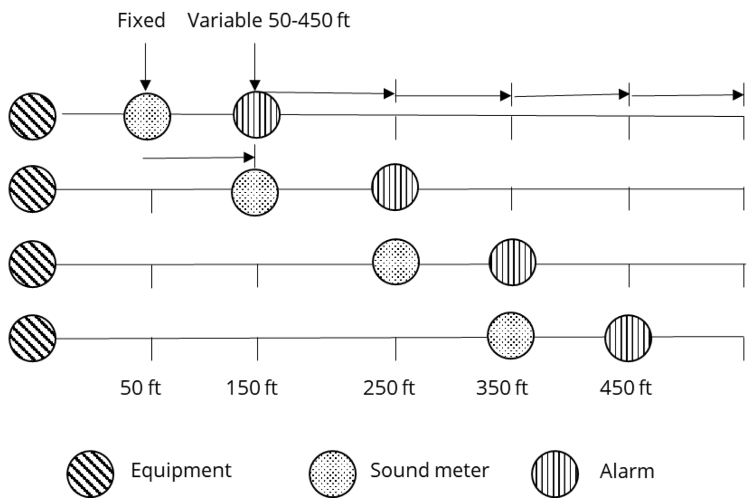


Figure 4-21. Experimental arrangement for evaluating sound intensity in presence of equipment: Scenario 1

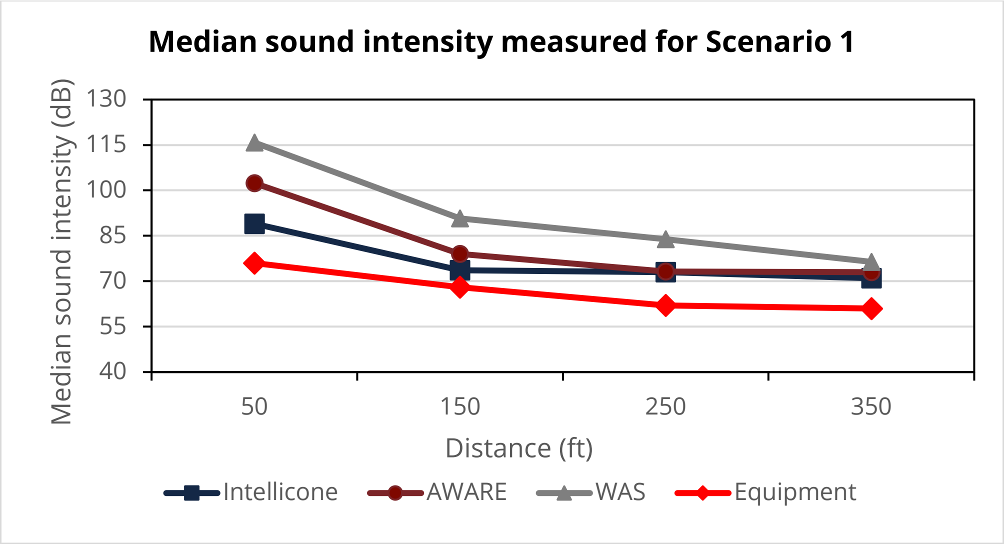


Figure 4-22. Results from experimental evaluating sound intensity in presence of equipment: Scenario 1

Results from the experiments suggests that the sound alerts produced by all three technologies were louder than the idling backhoe as evident from Figure 4-22. However, as distance increased, the difference in intensity of alarm sounds and the idling backhoe decreased suggesting that over large distances, the sound of equipment could potentially mask or overpower the alarm sounds.

4.2.4.2 Scenario 2: Alarm is between the worker and equipment

A similar procedure to scenario 1 was adopted for the second scenario with one key difference. In the second scenario, the sound meter was temporarily fixed in place of the sound meter. Figure 4-23 outlines the experimental procedure followed for this scenario.

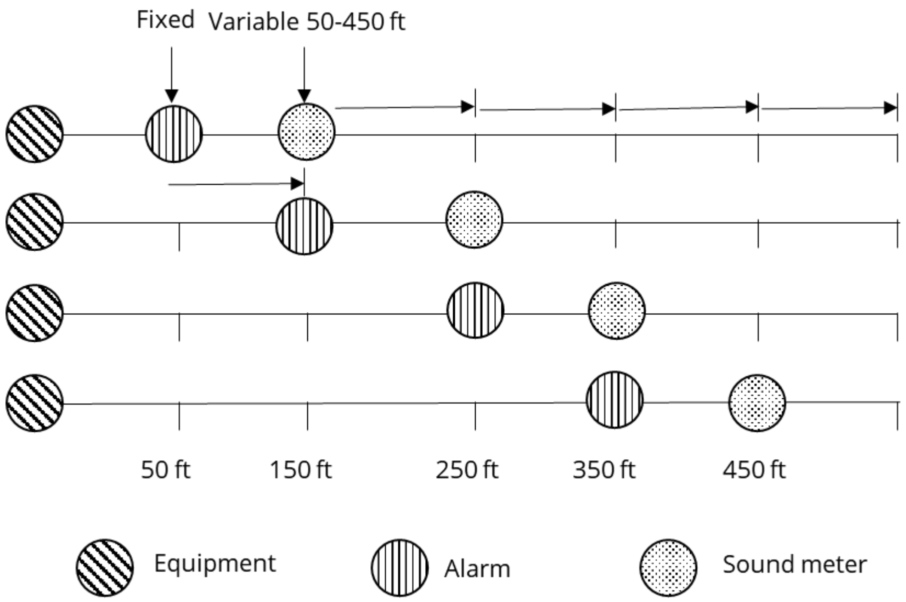


Figure 4-23. Experimental arrangement for evaluating sound intensity in presence of equipment: Scenario 2

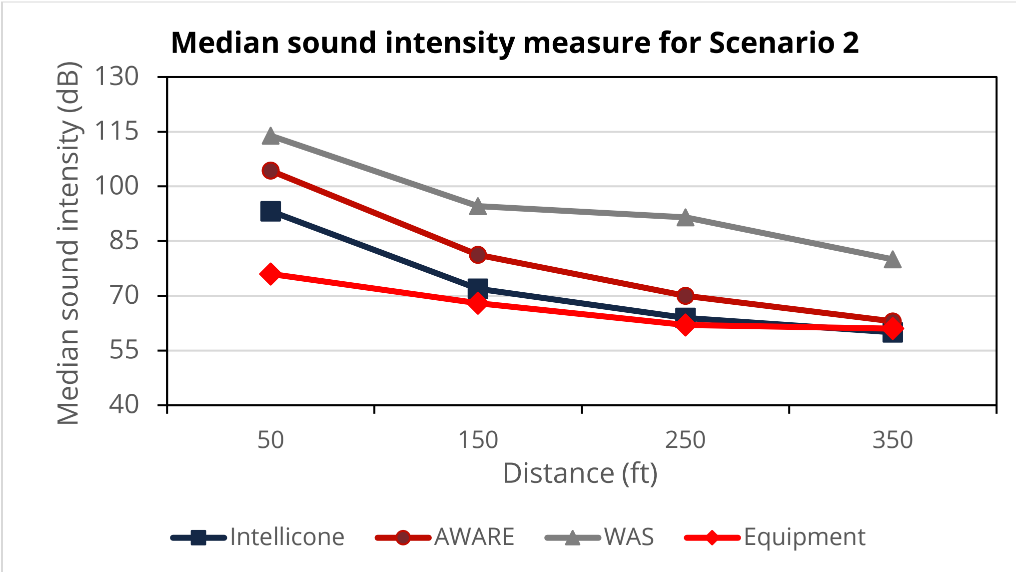


Figure 4-24. Results from experimental evaluating sound intensity in presence of equipment: Scenario 2

Results from the experiment on the second scenario suggested that although over short distances the sound of equipment was lower compared to the alarms, over long distances it could potentially diminish the alarm sounds. Figure 4-24 suggests that the sound from the backhoe was louder than alarms produced by Intellicone. However, it should be considered that the alarm sounds produced by the systems are high pitched and could be more distinct and noticeable. Therefore, the results highlighted the need to consider noticeability of alarms from the perspective of a worker working with or close to noisy equipment in real work conditions.

