

# Active Work Zone Safety Using Emerging Technologies 2017

By

Dr. Eric Marks, Dr. Stephanie Vereen, Ibukun Awolusi  
Department of Civil, Construction, and Environmental Engineering  
The University of Alabama  
Tuscaloosa, Alabama

Prepared by

# UTCA

University Transportation Center for Alabama  
The University of Alabama, The University of Alabama at Birmingham, and  
The University of Alabama in Huntsville

UTCA Report Number 15412  
July 2017

**UTCA Theme: Management and Safety of Transportation Systems**

# University Transportation Center for Alabama

**About UTCA** The University Transportation Center for Alabama (UTCA) is headquartered in the Department of Civil, Construction, and Environmental Engineering at the University of Alabama (UA). Interdisciplinary faculty members perform research, education, and technology-transfer projects using funds provided by UTCA and external sponsors.

**Mission Statement and Strategic Plan** The mission of UTCA is “to advance the technology and expertise in the multiple disciplines that comprise transportation through the mechanisms of education, research, and technology transfer while serving as a university-based center of excellence.”

The UTCA strategic plan contains six goals that support this mission:

- Education – conduct a multidisciplinary program of coursework and experiential learning that reinforces the theme of transportation;
- Human Resources – increase the number of students, faculty and staff who are attracted to and substantively involved in the undergraduate, graduate, and professional programs of UTCA;
- Diversity – develop students, faculty and staff who reflect the growing diversity of the US workforce and are substantively involved in the undergraduate, graduate, and professional programs of UTCA;
- Research Selection – utilize an objective process for selecting and reviewing research that balances the multiple objectives of the program;
- Research Performance – conduct an ongoing program of basic and applied research, the products of which are judged by peers or other experts in the field to advance the body of knowledge in transportation; and
- Technology Transfer – ensure the availability of research results to potential users in a form that can be directly implemented, utilized or otherwise applied.

**Theme** The UTCA theme is “*MANAGEMENT AND SAFETY OF TRANSPORTATION SYSTEMS.*” UTCA concentrates upon the highway and mass transit modes but also conducts projects featuring rail, waterway, air, and other transportation modes as well as intermodal issues.

**Acknowledgement** This project was sponsored by Alabama Department of Transportation (ALDOT). UTCA is grateful for ALDOT’s continued encouragement and support.

**Disclaimer** The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of Alabama DOT, the University of Alabama, or UTCA, and they assume no liability for the contents or use thereof. This report does not constitute a standard, specification, or regulation. Comments contained in this report related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

# Active Work Zone Safety Using Emerging Technologies 2017

By

Dr. Eric Marks  
Dr. Stephanie Vereen  
Ibukun Awolusi  
Department of Civil, Construction, and Environmental Engineering  
The University of Alabama  
Tuscaloosa, Alabama

Prepared by

# UTCA

University Transportation Center for Alabama

The University of Alabama, The University of Alabama at Birmingham,  
and The University of Alabama in Huntsville

UTCA Report Number 15412  
July 2017

## Technical Report Documentation Page

1. Report No FHWA/CA/OR-	2. Government Accession No.	3. Recipient Catalog No.	
4. Title and Subtitle  Active Work Zone Safety Using Emerging Technologies 2017		5. Report Date July 2017	
		6. Performing Organization Code 25608-214231-200	
7. Authors Dr. Eric Marks, Dr. Stephanie Vereen, Ibukun Awolusi		8. Performing Organization Report No. UTCA Report Number 15412	
9. Performing Organization Name and Address University Transportation Center for Alabama The University of Alabama Box 870205 Tuscaloosa, Alabama 35487-0205		10. Work Unit No.	
		11. Contract or Grant No. ALDOT Distribution Code GR25608	
12. Sponsoring Agency Name and Address Alabama Department of Transportation 1409 Coliseum Boulevard Montgomery, AL 36110		13. Type of Report and Period Covered July 1, 2016 - August 16, 2017	
		14. Sponsoring Agency Code ALDOT 930-915 Project #100065678-2 (K-15_1732)	
15. Supplementary Notes			
<b>16. Abstract</b> <p>Highway construction work zones are hazardous environments characterized by a dynamic and limited work space. A host of interactions between workers, passing commuter vehicles, and moving construction equipment occurs in highway work zones fostering dangerous situations which can result in an injury or fatality. Active strategies such as the deployment of intrusion sensing and alert technologies in highway work zones and in transportation infrastructure construction and maintenance can be effective in mitigating these unforeseen conditions. The main objective of this study was to conduct both conceptual analysis and experimental evaluation of intrusion sensing technologies for work zone safety. To achieve the objectives of this research, a comprehensive review of the applicable technologies was conducted to identify the intrusion technologies that can be implemented for work zone safety. An objective assessment of each technology was provided based on selected weighing metrics to elicit their capabilities. Candidate commercially available technologies were selected and evaluated using field experiments in simulated work zones. The findings of the study indicate that a limited number of the applicable technologies exists and the selected commercially available technologies evaluated have the capabilities to effectively provide alerts to highway work zone personnel when a hazardous situation is present.</p>			
17. Key Words Work zone technologies, construction safety, intrusion alerts		18. Distribution Statement	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	20. No of Pages 27	22. Price

Form DOT F 1700.7 (8-72)