4.2.5 Summary of findings

The primary goal of controlled testing was to evaluate the performance of the selected technologies. Specifically, the accuracy, efficacy and work zone coverage were the focus of the controlled experiments. The likelihood of false alarms was found to be higher with Intellicone and WAS. Although occasionally, they were also found to have delayed transmission of signals. However, based on their deployment and use cases, both were found to be appropriate for use in specific types of work zones. Intellicone, due to its lengthy setup time and the ability to cover larger work zone perimeter through its IoT platform, can be ideal for long tapers and construction projects where traffic channelizers are fixed for long durations. On the contrary, WAS is suitable for short tapers, mobile work zones and short-term repairs away from the roadway (e.g., on shoulders), mainly due to its quick and easy deployment. AWARE was found to be the most accurate of the three technologies. It would be best suited for work zones with medium tapers and projects where flagging is required. It is noteworthy that although several strengths and weakness were identified for each technology, controlled tests provided an overall impression their abilities and ideal scenarios for implementation.

4.3 Live testing of technologies

After completion of controlled tests, the technologies were tested on live work zones where workers used them in on-going highway projects. Findings from controlled tests highlighted the need for additional research on noticeability of alarms in the presence of equipment. Furthermore, there was a need to evaluate user acceptance and collect feedback which could only be gathered from their use on actual work zones. The focus of live testing was to address these research needs.

On-going highway construction, repair, and maintenance projects in and around Shelby County were considered for live testing. Projects were selected primarily based on work zone typology. After the projects were identified, appropriate technologies were chosen for testing on each one. The projects were chosen a few days before the testing to be able to formulate a research plan. On the day of testing, before any work began, the research team briefed the work crew on the goal of the project and then provided an overview of the technology being tested. The technology chosen for testing was set up by the workers with help from the research team and used over a period of several hours until the end of the work. After the work was completed, feedback on the tested device(s) was collected using an on-site survey. The survey included questions on user friendliness, alarm noticeability, likelihood of use, and accuracy. Additionally, users were asked to provide comments and recommendations. An overview of the live testing schedule is presented in TABLE 4-10.

TABLE 4-10

LIVE TESTING SCHEDULE

Projects	**Date and time**	**Work zone type**	**Technology tested**	**Tests carried out**
Bridge repair on TN-195, Williston, Fayette County	12/3/2019 9 am-3 pm	Stationary	AWARE Sentry	• Driver reaction • User-friendliness
Pothole patching and asphalt resurfacing on I-269 (N bound) in Collierville, Shelby County	12/4/2019 10 am-3 pm	Mobile	Intellicone	• User-friendliness • Worker reaction and recommendations
Curb ramp repair on Park Ave. and Lamar Ave., Memphis, Shelby County	12/5/2019 8 am-4 pm	Stationary	Intellicone and WAS	• Effectiveness in presence of noisy equipment • Worker reaction and recommendations
Asphalt Resurfacing on South 3rd St., Shelby County	8/6/2020-8/7/2020 11 am-3 pm	Mobile	Intellicone	• User-friendliness • Worker reaction and recommendations
Curb ramp repair on S 3rd St. and W Shelby Dr., Shelby County	8/8/2020 8 am -5 pm	Stationary	Intellicone and WAS	• User-friendliness • Worker preference

4.3.1 Project 1: Bridge repair on TN-195

4.3.1.1 Project description

A bridge repair operation was being undertaken on a bridge deck on TN-195. The roadway consisted of a two-lane road (one lane in each direction) with narrow shoulders. The bridge deck was located at a lower elevation than the roadways connected to it in either direction. Therefore, vehicles needed to travel on a downgrade while approaching the work site and on an upgrade after crossing it. The eastbound lane on the road was closed for the duration of the repair and flaggers were deployed on both ends of the work zone to control traffic. The length of the lane closure was approximately 300 ft in either direction of the activity area. Two crews were working on the project, a seven-member crew for bridge repair and a four-member crew for flagging. An impact attenuator was used by the flaggers on the downstream end of the lane closure. Considering the need for flaggers, AWARE Sentry was chosen for testing. Figure 4-25 presents a layout of the work site.

Figure 4-25. Project 1: Arrangement of AWARE Sentry

4.3.1.2 Research plan

The research team, along with a representative from the manufacturing company provided a 5-minute overview of the Sentry to the flaggers. The flaggers were shown the procedure for arming and disarming it when restricting and allowing vehicle to pass through, respectively. One Sentry was provided to each flagger positioned at the ends of the work zone closure. Worktrax personal alarms were distributed to the flaggers. No speed limits were posted within 1 mile of the work area; therefore, the Sentry was set up with a speed limit of 30 mph since vehicles approaching the work site encountered a downward grade. During the duration of the work, a video camera was set up close to the flaggers to record the reaction of drivers while they are approaching the Sentry. After completion of the project, a paper survey and a short interview was administered to the flaggers.

Figure 4-26. Project 1: A company representative providing an overview of the Sentry

4.3.1.3 Findings

Users' opinions on the Sentry were positive overall. Flaggers expressed content when using the system. The flaggers noted that the sound alarm was able to capture the attention of negligent drivers due to its resemblance with the siren used by law enforcement. The repair crew located about 250 ft away from the Sentry, who were operating a generator and grinders, reported hearing the alarms. The sound intensity of the generator when measured was 65dB at 10 ft away. However, there were two key issues that were pointed out by flaggers in the survey comments and follow up interviews. These were as follows.

"The need to use a mobile app to configure the system does not seem right. The field setup is easy but many of our project supervisors are not up to date with smartphone applications and they may not always be present on-site. I think if we could use physical buttons or knobs to manually set the speed limit on the Sentry, it would be so much easier."

"The alarm sound definitely helps. Some people always speed even after seeing workers. The sound definitely seems to get their attention."

"The price tag seems overwhelmingly expensive. But I think it will be worth it."

4.3.2 Project 2: Pothole repair and asphalt resurfacing on I-269

4.3.2.1 Project description

The second project was pothole patching and asphalt resurfacing on I-269. The maintenance work was being undertaken on a four-lane divided highway (two lanes in each direction). Patching and resurfacing was being done on the two northbound lanes, one lane at a time. The lane closure setup for the maintenance work was approximately 2500 ft (see Figure 4-27). After the completion of repair on one of the closed lanes, the lane closure was moved to the adjacent lane. The project was being undertaken by a ten-member maintenance crew from TDOT. Heavy machinery such as a roller compactor, loaders and trucks were used on the job site for placing, leveling, and compacting asphalt concrete. Considering the length of the lane closure, Intellicone was considered for testing in the location.

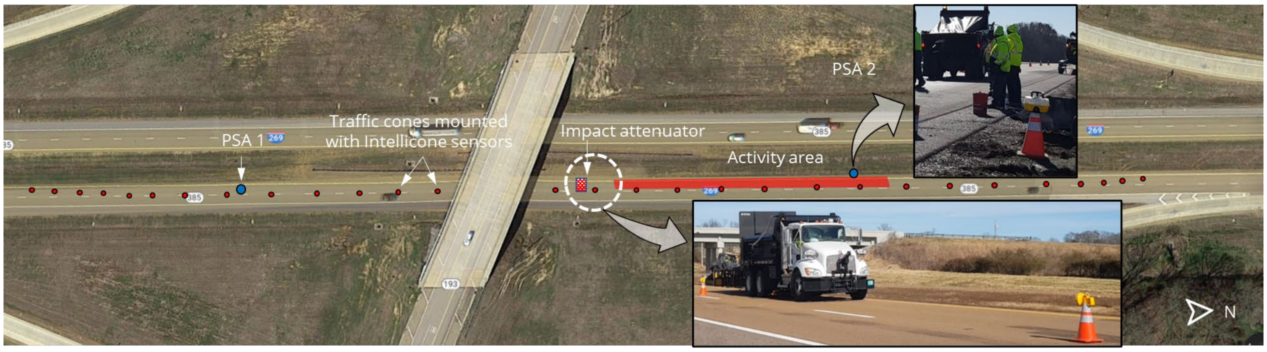


Figure 4-27. Project 2: Arrangement of Intellicone components

4.3.2.2 Research plan

Prior to the start of the work, the research team provided a short demonstration of Intellicone to the crew. The crew was given installation and use instructions. During the testing, Intellicone sensors were mounted on all traffic cones around the work zone perimeter. Two PSAs were then placed within the lane closure (one in the transition area and the second within the activity area as shown in Figure 4-27). A video camera placed close to the activity area was used to record workers' reaction to alerts produced by the alarm. After completing the repairs on one lane, the Intellicone setup was moved to the adjacent lane along with the construction equipment. After the work was complete, a survey was administered to the workers.