# Contents

Contents.....	iii
Executive Summary.....	vi
1.0 Introduction.....	1
2.0 Literature Overview.....	3
2.1 Work Zone Safety Statistics.....	3
2.2 Work Zone Intrusion Technologies.....	3
2.3 Previous Assessments of Intrusion Alerts.....	4
2.4 Research Needs Statement.....	5
3.0 Research Methods.....	6
3.1 Review of Applicable Technologies.....	7
3.2 Kinematic Intrusion Technology Systems.....	8
3.3 Infrared-Based Intrusion Technology Systems.....	9
3.4 Pneumatic and Microwave Intrusion Technology Systems.....	10
3.5 Radar-Based Intrusion Technology Systems.....	11
3.6 Radio-Based Intrusion Technology Systems.....	13
4.0 Experimental Procedure and Results.....	15
4.1 Experimental Set-up and Data Collection.....	15
4.2 Experimental Evaluation Results.....	16
4.3 Sound Levels of the Intrusion Alert Technologies.....	17
4.4 Worker’s Reaction to the Intrusion Alert Technologies.....	17
4.5 Response of Vehicle Driver to the Intrusion Alert Technologies.....	18
4.6 Vehicle Stopping Time.....	19
4.7 Vehicle Stopping Distance.....	20
4.8 Implication of the Experimental Findings for Work Zone Safety.....	20
5.0 Recommendation.....	22
6.0 Conclusion.....	23
References.....	24

## Tables

Number		Page
3-1	Applicable and Commercially Available Work Zone Intrusion Technology	8
5-1	Selection Guide for Work Zone Intrusion Detection Devices	22

## Figures

Number		Page
3-1	Research Methodology Framework	6
3-2	SonoBlaster Alarm Unit	9
3-3	Traffic Guard Worker Alert System	11
3-4	AWARE System Demonstration	12
3-5	Intellicone Alarm System	13
4-1	Test Bed for Experimental Trials	15
4-2	Layout of the Experimental Trials Site	16
4-3	Sound Level of Intellicone and Traffic Guard Alerts	17
4-4	Results of Worker's Reaction Time	18
4-5	Results of Vehicle Stopping Time	19
4-6	Results of Vehicle Stopping Distance	20
4-7	Summary of Experimental Results	21

## **Executive Summary**

Highway construction work zones can be characterized as hazardous work environments with traveling vehicles and pedestrian employees working at close proximity. The main objective of this study was to conduct both conceptual analysis and experimental evaluation of intrusion sensing technologies for the potential improvement of safety performance. The following were identified results from the experimental trials and review:

- A comprehensive review of applicable technologies was conducted to identify intrusion technologies applicable to this study
- A test bed in an open, flat and unobstructed location to establish a simulated work zone environment
- Scientific evaluation data from experimental trials to validate limitations of select highway work zone intrusion technologies
- A recommendation of specific work zone intrusion technologies for adoption by ALDOT
- An implementation guide for implementing and maintaining a work zone intrusion alert system



# Chapter 1

## Introduction

Work zone safety is a major concern for many community members including government agencies, the legislature, and the traveling public (Ullman et al. 2008, Chambless et al. 2002). Transportation infrastructure provides many social benefits to any society and plays a critical role in the proper functioning of the economy (Andrijcic et al. 2013). The need to maintain and rehabilitate existing roadway systems rises as traffic volume increases and highway infrastructure ages (Cerezo et al. 2011). Thus, the maintenance, reconstruction, and constant upgrade of these infrastructure are pivotal to meeting the ever-increasing needs of a growing economy (Duranton and Turner 2012). The increasing number of roadway widening, rehabilitation, and reconstruction projects has made work zone safety a critical concern (Cerezo et al. 2011). This is because the hazardous exposures of construction workers increase with the rising number of transportation infrastructure construction projects (Benekohal et al. 2004).

Highway construction and maintenance operations commonly require personnel to work near ongoing traffic, a situation which creates significant safety risk for both the construction employees and traveling motorists (Gambatese and Lee 2016). One commonly implemented control strategy is to place traffic control devices near work zone areas to alert motorist (Noyce and Smith 2003). However, drivers often disregard or ignore work zone traffic control devices, and other warning information systems which has led to serious accidents during a work zone intrusion (Hourdos 2012). Since the work environment on the highway is often chaotic and noisy, it can be difficult for personnel to spot an errant vehicle in time to take appropriate action (Fyhrie 2016). Inattentive or speeding drivers, careless workers, misplaced traffic control devices, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities (Gambatese and Lee 2016, Khattak et al. 2002).

A need exists for a management approach which considers not only the implementation of active intrusion sensing technologies but also their effectiveness in alerting both the pedestrian workers and vehicle drivers in work zones. As vehicle miles traveled, driver distraction, work zone activity, and nighttime work increase, safety incidents and work zone crashes can be expected to rise (Krupa 2010, Gambatese and Lee 2016, Pratt et al. 2001). Intricate situations such as those obtained in work zones require active monitoring to provide real-time information about the condition of the work environment. To reduce the incidence of and potential for incidents on highway construction and maintenance sites, some government authorities have deployed safety devices and systems to safeguard employees using intrusion alarms (Krupa 2010, Phanomcheong et al. 2010). Intrusion alarms are used primarily in temporary work zones with short work duration where adding a positive protection system such as concrete barrier is not feasible (Givechi 2015).

The purpose of this research was to provide an objective evaluation of the applicable intrusion technologies for work zone safety and to implement commercially available intrusion sensing technologies in a simulated highway work zone testbed through field experimentation. To achieve this, a contextual study was conducted to determine the previous applications of intrusion alarm systems for work zone safety. Information about work zone intrusion sensing technologies from the manufacturers' specifications documents and published research results were collected and evaluated. An assessment of each technology was provided based on selected weighing metrics to

elicit their capabilities. Candidate intrusion sensing technologies were selected and implemented for work zone safety using field experiments in simulated work zones.

## **Chapter 2**

### **Literature Review**

Highway construction work zones are risky due to the dynamic and complex nature of the work environments (Lin et al. 2004). Motorists are exposed to unfamiliar situations in a normally familiar setting, and such unexpected unfamiliarity could lead drivers to behave in unforeseen ways (Bathula et al. 2009). The following review presents work zone safety statistics, an overview of work zone intrusion technologies, and selected previous applications of intrusion alarm systems for work zone safety. This section also presents a research needs statement derived from the review.

#### **2.1 Work Zone Safety Statistics**

Over the past decade, a considerable amount of work zone crashes occurred, leading to damage of valuables, injuries to workers, and loss of lives (Li and Bai 2008). In the U.S., an average of 595 work-zone-related fatalities occurred every year within the last five years (FHWA 2016). In 2014, 669 fatalities occurred in work zones nationwide, representing two percent of all highway fatalities (NWZSIC 2016). Highway work zones account for nearly 24 percent of non-recurring congestion, or 888 million vehicle hours of delay in 2014 (FHWA 2016). Furthermore, more than 20,000 workers are injured in work zones each year in the U.S in which 12% result from traffic incidents (Krupa 2010). These injuries and fatalities have cost implications on the economy of the nation. In 2010 for instance, the total economic cost of motor vehicle crashes in the U.S. was \$242 billion (Blincoe 2017).

Many of the crashes near work zone areas occur when drivers fail to take heed of traffic warning and control measures upstream of the work zone area often due to distracted driving (Hourdos 2012). The cited statistics of work zone incidents indicate much need in improvement of safety performance in and around construction highway work zones. This information also projects a need for more effective strategies to reduce and eventually eradicate these fatalities and delays in work zones.

#### **2.2 Work Zone Intrusion Technologies**

Work zone hazard awareness systems can be divided into three major categories: mechanical systems, electronic systems, and dedicated observers (Bryden and Mace 2002). Mechanical systems use mechanisms, such as impact-activated or pressure-activated systems, which are triggered by physical contacts or impacts of intruding vehicles (Sun et al. 2007). Electronic systems on the other hand apply sensing technologies, such as laser switch systems, which require the alignment of transmitters and receivers to detect intruding objects (Liu et al. 2007). If a receiver fails to receive signals from a transmitter, the system activates an alarm. Other practices employ dedicated observers, such as workers or flaggers, to spot intrusions and trigger alarms (Tsai 2011).

Intrusion alarms are a technology which utilizes one or more sensors mounted on typical work zone barriers such that when an errant vehicle contacts a sensor, an alarm would be activated to warn workers that their protective zone had been violated (Wang et al. 2011). The concept of such systems is that the alarm mechanism would sufficiently warn workers with enough reaction time

to move away from the hazard location (Wang et al. 2011). Some intrusion alarm systems consist of a detection unit and a receiving unit in which the alarm is activated when the detection unit is triggered or activated (Ozbay et al. 2012). The alarm could also possibly alert a distracted or drowsy driver and permit them to avoid the work zone or decelerate prior to reaching workers or their equipment (Wang et al. 2011).

The first set of work zone intrusion alarm systems was developed under the Strategic Highway Research Program (SHRP) where ultrasonic and infrared beams were used for detection (Wang et al. 2011, Ozbay et al. 2012). Two types of intrusion alarm systems developed by the SHRP utilized microwave and infrared wireless technology in respective models that mounted on work zone barriers (Ozbay et al. 2012). The systems used either microwave signals or beams of infrared light to connect to base units (Wang et al. 2011). When a vehicle crossed into the work zone and interrupted the signal or beams, a high-pitched alarm was sounded by the base station near the workers. A third type utilized pneumatic tubes placed on the ground such that the tubes were laid around the working area. When a vehicle drove into the area and over the tubes, an alarm was activated (Wang et al. 2011). Other similar intrusion alarms have been developed using microwave, pressure activated tubes and laser technologies (Ozbay et al., 2012, Khan 2007). Another type of work zone intrusion alarm system, a kinematic model was identified by Fyhrie (2016). The kinematic models usually mounted on a traffic cone (or other similar hardware) produce an alarm when the change in orientation angle of the cone indicates it has been tipped over (Khan 2007). This system works based on the assumption that an errant vehicle has knocked over the hardware and has entered the work area (Khan 2007).

### **2.3 Previous Assessments of Intrusion Alerts**

A few work zone safety devices from the Strategic Highway Research Program (SHRP) were evaluated under the direction of the Kentucky Transportation Cabinet through trial use (Agent and Hibbs 1996). Five intrusion alarm systems were evaluated including one microwave system, one infrared system, and three pneumatic tube systems. Modifications based on feedback from various states, counties, and private agencies were implemented, mostly concentrated on increasing the ease of setup and the volume of the alarm (Agent and Hibbs 1996). Although the devices were found to be durable, workers were generally not enthusiastic about using the devices. Consequently, a definite recommendation was not made due to the continuous modifications, but devices were supposedly accepted to have potentials for use on major projects, with cost being a limiting factor (Agent and Hibbs 1996).