4.3.2.3 Findings

Workers had mixed opinions on Intellicone. While the workers were optimistic about its ability to mitigate crashes, they were concerned about its effectiveness in the setting they were being tested. False alarms were frequently encountered during the testing as the traffic cones where were knocked down several times by gusts from passing trucks (see Figure 4-28). To prevent this, the site supervisors suggested that the sensors could be mounted facing sideways to reduce the air resistance and prevent them from falling over. Although this prevented some false alarms, they could not be entirely avoided. Workers also suggested that false alarm could be reduced by making the cone mounted traffic cones more stable by lowering its center of gravity by allowing the sensors to mount further down the cones.

Figure 4-28. Project 2: Traffic cones knocked down by gusts from passing vehicles

Some representative comments of the workers were as follows.

"Overall, the idea sound interesting but frequently picking up knocked down traffic cones and resetting the false alarms is difficult especially when you are working close to high-speed traffic. I wish they would find a way to make it more stable so that passing vehicles don't knock it down. Maybe if the sensors could be mounted even lower, it would be more stable."

"The alarm is loud and clear. I could hear the alarm from the other end of the work zone. But moving the alarms is troublesome considering all the sensors and alarms must be moved and they trigger easily. It would help if we could temporarily deactivate them (sensors) somehow while we move them."

4.3.3 Project 3: Curb ramp repair on Park Ave. and Lamar Ave.

4.3.3.1 Project description

The repair of the curb ramp on Park Ave. and Lamar Ave. was being done by a TDOT maintenance crew of twelve workers. Of the two lanes on westbound Lamar Ave., approximately 350 ft of the right lane was closed to traffic, as shown in Figure 4-29. A crash attenuator was placed at the transition area along with a variable message sign informing drivers to merge into the adjacent lane. The work required the workers to operate a concreter breaker, a metal cutter and a power generator within the activity area. Considering the proximity of the activity area to nearby traffic and traffic flow, Intellicone and WAS were chosen for testing on the project.

4.3.3.2 Research plan

Since Intellicone and WAS were chosen for testing, about four hours were allocated for each one. First, the workers were provided an overview of Intellicone prior to beginning the work. Workers were provided instructions on setting up Intellicone. The PSA was kept within the activity area as shown in Figure 4-29. Since no intrusions were observed within the first two hours of the experiment, the sensors were deliberately triggered twice to capture worker reaction. This was done at approximately 1-hour intervals. After the was completed, an on-site survey was administered to the workers. Then, a brief overview of WAS was provided, and workers were guided on its installation. The pneumatic sensor was placed behind the traffic attenuator between two traffic barriers shown in Figure 4-29. Three workers were provided PSDs to carry on their pockets and the PAC was placed within the activity area. As no intrusions were observed, the pneumatic sensor was triggered intentionally to observe worker reaction. The testing was followed by a survey.

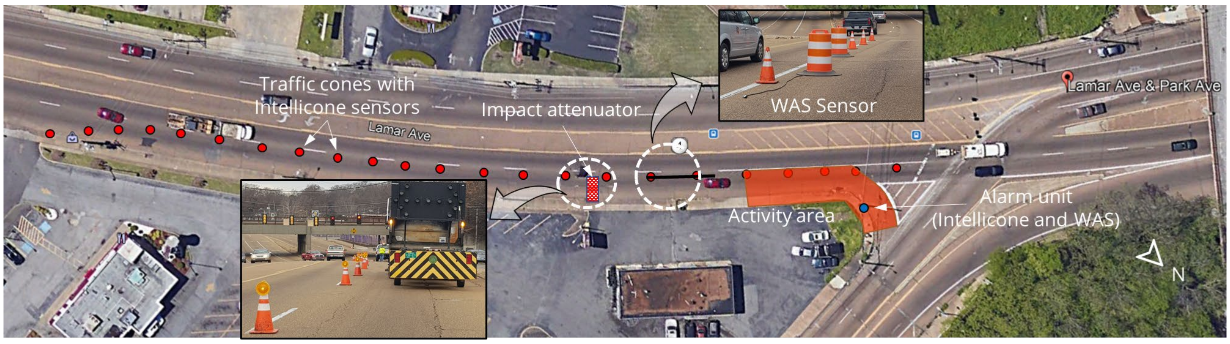


Figure 4-29. Project 3: Arrangement of Intellicone and WAS components.

4.3.3.3 Findings

A TDOT supervisor inspecting the work site reported that the traffic cones mounted with sensors made them more visible than conventional traffic cones as seen in Figure 4-30. Of the two attempts made to activate Intellicone alarms intentionally, only one was successful. Both attempts to activate alarms on WAS were successful. Sound alarms from Intellicone and WAS were clearly audible to the workers even when operating machinery. Workers also reported that the vibration from the PSD was noticeable, except when operating a concrete breaker.

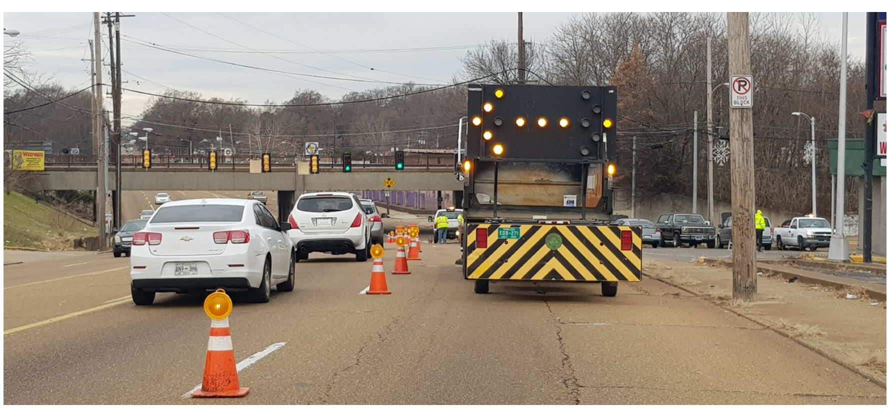


Figure 4-30. Project 3: LEDs on Intellicone sensors

The workers in general highlighted concerns regarding the efficacy of the system when used in work zones that are close to traffic. In the case of Intellicone, workers recommended better tuning of Intellicone sensors to make them less prone to false negative alarms. A common concern among the workers with both technologies was their effectiveness when used in work zones that are close to the traffic. Under such circumstances, workers expressed doubts whether the alarms would be able to provide any safety at all. Furthermore, workers felt that WAS would not be effective in covering larger work zone perimeters.

Some representative comments collected from the workers during the survey were as follows.

On Intellicone:

"I noticed the lamp sensors while making rounds. They are distinctively different compared to the cones we use. Vehicles knocking down traffic cones is common around here. These lamps I think will make drivers more aware so they don't get too close and knock them down."

On WAS:

"I have never come across such a device. The sound and vibrations were loud. But we work too close to the edge of the work area and I doubt it would be effective if a speeding vehicle entered the perimeter and hit us. But it is better than having nothing".

4.3.4 Project 4: Asphalt resurfacing on South 3rd St.

4.3.4.1 Project description

An asphalt resurfacing project on a four-lane (two lanes in each direction) section of South 3rd St. in Shelby county was chosen as the next project for live testing. About 1500 ft of the right southbound lane was closed to traffic as shown in Figure 4-31. The work was being undertaken by a private contracting firm and was overseen by a TDOT supervisor. Heavy machines, including an asphalt paver and a roller compactor, were actively used in the activity area. During maintenance, workers would typically pour concrete, use rollers to compact it and move to a new location further downstream to work on the next area. This necessitated a work zone to be set up over a long section of the newly resurfaced road. Considering the length of lane closure and duration of work, Intellicone was chosen for testing in this location.

Figure 4-31. Project 4: Arrangement of Intellicone components

4.3.4.2 Research plan

The work crew was first briefed on the objective of the study and then provided instructions on Intellicone setup. The sensors were installed on the traffic cones with the help of the crew while the lane closure was being setup. Since the workers were using loud, heavy equipment and constantly moving, PSAs were placed on the equipment as shown in Figure 4-32. To prevent false alarms due to vibrations from nearby equipment, the crew was instructed to remove nearby sensors before they began working with heavy equipment and reinstall them before moving to a new location after the work was completed. After the testing was completed, a follow up interview was conducted on the workers.

(a) PSA on a paver (b) PSA on a roller compacter

Figure 4-32. Project 4: PSA mounted on equipment

4.3.4.3 Findings

Intellicone produced several false positive alarms during the duration of the testing. The vibration from the roller compactor set off the alarms on several occasions. To prevent this, sensors within 50 ft of the roller compacter were removed before it was used. As a result, the sensors had to be constantly removed and reinstalled. The workers considered this to be time consuming and labor intensive and therefore often chose not to reinstall the system after they had completed the work. Otherwise, the workers however were positive towards using Intellicone.

Representative comment collected from a worker was as follows.