A microwave-based alarm system was rejected by the Alabama, Colorado, Iowa, and Pennsylvania Department of Transportation's (DOT's) because of setup problems and false alarms due to difficulties in keeping the devices aligned (Carlson et al. 2000). The Iowa Department of Transportation attempts to minimize the amount of time that crews are exposed to traffic, and the setup of the intrusion alarms would serve to extend the amount of time that a crew would need to do their job (Fyhrie 2016). It was noted that false alarms were so frequent that workers ignored the alerts (Trout and Ullman 1997). Although potential benefits were identified from these work zone intrusion sensing systems, multiple limiting factors have been experienced. These limitations include nuisance alerts that can desensitize work zone employees (Trout and Ullman 1997), significant space required to install the system (Carlson et al. 2000), time and effort required for

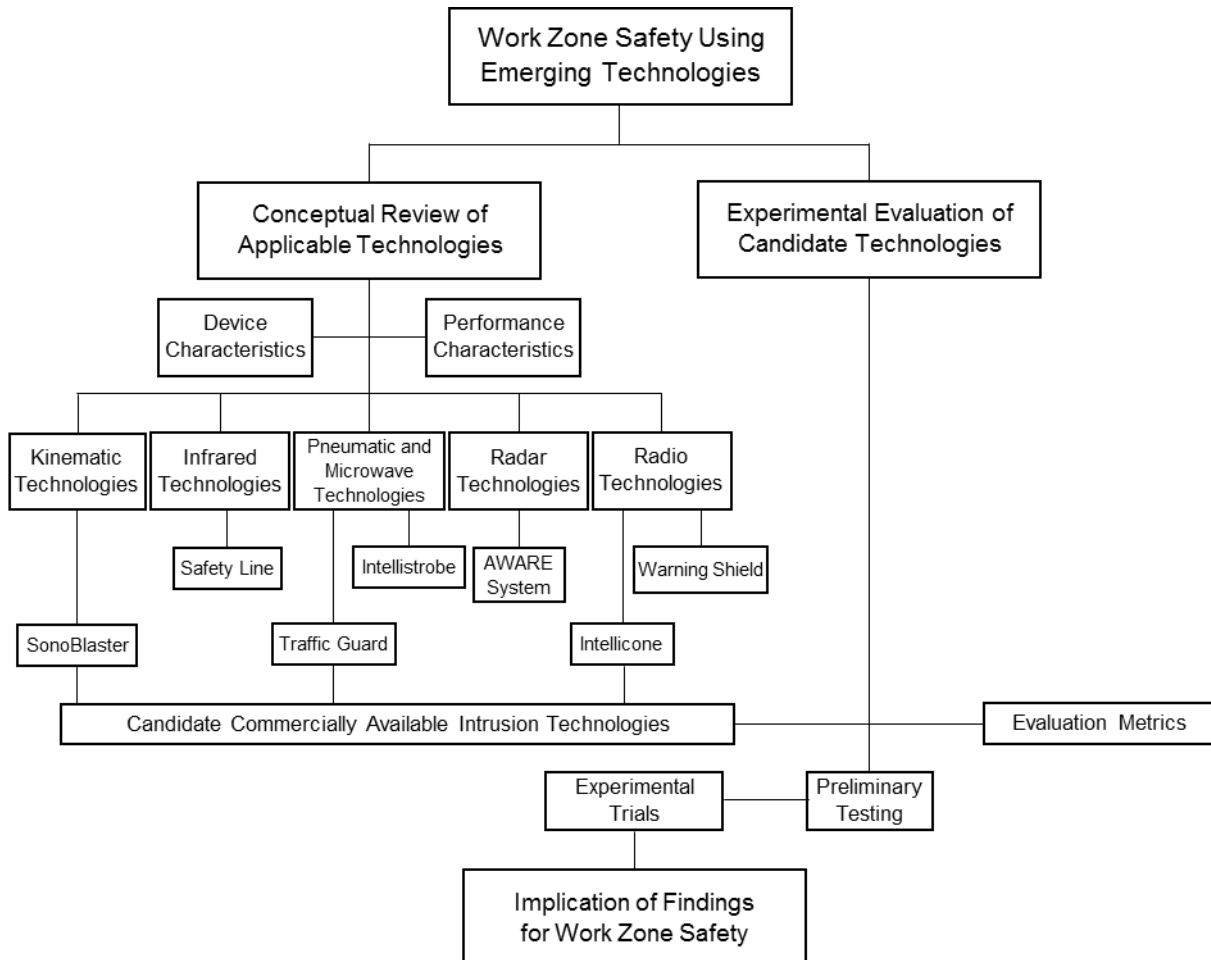
set-up (Trout and Ullman 1997), durability of the system (Carlson et al. 2000), and misalignment of detection area (Novosel 2014).

## **2.4 Research Needs Statement**

Although intrusion alarm systems have the potential to warn workers when an errant vehicle intrudes the work zone, existing studies show certain limitations in their capabilities, effectiveness, and wide-spread implementation. The previous applications of these systems indicate the need to improve the systems to ensure maximum benefits are derived from their deployment for work zone safety. Research needs exist to complete a conceptual analysis of the applicable intrusion sensing technologies to identify and experimentally evaluate the commercially available technologies that can be implemented to enhance work zone safety. These conceptual and experimental evaluations are expected to provide information on the capabilities of these intrusion sensing technologies in order to elicit their benefits and areas for improvement.

## Chapter 3 Research Methods

The methods adopted in achieving the objectives of this research involved two parts. The first part involves the conceptual review of applicable intrusion technologies while the second aspect involves the experimental evaluation of selected intrusion sensing technologies for work zone safety. The research methodology framework is presented in Figure 3-1.



**Figure 3-1** Research Methodology Framework

A review of intrusion technologies from previous applications and manufacturers' documents was conducted by the research team. Based on the review, these five categories of intrusion technology systems were identified: 1) Kinematic Intrusion Technology Systems, 2) Infrared-Based Intrusion Technology Systems, 3) Pneumatic and Microwave Intrusion Technology Systems, 4) Radar-Based Intrusion Technology Systems, and 5) Radio-Based Intrusion Technology Systems. The different types of applicable intrusion technology devices under each of these categories were identified and assessed using selected weighing metrics. The review culminated into the selection of candidate commercially available technologies which were then evaluated using experimental trials to assess their implementation for work zone safety.

This section presents the results of the conceptual review of applicable work zone intrusion technologies. The assessment of applicable and commercially available work zone intrusion sensing technologies is presented based on selected weighing metrics (i.e. device attributes and performance characteristics).

### **3.1 Review of Applicable Technologies**

A thorough review of applicable intrusion sensing technologies indicates that a few commercially-available intrusion alarm systems exist. Table 3-1 presents the applicable and commercially available intrusion sensing technologies that can be implemented in highway work zones and the comprehensive review of the technologies is also presented. The intrusion technologies in bold in Table 3-1 indicate the commercially available work zone intrusion technology systems.

**Table 3-1** Applicable and Commercially Available Work Zone Intrusion Technology

System Type	Intrusion Technology	States Tested	Alert Type		
			Audible	Visual	Vibratory
Kinematic	<b>SonoBlaster</b>	New Jersey DOT (Krupa 2010), Kansas DOT (Novosel 2016)	Yes	No	No
Infrared-Based	Safety Line	None	Yes	Yes	No
Pneumatic and Microwave	<b>Traffic Guard Worker Alert System</b>	None	Yes	Yes	Yes
	<b>Intellistrobe</b>	None	Yes	Yes	No
Radar-Based	AWARE System	Missouri and Texas (Cleaver 2016)	Yes	Yes	Yes
Radio-Based	<b>Intellicone</b>	Kansas DOT (Novosel 2016)	Yes	Yes	No
	Wireless Warning Shield	None	Yes	No	Yes

### 3.2 Kinematic Intrusion Technology Systems

Kinematic intrusion alarm systems are impact-activated devices attached to a traffic control device which produces a warning sound to alert workers when the device is struck by a vehicle (Fyhrie 2016). The SonoBlaster Work Zone Intrusion Alarm is an impact and tilt activated safety device that warns roadway workers and errant vehicle drivers simultaneously to help prevent crashes, injuries, and fatalities on roadway work zones. The SonoBlaster is usually mounted on typical traffic control devices including work zone barricades, cones, drums, delineators, A-frames, and other barriers. Upon impact by an errant vehicle, the SonoBlaster's built-in Carbon dioxide (CO<sub>2</sub>) powered horn blasts at 125 decibels for 15 seconds to signal workers that their protective zone has been violated, allowing them critical reaction time to escape the hazard (Transpo 2010). Figure 3-2 shows the SonoBlaster alarm system. The SonoBlaster is an entirely mechanical device which emits an auditory alarm and does not require batteries. It is entirely constructed of hard plastic, except for the CO<sub>2</sub> nozzle constructed of metal.





**Figure 3-2** SonoBlaster Alarm Unit

SonoBlaster-equipped traffic cones were used with standard cones in a pilot test to close a lane of traffic for maintenance work in New Jersey (Krupa 2010). Two impact simulations were performed resulting in sounding of the alarm, as no impacts occurred from traveling vehicles. The alarm’s sound volume and duration were satisfactory during normal traffic conditions for distances of at least 60 meters, including when ear protection was worn, but no conclusion could be made about hearing the alarm during jack hammer operations. Employees indicated that several set-up procedures were difficult (Krupa 2010). Moreover, in multiple instances the alarm fired when the control knob was in the locked and unarmed position. Overall, quality control was a major issue due to problems with setting up the device and its durability. Reliability as a safety-promoting device was also an issue because of misfires. Wang (2011) stated that the findings of a survey indicated that 44 percent of states that have tested the SonoBlaster believe the device was ineffective due to issues with false alarms and maintenance of the system.