"The alarm works well but we don't have the time to set up the sensors. We have limited workers and time, and everyone is assigned a particular task. That makes it really difficult for us to work with the system."

4.3.5 Project 5: Curb ramp repair on South 3rd St. and West Shelby Dr.

4.3.5.1 Project description

Curb repair on South 3rd St. and West Shelby Dr. involving the removal of the existing damaged concrete curb and casting a new curb ramp was chosen as the next project for live testing. The project was being undertaken by a crew of six workers from a private contracting firm in presence of a TDOT supervisor. The curb ramp undergoing reconstruction was located on a right turn slip lane. Throughout the work duration, the right turn lane was closed to the traffic. The maintenance work required casting the curb using concrete. Therefore, a concrete mixer truck was frequently required to enter and exit the work area. The lane closure was approximately 175 ft long as shown in Figure 4-33. Based on the type of work, Intellicone and WAS were selected for testing at the location.

4.3.5.2 Research plan

Similar to the procedure followed on earlier live tests, Intellicone and WAS were tested successively after providing a brief overview of the technologies. Since no intrusions were detected, alerts were deliberately triggered on the alarm units to gather worker reaction and feedback.

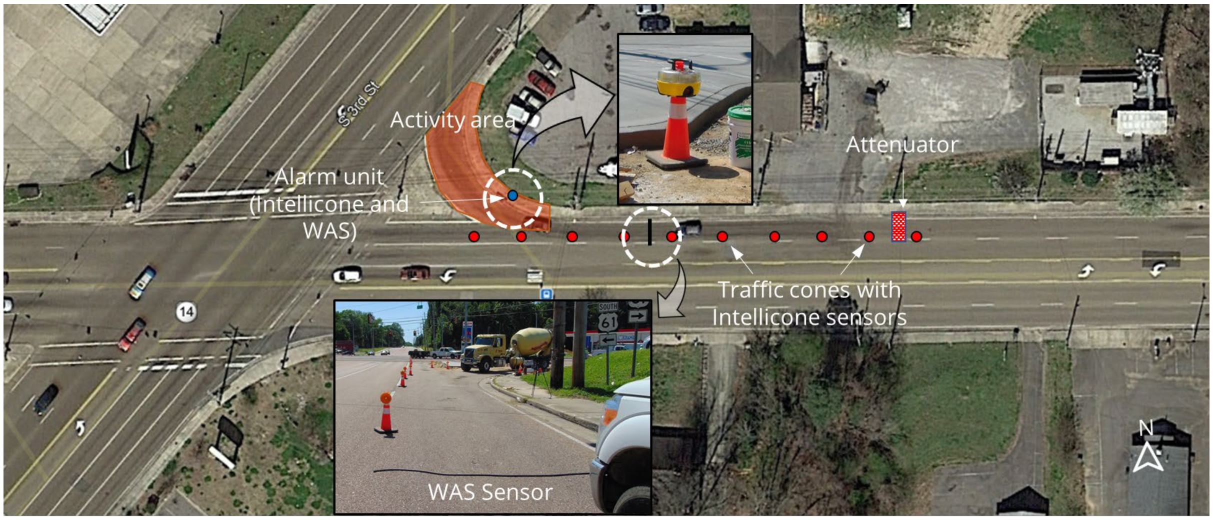


Figure 4-33. Project 5: Arrangement of Intellicone and WAS components

4.3.5.3 Findings

Survey and follow up interviews revealed similar findings to those of previous project. Workers expressed reluctance towards using the technologies, mainly due to the time involved in their setup. Since the nature of the work entailed working close to the traffic, according to the workers, their effectiveness was questionable. This was particularly relevant for Intellicone since the work traffic cones needed to be moved frequently to allow concrete mixer trucks into the work area. Although the workers were initially accepting towards using Intellicone, frequent false alarms when moving the cones resulted in workers ignoring the alarm sounds altogether and leaving the work zone perimeter open to avoid any further alarms.

Figure 4-34. Project 5: Work zone perimeter left open

Key representative comments from workers involved in testing were as follows.

On Intellicone and WAS:

"I have been working for several years on this type of job, but I have never encountered any crashes. In my opinion, setting up and removing system every time some equipment comes in or goes out just wastes our time. If something (errant vehicle) was to enter the work area and hit us, these devices would not help. We work too close to the road."

On WAS:

"I could feel the alarm in my pocket even when I was working but I noticed a lag. The alarm went off after some delay. I like the idea of sensor and alarms, but I am not sure if this would be very effective. If something were to hit us, it would happen too fast for us react."

4.3.6 Summary of findings from live testing

Results from live testing in general suggested that workers were hopeful and open to using WZIA technologies. However, accuracy and effectiveness of the alarms were concern for most workers. Most of the workers suggested that adopting at least some alert technology would be helpful. TABLE 4-11 presents a summary of findings from live testing the systems.

4.3.7 Results from on-site survey

Results from on-site survey is presented in the following subsections. Of all the survey responses collected from workers in five projects, 37 (Intellicone-24, AWARE-4, WAS-9) were complete. Results from these are summarized here.

4.3.7.1 Prior experience with work zone safety systems

Reponses from on-site surveys suggested that most of the workers surveyed had some prior experience with at least one work zone safety system. The majority of workers reported familiarity with flagging operations followed by portable changeable message signs, and rumble strips.

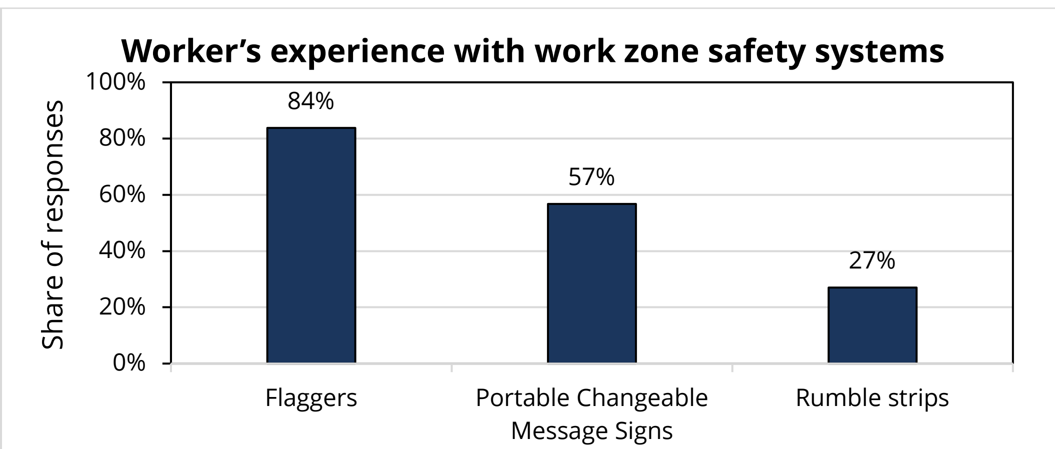


Figure 4-35. Workers' response: Prior experience with work zone safety systems

TABLE 4-11

SUMMARY OF FINDINGS FROM LIVE TESTING

Projects	Technology tested	Observations	Recommendations
Bridge repair on TN-195, Williston, Fayette County	AWARE Sentry	• The workers approved of the nature of the AWARE alarm, i.e., its close resemblance with law enforcement. • Vehicles approaching the flagger at high speeds tend to slow down on hearing the alarms. • The sound from the alarm unit was clearly discernable to the workers at a distance of 150 ft in the presence of an idling generator running next to them.	• Setup of the Sentry unit using a mobile application didn't seem practical to the flaggers. Flaggers recommended addition of physical buttons or knobs to be able to configure the device on site. • The Sentry might be too expensive for large scale use.
Pothole repair and asphalt resurfacing on I-269 (N bound) in Collierville, Shelby County	Intellicone	• The idea of sensors lamps, and alarm units seemed appealing. • The sound of the alarm could be clearly heard up to 300 ft away, despite heavy equipment operating nearby.	• Because of the frequent false alarms, workers recommended making the sensors more stable and less prone to being activations by vibrations by lowering the mounting position of the sensors to a lower portion of the cones. • There is a need for a mechanism that temporarily deactivates the sensors while they are being moved.
Curb ramp repair on Park Ave and Lamar Ave., Memphis	Intellicone and WAS	• Workers driving by the work site noted that traffic cones with Intellicone sensors were more effective than traffic cones in gaining attention of the drivers. • Vibration from WAS personal safety device was noticeable while working, except while operating heavy machinery with vibration such as concrete breakers.	• Workers recommended tuning the sensors, to make them more accurate before being used in the future. • Application of WAS for similar work zones seemed impractical considering the workers would be working close to traffic.
Asphalt Resurfacing on South 3rd St., Shelby County	Intellicone	• Frequent false alarms from vibration of nearby equipment (roller compactor).	• Setup is time consuming and labor intensive.
Curb ramp repair on S 3rd St. and W Shelby Dr., Shelby County	Intellicone and WAS	• The workers approved using both technologies but felt they were inappropriate for work zones close to the traffic.	• WAS seemed impractical for use in maintenance work zones where workers work close to traffic. • Intellicone would be appropriate where frequent movement of equipment and people are not required.