### 3.3 Infrared-Based Intrusion Technology Systems

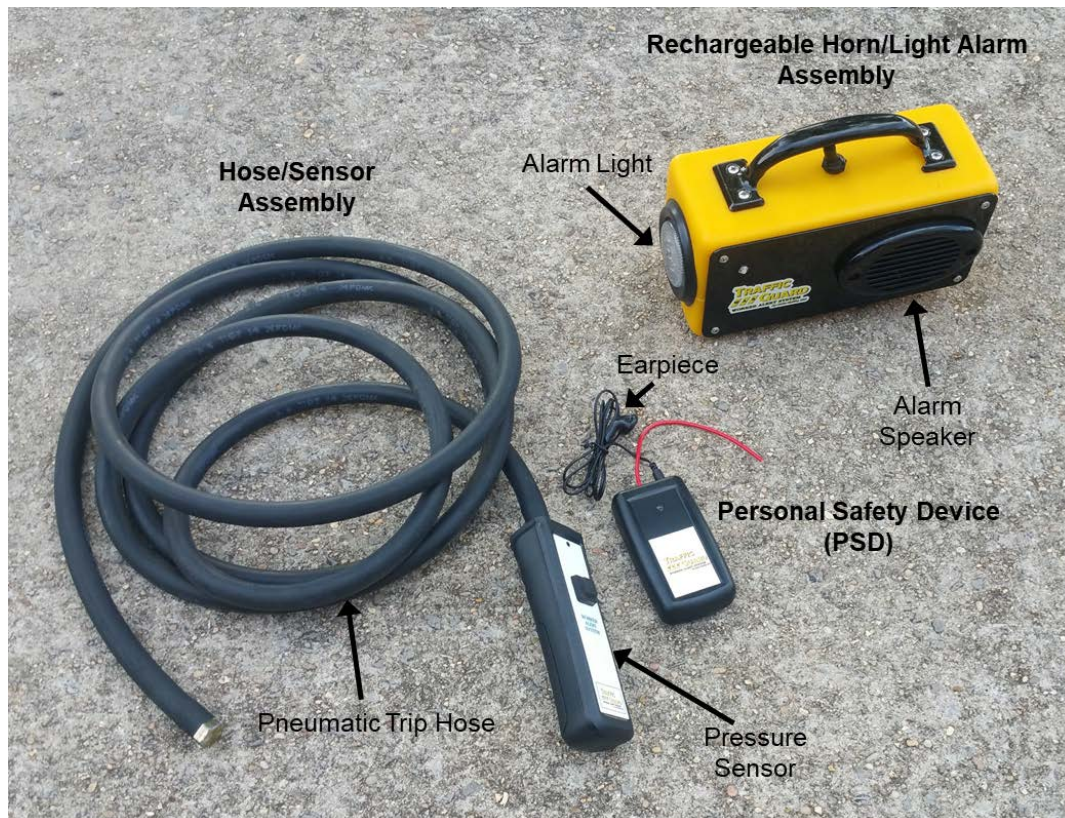
The Safety Line provides workers with a warning when a vehicle intrudes an area closed off by traffic control devices. The system consists of a transmitter, a receiver, and an alarm unit. The transmitter is placed at the bottom left of the lower lane, inside of the channelizing devices (Kocheva 2008) while the receiver can be placed up to 300 meters away, closest to the workers. The transmitter projects a dual infrared beam to the receiver and if a vehicle enters or intrudes the buffer area, the dual transmitted beams would be obstructed, thus causing the receiver to activate the 147 decibels air horn, alerting the workers. The system uses a sealed gel cell battery type with a 3-day life and recharging time of between 5 and 6 hours. The transmitter has the solar charger option while the receiver has the solar charger and strobe light option. Multiple units can be linked to protect a larger area. Ozbay et al. (2012) believe that this technology has potential benefits for

short-term and long-term work zones. According to Kocheva (2008), Safety Line is easy to use, rugged, lightweight, portable, completely self-contained and can be aligned in less than a minute using the alignment light emitting diodes (LED's). Unfortunately, the Safety Line system is not commercially available and thus cannot be further evaluated using experimental trials.

### **3.4 Pneumatic and Microwave Intrusion Technology Systems**

The pneumatic road tube intrusion alarm system involves placing road tubes or hose on the roadway perpendicular to the flow of traffic at the beginning of the work zone. The tubes are connected to a transmitter that activates a siren and a strobe light when a vehicle drives over them (Carlson et al. 2000). A typical microwave intrusion alarm features a transmitter mounted on one drum and a receiver and siren mounted on another drum up to 300 meters away. Strobe lights can also be included in the system to alert workers under noisy conditions (Carlson et al. 2000). The Traffic Guard Worker Alert System and the Intellistrobe Automated Flagger Assistance Device (AFAD) Lane Intrusion Safety System were the two devices identified under this category of intrusion technology systems as applicable for work zone safety.

The Traffic Guard Worker Alert System consists of a lightweight, easy-to-transport pneumatic trip hose and sensor assembly that sends a signal to an alarm and flashing light up to 300 meters away (Fyhrie 2016). The pneumatic trip hose is placed ahead of or behind workers on the road, far enough away to provide ample warning if an unauthorized vehicle crosses over the hose. The flashing light and alarm alert workers so they can quickly move out of the way of an oncoming vehicle. The faster the traffic is moving, the more distance there should be between the pneumatic trip hose and work area (NWZSIC 2016). The Traffic Guard system has an additional Personal Safety Device (PSD) which produces vibratory and audible alerts to the worker in possession of it. A signal is transmitted from the impacted device to the PSD, a personal body alarms which both vibrates and emits an auditory alarm (Novosel 2014). Figure 3-3 shows the Traffic Guard Worker Alert System. The pneumatic trip hose with attached sensor uses two alkaline batteries while the horn and light alarm assembly uses an in-built rechargeable battery and the Personal Safety Device with included earpiece uses two AAA 1.5V Copper Top Alkaline Batteries (Astro Optics, 2017).



**Figure 3-3** Traffic Guard Worker Alert System

The Intellistrobe system is an Automated Flagger Assistance Devices (AFAD) that is highly visible, stand-alone units controlled electronically from a transmitter carried by an operator located safely out of harm’s way (Intellistrobe 2016). The systems conform to the Interim Approval guidelines for AFAD’s and have met the federal NCHRP 350 crashworthy performance criteria (FHWA 2004). A flagger for each AFAD is specified for limited line-of-site instances or distances over 250 meters. The AFAD Lane Intrusion Alarm is activated when traffic crosses the hose and enters work zone. The Modified Gate Arm allows visual confirmation for the controller. Signal heads must be covered when the system is being used for lane intrusion only (Intellistrobe 2016).