4.3.7.2 Effectiveness of technology in improving work zone safety

In response to the technology's potential to benefit work zone safety, workers were mostly optimistic. Flaggers found AWARE to be very effective (100%). A small portion of workers were doubtful regarding Intellicone (4%) while some workers were unsure whether Intellicone (8%) and WAS (11%) would be beneficial.

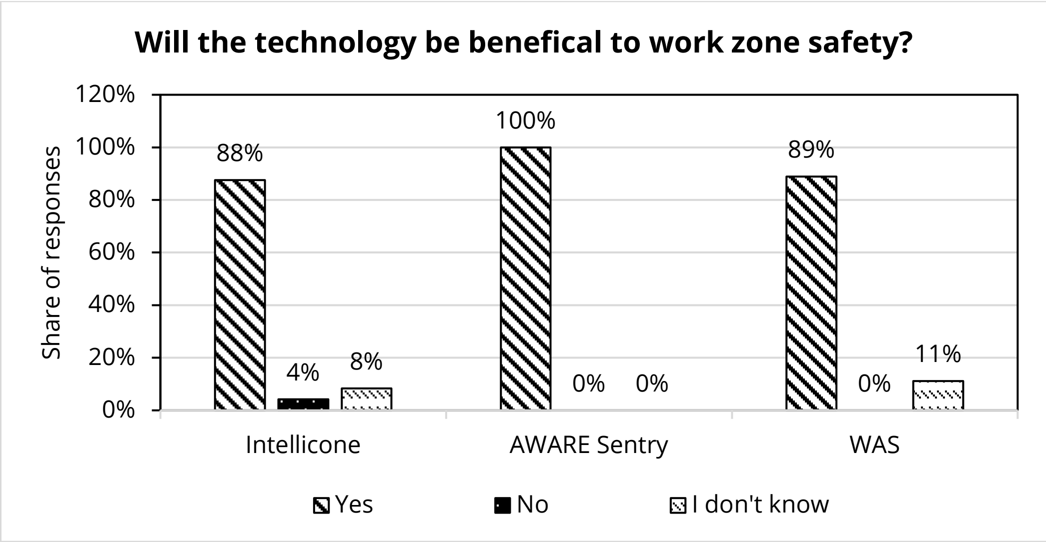


Figure 4-36. Workers' response: Effectiveness of systems

4.3.7.3 User friendliness

Overall, installation of the three technologies was convenient according to the workers. Responses indicated that all the systems were perceived to be user friendly to install and use.

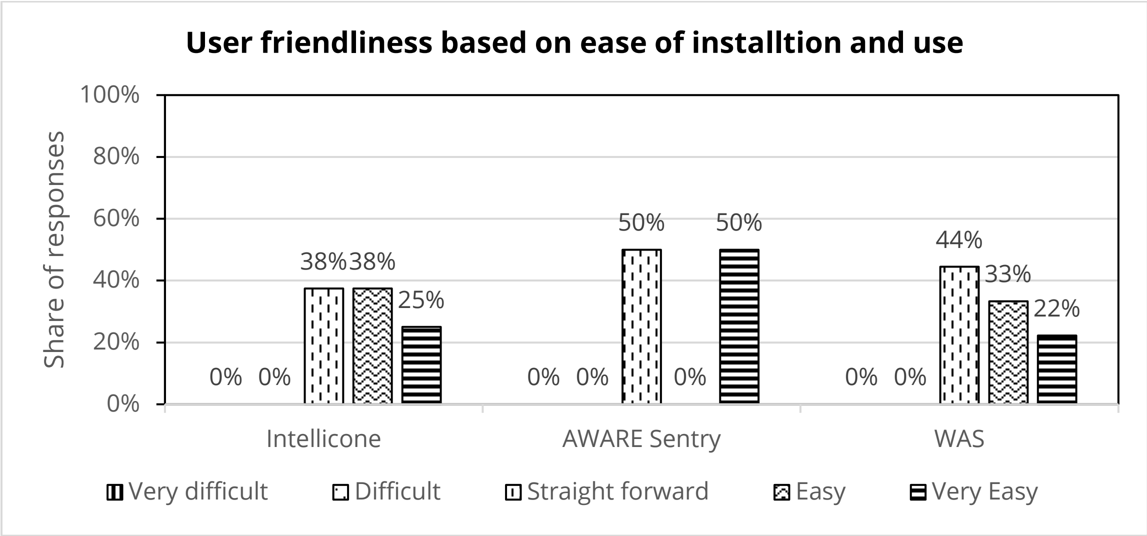


Figure 4-37. Workers' response: User friendliness

4.3.7.4 Overall alarm noticeability

No considerable issues related to the noticeability of alarms was observed from experiments carried out on the technologies during controlled and live testing. Additionally, workers were also found to be generally content with the noticeability of alerts produced by the devices.

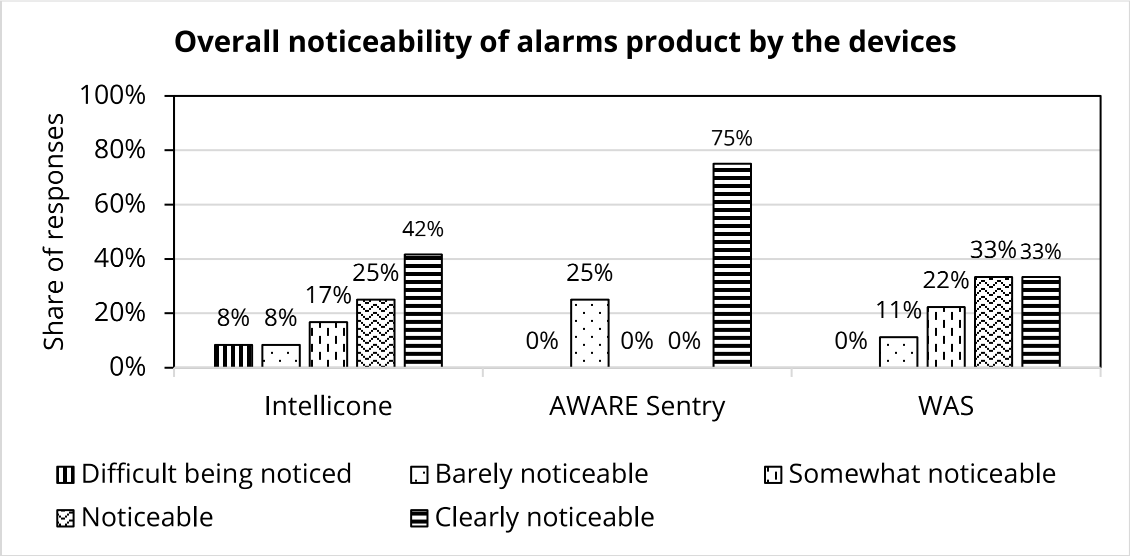


Figure 4-38. Workers' response: Noticeability of alarms

4.3.7.5 Likelihood of false alarms

Workers expressed that Intellicone and WAS were more likely to cause false alarms compared to the Sentry.