### 3.5 Radar-Based Intrusion Technology Systems

According to Cleaver (2016), the AWARE system is a radar-based system that can detect a potential work zone intrusion from multiple vehicles, and, simultaneously, warn an errant driver and workers who may be in harm’s way. The system consists of a sensor that includes electronically-scanned radar, high-precision differential GPS, accelerometers, gyroscopes, and magnetometers for position and orientation sensing. High-definition video and several wireless interfaces are used to monitor traffic in the area. All the different components of the system work together to broadcast a warning when an intrusion is detected. A second sensor includes a tracking device that is typically strapped to the workers’ hard hats, vests or armbands with high-precision position sensing as well as wireless interfaces which receive warning signals from the other system sensor. If the worker is in the path of an oncoming threat, a vibrator motor and acoustic buzzer

will alert the user that a threat is approaching. Visual and audible alerts will also be activated if a threat is detected.

The initial pilot project that used the Oldcastle's AWARE System was in Missouri. Based on the experience in Missouri and another project in Texas, the company was able to make improvements which made the system fully functional on a divided highway project in Texas as reported by Cleaver (2016). The manufacturer of the system is now focused on making it user-friendly so that supervisors can utilize it without external assistance. The company planned to test the system on 12 more projects across eight states in 2016. The AWARE system is a trademark technology owned by Oldcastle Materials.

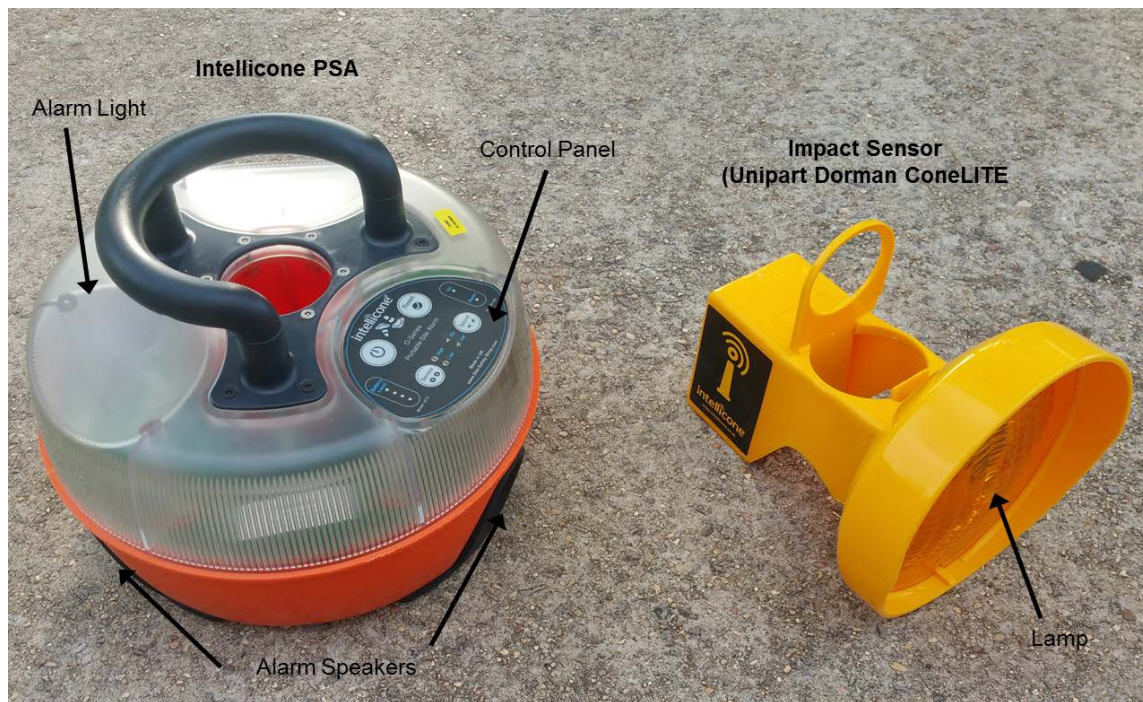
Due to the development status of the AWARE system, the research team was unable to acquire the technology as the technology company was not allowing their product to be purchased. Instead, the research team evaluated the AWARE system through a demonstration during an active highway rehabilitation project in Tuscumbia, Alabama. The system and demonstration are shown in Figure 3-4. The two pictures on the top right and bottom right show a flagger cart that detects work zone intrusions. The picture on the top left shows the AWARE System deployed on an asphalt paver. The picture on the bottom left shows the personal AWARE device worn by all employees.



**Figure 3-4** AWARE System Demonstration

### 3.6 Radio-Based Intrusion Technology Systems

The Intellicone and the Wireless Warning Shield were the two radio-based technology systems identified for work zone safety applications. The Intellicone system is a system of a base Portable Site Alarm (PSA) that acts as a signal receiver and auditory-visual alarm and a set of integrated lamps and impact sensors (Unipart Dorman ConeLITE). The impact sensors are powered by heavy duty batteries in the base of the unit and the lamps are yellow Light-Emitting Diodes (LEDs). When activated, the sensors become active and the lamps begin to flash in steady intervals. The lamps, when desired, are also intended to function as sequential lighting. These sensor units are attached to the top of a standard traffic cone or channelizer using a single bolt. Once activated, the sensors use a three-axis accelerometer to measure both tilt and impact. Signal processing algorithms are used to remove false positives. The sensors then transmit a signal using a 433 Megahertz radio frequency transmitter. If the sensor is close enough to the PSA unit for it to receive the signal, the alarm will activate. If not, the signal is repeated through the sensor network, which acts as a mesh network, chaining the information until it reaches the PSA unit (Novosel 2014, Intellicone 2016). The Intellicone system has only been tested in Kansas and it is commercially available. Figure 3-5 shows the different units of the Intellicone Alarm System. The Intellicone Portable Site Alarm (PSA) uses an internal rechargeable battery while the Intellicone Unipart Dorman ConeLITE (i.e. impact sensor) uses a 6V Carbon-Zinc Heavy Duty Lantern Battery (Intellicone 2016).