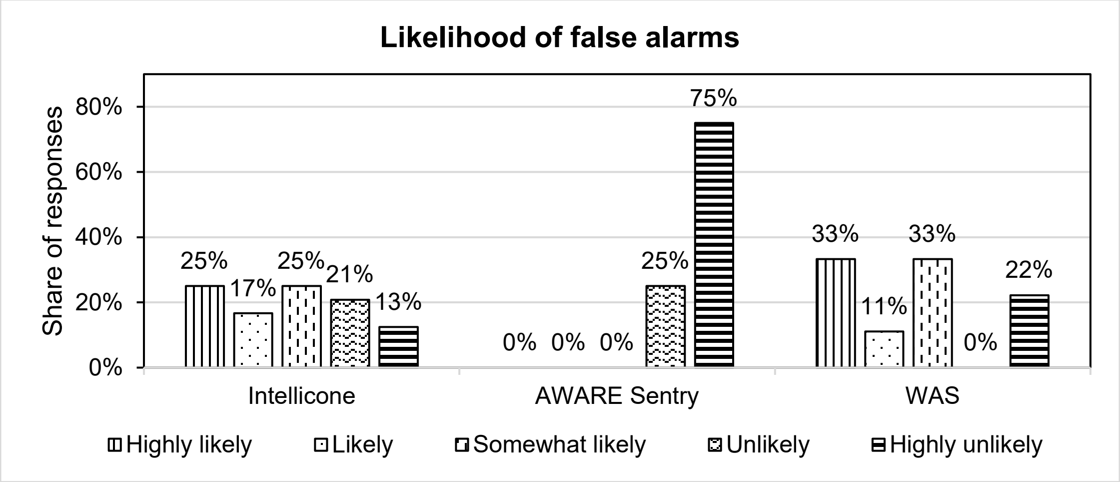


Figure 4-39. Workers' response: Likelihood of false alarms

4.3.7.6 Durability of system components

Although workers in general believed the components of all three technologies were durable. In comparison to the Sentry, Intellicone and WAS were perceived to be less durable.

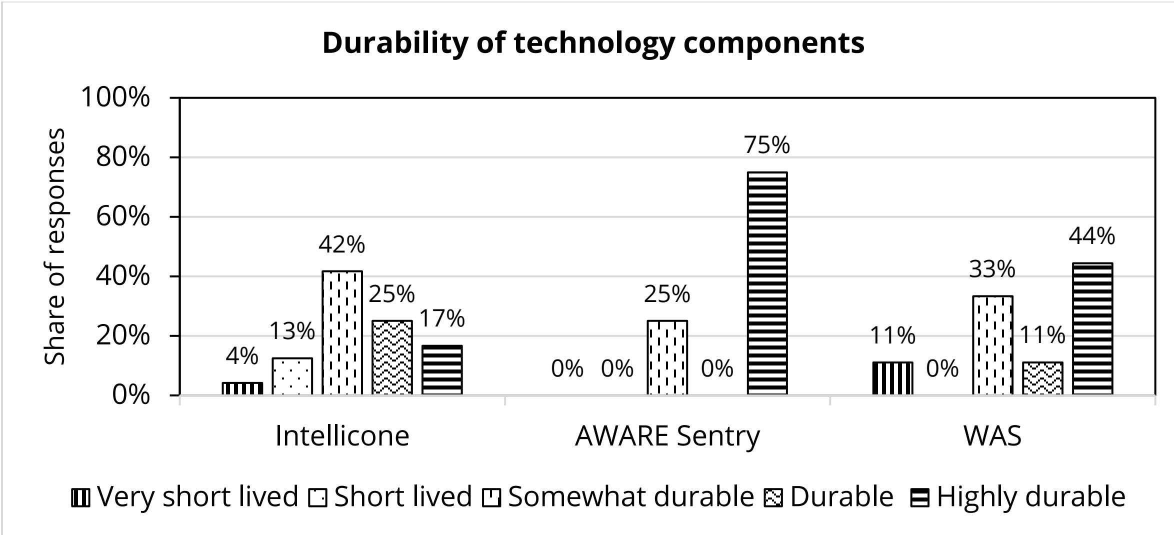


Figure 4-40. Workers' response: Durability of systems

4.3.7.7 Likelihood of adoption given cost

Since a reasonable estimate for Intellicone and the Sentry was not available during the tests, workers were provided with a hypothetical scenario where they were asked the likelihood of the technologies being used in work zones considering the cost of the technologies. Cost estimates for Intellicone and AWARE Sentry were based on previous research. The survey question was as follows:

"Intellicone PSA along with 10 sensor lamps costs about $2,500.
WAS with the sensor, alarm and 2 personal safety devices costs about $850.
AWARE Sentry comes with 4 Worktrax personal alarms and costs about $30,000.

Given these costs how likely are you to adopt it for work zone safety on a scale of 1 to 5 with 1 being "very unlikely" and 5 being "very likely"?"

Despite the high prices, workers believed that the technologies should be implemented on work zones.

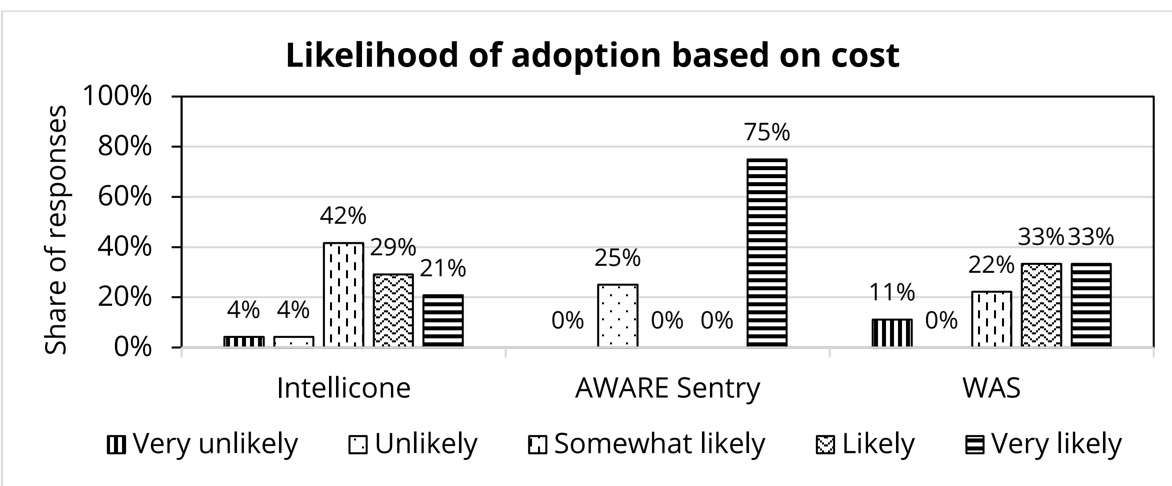


Figure 4-41. Workers' response: Adoption considering cost of the technology

4.4 *Live tracking abilities of the technologies*

Intellicone and AWARE both provide live tracking features using their respective platforms that is accessible through the internet. Both also support a mobile app that can track all units deployed in the field. On the contrary, no live tracking features is offered by WAS.

Seven scoring factors were identified from a related research to score the two technologies on their live tracking features [25]. While scoring, full points were awarded on features supported by the technologies.

TABLE 4-12

SCORING OF LIVE TRACKING ABILITIES

Scoring factors		**Description**	**Total score**	**Scoring**	
				Intellicone	**AWARE**
Work zone information	Temporal	Time stamps for the beginning and ending of work zone is provided and updated in real time.	0.5	0.5	0.5
	Spatial	System can track the location of work zone in real time	0.5	0.5	0.5
Incident detection and reporting	Detection	System can detect crashes and other incidents and communicate them in real time.	0.5	0.5	0.5
	Reporting	Incidents are reported through several means such as a mobile text, email, and mobile application push alerts.	0.5	0.5	0.5
Incident data		Incident data, such as type of incident and speed of vehicle, can be recorded and shared in real time.	1	0	1
Surveillance		System can record and communicate surveillance videos of incidents in real time.	1	0	0*
Inventory tracking		Assets deployed can be tracked in real time (e.g., number of active components, status of active components)	1	1	1
Total score			**5**	**3**	**4**

Note: *The Sentry can record a video of incidents; however, the video feed cannot be shared in real time. Video recordings are stored in Sentry's system until they are connected to a Wi-Fi network and uploaded to the cloud, after which they are available for viewing across the mobile and internet platforms.

After a review of the live tracking features for Intellicone and AWARE, both were found to have comparable features integrated into their platform. AWARE scored slightly higher than Intellicone due to its ability to capture more detailed incident data, which includes intrusion speed and a recording of the intrusion. It is noteworthy that currently, AWARE's live tracking platform is limited to testing only while Intellicone's live tracking feature is used by customers across the UK. Table 15 presents the scoring of various features supported by Intellicone and AWARE.

4.5 Life cycle cost evaluation

The evaluation of life cycle costs was done to gather an idea of the potential cost to be incurred in implementing a technology. The life cycle cost of each technology was based on price, and deployment based on manufacturer's recommendations. The following equation was used to calculate life cycle costs of the technologies.

$$LC_{present} = Cap + OM\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] + (Sal - Disp)(1+i)^{-N} \qquad (2)$$

Where
$LC_{present}$ is the life cycle cost, in today's dollars,
Cap is the capital cost of the WZIA,
OM is the annual operating and maintenance cost of the WZIA,
i is the interest rate,
N is the predicted useful life of the WZIA,
Sal is the salvage value of the WZIA at the end of its useful life, and
$Disp$ is the cost to dispose of the WZIA at the end of its useful life.

Certain assumptions were made to estimate the life cycle cost. A hypothetical work zone 1000 ft long, on a highway with 45 mph speed limit is assumed to calculate the number of devices needed to cover the work zone perimeter. Life cycle costs for the three technologies are then calculated based on the hypothetical work zone.

As per MUTCD guidelines the work zone setup should have a transition taper of length L given by:

$$L = WS \qquad (3)$$

Where
L = taper length in feet,
W = Width of the offset in feet, and
S = Posted speed limit in mph.

The corresponding length of transition taper that is needed to allow safe merging of vehicles to the adjacent lane can be calculated as $L = W*S = 12*45 = 540$ ft. Also, downstream taper as per the MUTCD guidelines can be set as 100 ft. The length of the resulting activity area then is equal to 1000-540-100 = 360 ft.

To further simplify calculation, the predicted useful life of all WZIA technologies is assumed to be 1 year. It is possible that the useful life could extend over 1 year. This would primarily depend on the extent of their use and handling. The technologies are also assumed to have zero salvage value after the end of their useful life and the cost of disposal is assumed to be $100. Further, an interest rate of 7% is assumed.

4.5.1 Intellicone

MUTCD guidelines suggest a minimum spacing of 45 ft between traffic cones on highways with a posted speed limit of 45 mph. Thus, a total 23 sensors (12 on transition taper, 8 in activity area and 3 on downstream taper) will be needed to cover the hypothetical work zone perimeter. Two PSAs will be needed for any work zone, i.e., one PSA near transition taper and the other near the activity area. Assuming the capital cost of the devices as $6600, and no surplus charge on replacement and maintenance of the components, the cost estimates for Intellicone is shown in TABLE 4-13.

TABLE 4-13

LIFE CYCLE COST FOR INTELLICONE

Components	Number of units	Unit cost (US$)	Total cost (US$)	Comments
Capital				
PSA	2	6,600	6,600	Assuming this set of PSA and sensors are leased at $25/day for a year
Lamp sensors	20			
Annual maintenance cost	0	0	0	All replacement and maintenance cost undertaken by the manufacturer
Salvage value			0	
Cost of disposal			0	
Life cycle cost			6,600	

4.5.2 AWARE Sentry

When used for flagging, two Sentries will be needed on either end of a work zone. For simplification, it is assumed that no repair or maintenance will be needed for the main sensor/alarm assembly over the 1-year period. However, since the Worktrax alarms might undergo wear and tear due to frequent handling, it is assumed that they will have to be replaced on an annual basis. The capital cost of the main sensor/alarm assembly is based on manufacturer’s estimates. However, no reasonable estimates were provided for Worktrax alarms. Therefore, a reasonable estimate of $150 based on the price of a similar device (WAS PSD) is assumed.

TABLE 4-14

LIFE CYCLE COST FOR AWARE SENTRY

Components	Number of units	Unit cost (US$)	Total cost (US$)	Comments
Capital				
Sensor/Alarm assembly	2	15,000	30,000	This is just a crude estimate provided by the manufacturer
Worktrax alarms	8	0	0	Four sensors included with each sensor
Annual maintenance cost				
Sensor/Alarm assembly	0	15,000	0	No replacement
Worktrax alarms	8	150	1,200	All Worktraxs replaced
Salvage value			0	
Cost of disposal			100	
Life cycle cost			31,028	

4.5.3 WAS

The typical deployment strategy for WAS is to place the pneumatic sensors at the end of the transition taper. However, to ensure better area coverage the sensors would also have to be placed along the perimeter of the activity area as well. Assuming every pneumatic sensor has a length of 12 ft, besides the sensor laid across the road in the transition taper, an additional 30 sensors (360 ft/12 ft) will be needed to cover the work zone perimeter. When bought together, a PAC is sold along with a pneumatic sensor while the PSDs need to be bought separately. The cost of PAC with a pneumatic sensor is about $550 and each PSD costs about $150. In controlled testing, the pneumatic sensor was able to withstand several passes from a heavy dump truck without any visible damage. However, the risk of damage to the transmitter attached to the sensor is considerable. Therefore, for the evaluation of life cycle cost, the replacement of sensors as well as PSDs is assumed.

TABLE 4-15

LIFE CYCLE COST FOR WAS

Components	Number of units	Unit cost (US$)	Total cost (US$)	Comments
Capital				
Pneumatic sensor	31	550	17,050	One 12-ft pneumatic sensor included with a PAC
PAC	31			
PSD	8	150	1,200	

Components	Number of units	Unit cost (US$)	Total cost (US$)	Comments
Annual maintenance cost				
Pneumatic sensor	15	550	0	Assuming half of sensors would have to be replaced
PAC				
PSD	8	150	1,200	All PSDs replaced
Salvage value			0	
Cost of disposal			100	
Life cycle cost			19,278	

4.6 Multicriteria evaluation

Multicriteria effectiveness was used to assess the overall efficacy of each technology. The criteria used in evaluation were based on the objectives with the research which was the identification of the most accurate, user friendly, and cost-effective system with live-tracking abilities. Therefore, the following criteria were chosen for evaluation. Existing research also corroborated the validity of the criteria considered for evaluation [3].

i. Alarm noticeability
ii. Alarm accuracy
iii. User friendliness
iv. Likelihood of use based on cost
v. Live tracking

Worker responses from on-site surveys were used to score the first four criteria. Scoring of the last criterion was based on live tracking features presented in TABLE 4-12. The scores for the criteria is presented in TABLE 4-16 and presented in Figure 4-42. Of the three technologies, AWARE Sentry scored highest on multicriteria effectiveness. This is attributed to its higher scoring from surveys and also its live tracking abilities.

TABLE 4-16

MULTICRITERIA SCORING

Evaluation criteria	Mean rating (Std. Dev.)		
	Intellicone	**AWARE Sentry**	**WAS**
Survey based scoring			
Alarm noticeability	3.83 (1.28)	4.25 (1.30)	3.89(0.99)
Alarm accuracy	2.79 (1.35)	4.75 (0.43)	2.67 (1.49)
User friendliness	3.88 (0.78)	4.00 (1.00)	3.78 (0.79)
Likelihood of use based on cost	3.58 (1.00)	4.25 (1.30)	3.78 (1.23)
Feature based scoring	**Total score**		
Live tracking	3	5	NA
Cumulative score	17.08	22.25	14.11

Note: For survey-based scoring: Intellicone, n=24; AWARE, n=4, WAS, n=9.

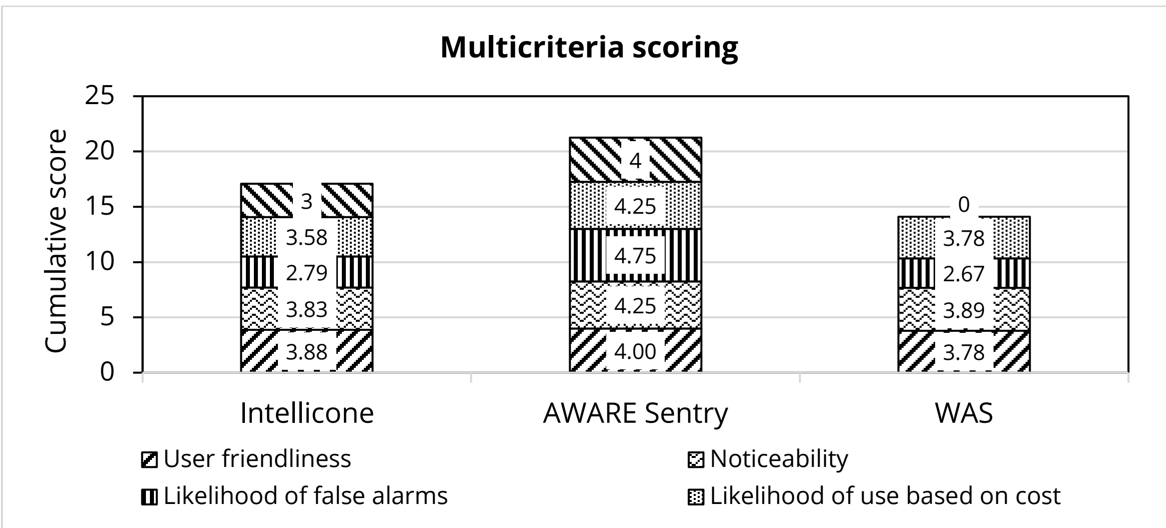


Figure 4-42. Multicriteria evaluation: Cumulative score of the systems

Chapter 5 Conclusion and Recommendations

This project identified and conducted a detailed evaluation of three WZIA technologies that could be potentially implemented on highway work zones. A two phased evaluation approach was used to assess the technologies. In the first phase, the technologies were tested under controlled predefined conditions to evaluate their performance based on alert accuracy, alarm intensity and duration, and work zone coverage based on transmission range. After completion of controlled tests, appropriate use cases for each technology were identified based on work zone typology. In the second phase, the technologies were tested on active highway projects. Selection of technology for testing on each project was based on the work zone typology. The objective of tests in the second phase was to collect response and feedback from workers after they the technologies had been used on actual work zones. Responses from workers were collected from each project using on-site surveys. Collect survey responses, live tracking features, and life cycle cost for each technology was then evaluated to find an overall effectiveness score.

5.1 System selection

Based on the results from controlled testing, we recommend technologies for use in different work zone typologies summarized in TABLE 5-1. Intellicone, with its unlimited transmission range is best suited for long lane closures in excess of 1,000 ft long. This typically includes major highways such as state highways and interstates. However, considerable time is needed to set up and remove the system, therefore, it is best applicable for construction work zones on highways where long lane closures are typically maintained for several days or months at a time. Furthermore, the live tracking feature that facilitates live tracking of Intellicone components can be particularly helpful in monitoring the status of work zones remotely. On a related note, as suggested by work zone crash statistics, construction work zones on interstates and state highways are major areas where work zone fatalities occur. In this regard, Intellicone can be useful in mitigating most highway crashes and fatalities if implemented effectively. Although inconsistencies were observed in its ability to detect and communicate alerts, according to the manufacturers, these issues are attributed to unreliable mobile connection between the device and mobile network in the US which could be addressed by future improvements. Considering the comparatively low life cycle cost of the technology, potential areas of application, and on-going technology improvements, pilot tests focusing on the technology could further help with decision making on its wide range implementation.

There are two versions of the AWARE system. The first is an equipment mountable system capable of detecting lane intrusions in advance called the Lane Intrusion System. The second is a flagger system called the Sentry. According to the manufacturers, the lane intrusion system currently is under development and not yet ready for evaluation, whereas the Sentry is ready for field deployment. Despite of their differences, both versions use identical components to detect intrusions and produce alerts. Although the Sentry is primarily intended for use by flaggers, results from our testing indicated that they could be used to maintain speed around highway work zones. During controlled tests, the system was found to be accurate with a range of about 400 ft, making it ideal for use in short and medium tapers. Compared to Intellicone, AWARE is easier to deploy and move around work zones which makes it appropriate for use in mobile work zones with medium to long tapers. Since the life cycle cost of the device is considerably higher, it is suggested for use only on short term work zones where it can be removed and stored safely after completion of work. Therefore, maintenance projects with flaggers, which typically last a few hours to a day at the most, is the ideal scenario where the Sentry could be used. Since the Sentry was found to be remarkably accurate, further testing on AWARE's Lane Intrusion System is suggested. Recent correspondence with the manufacturer suggested that although plans were underway to complete the Lane Intrusion System, there were delays due to the COVID-19 pandemic.

TABLE 5-1

RECOMMENDED IMPLEMENTATION FOR WZIA TECHNOLOGIES

Work zone setup and duration	Short tapers or speed limit < 30 mph (less than 500 ft)	Medium tapers or speed limit < 40 mph (500-1000 ft)	Long tapers or speed limit > 30 mph (longer than 1000 ft)
Short duration (less than or equal to one day)	AWARE or WAS	AWARE	AWARE
Long duration (more than one day)	Intellicone or AWARE	Intellicone	Intellicone
Mobile operation	WAS	AWARE	AWARE

The WAS is best suited for use in projects with short tapers. A significant upside with WAS is its portability and setup time. It is well suited for use in short term repair and mobile work zones. Limited range and delayed transmission were the two key issues with WAS in our testing. However, it can be effective on highways with slow traffic (typically less than 30 mph) where lane closures do not exceed 150 ft, and in repair projects on shoulders without lane encroachment.

5.2 Considerations on technology implementation

The implementation strategies mentioned herein are provided with the objective to identify the best use case scenarios for the technologies. However, several limitations and issues were encountered during the tests should be carefully considered. TABLE 5-2 presents a summary of these considerations. It is imperative that the key issues identified with the current version of the technologies be carefully considered before they are chosen for implementation.

TABLE 5-2

SUMMARY OF KEY CONSIDERATIONS NEEDED

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

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Appendix-I: Survey questionnaire

Location and date: ______________________________

Technology: __________________________________

Work description: _____________________________________

Supervisor Name and contact: _______________________________________

Personal information

1. Name (Optional): ____
2. Job title and agency (Optional): ____
3. Contact information (Optional): ____
4. Experience in the industry (in years): ____________
5. Do you have prior experience using any other work zone intrusion alert systems?
    Yes
    No
6. Which of these technologies have you used before for work zone safety?
    Work zone alert systems
    Flaggers
    Portable Changeable Message Sign
    Rumble strips
    Others: ____________________________________
7. Do you think the technologies mentioned in Question 6 are beneficial to work zone safety? If "Yes" name which ones. If "No" briefly explain why.

    Yes ____

    No ____

    I don't know

8. What are most common types of work zone intrusion crashes you have witnessed in the past?

    ____

    ____

9. Do you think the technologies tested today will beneficial to work zone safety? If your answer is "No" briefly explain why you think so.

 Yes

 No ____

 I don't know

User friendliness

10. How easy was it to deploy and the technology on-site?
     1 – Very difficult
     2 – Difficult
     3 – Straight forward
     4 – Easy
     5 – Very easy
11. How would you rate the time taken to arm and deploy the system between 1 to 5 with 1 being "very slow" and 5 being "very fast"?
     1
     2
     3
     4
     5
12. In your opinion which location of work would be the most appropriate for deploying this technology? Select all that apply.
     Outside shoulder
     On shoulder without encroachment
     On shoulder with encroachment
     Within the median
     Within the traveled way
     Others: ____
13. What type of work would you prefer the technology to be used in? Select all that apply.
     Short duration work zone that occupies a location up to 1 hour
     Mobile work zone that moves intermittently or continuously
     Short-term stationary work lasting 1 daytime at a location for more than 1 hour
     Intermediate-term stationary work that occupies a location for 1-3days, or night time lasting more than 1 hour
     Long-term stationary: work that occupies a location more than 3 days
14. Which location within the work zone would be the best to deploy the system? Select all that apply.
     On the transition taper area
     Along the activity area
     Other location: _________________________________
15. Based on your experience using the system, what would be benefits of using this system?

□ Effective in warning the workers
□ Cost involved in buying and maintaining it
□ Good site coverage
□ Easy to setup
□ Easy to use and transport
□ Others: ____

16. What is/are in your opinion the biggest downsides in adoption this work zone intrusion alert systems?
□ Ineffective in warning the workers
□ Cost involved in buying and maintaining it
□ Lack of adequate site coverage
□ Time and manpower needed for site deployment
□ Others: ____

Alarm noticeability

Please rate the following on a scale of 1 to 5 with 1 being "very ineffective" and 5 being "very effective".

Questions	1	2	3	4	5	Don't know
17. Is the sound produced effective in alerting the workers?	□	□	□	□	□	□
18. Is the light produced effective in alerting the workers?	□	□	□	□	□	□
19. Is the sound produced distinct from other sounds?	□	□	□	□	□	□
20. Overall how would you rate the noticeability of alarms produced by the system?	□	□	□	□	□	□

False alarms

21. In your experience using the system, how would you rate the likelihood of the system producing false alarms on a scale of 1 to 5 with 1 being "very unlikely" and 5 being "very likely"?
□ 1
□ 2
□ 3
□ 4
□ 5

Alarm use

22. Intellicone PSA along with 10 sensor lamps cost about $2,500.
WAS with the sensor, alarm and 2 personal safety device costs about $850.
AWARE sentry comes with 4 Worktrax personal alarms and costs about $30,000.

Given these costs how likely are you to adopt it for work zone safety on a scale of 1 to 5 with 1 being “very unlikely” and 5 being “very likely”?

 1
 2
 3
 4
 5

Durability

23. Based on the information presented to you, how would you rate the durability of the system between 1 to 5 with 1 being “very short lived” and 5 being “very durable”?

     1
     2
     3
     4
     5

24. Do you think the system has the potential to improve safety of the workers? Explain your response.

     Yes ____

     No ____

     I don’t know

25. Please provide any comments and recommendations you may have on the intrusion alert system.

    ____

    ____

    ____

    ____

    ____