**Figure 3-5** Intellicone Alarm System

The wireless warning shield uses a coded repeater-style radio system. The unit, which is triggered via an internal shock sensor, transmits a radio signal that is picked up and retransmitted by the next two or three repeaters, each of which repeat as well. For a range of about 90 meters, several cones

should be triggered at once, causing redundancy of repeater points. The repetition increases the reliability of the repeater chain. The signal is also picked up by any of the receiving alarm systems that are within range. These alarms, whether area alarms, personal body alarms, or headphone alarms, will all signal a “hit,” indicating possible danger (Kocheva 2008, Ozbay et al. 2012). The Wireless Warning Shield processor functions to allow for fewer false triggers. It can be mounted on almost any type of traffic control device and it is very economical. Detailed information on the performance wireless warning shield is not available because the technology is not commercially available and has not yet been applied or tested in any work zone.

## Chapter 4 Experimental Procedure and Results

This section presents the experimental evaluation of selected commercially available intrusion technologies based on the review of applicable technologies for work zone safety. As presented in Table 3-1, SonoBlaster, Traffic Guard Worker Alert System, and Intellicone were selected as the main commercially available technologies that can be implemented for work zone safety. Preliminary testing was first carried out on the technologies to test if they function well and provide the required alerts. Field experimental trials were then carried out to implement the technologies for work zone safety in a simulated work environment. Discussion points are provided based on findings from the implemented experimental methodologies.

### 4.1 Experimental Set-up and Data Collection

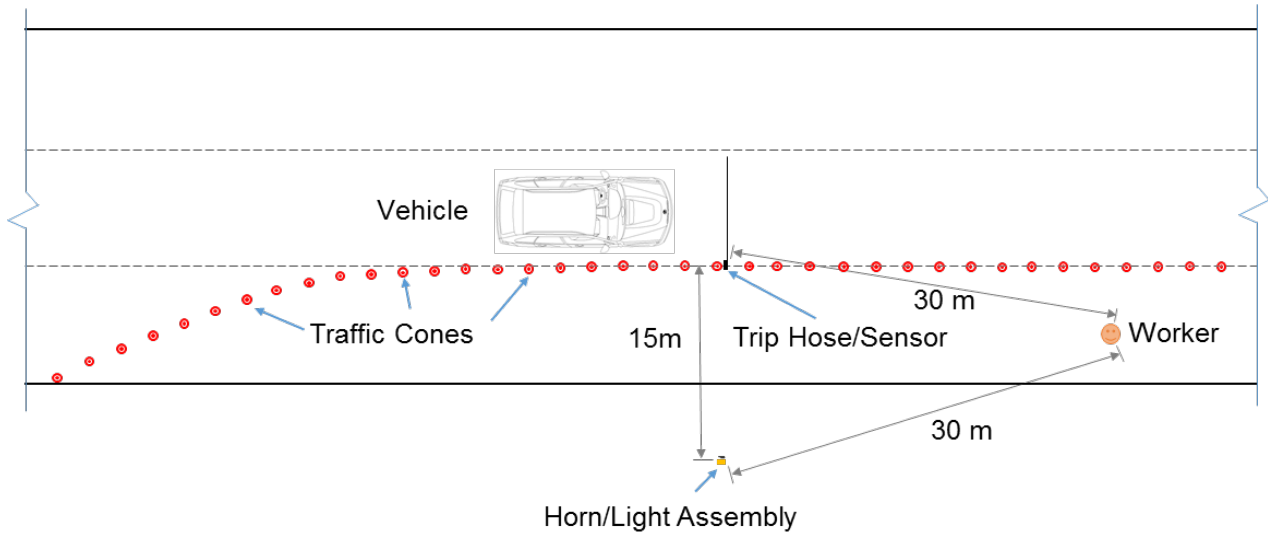
Several preliminary trials were completed at the University of Alabama's campus to determine the set-up procedure and overall feasibility of the tested systems. A test bed was established on an abandoned straight concrete roadway with minimal grade on the selected site for experimental trials as shown in Figure 4-1. The test bed was located at Craig Air Field in Selma, AL. The research team marked out about 300 meters of the roadway for the experimental trials. Traffic cones were placed at 6 meters intervals along the roadway for approximately 300 meters. A taper was created with the traffic cones at the beginning of the test bed to simulate a lane closure.

The setting up of the Intellicone involved mounting five 5 impact sensors on consecutive traffic cones (Figure 4-1). The Intellicone PSA was mounted on another traffic cone located at 9 meters, 9 meters, and 15 meters from the impact sensors for set 1, 2, and 3 of the experimental trials respectively. The Traffic Guard Worker Alert System was set up by placing a pneumatic trip hose with attached sensor lining the traffic cones along the testbed. The horn/light assembly was located away from the pneumatic trip hose sensor as shown in Figure 4-2. The SonoBlaster unit was set up by attaching the unit to a traffic cone. Figure 6 shows the test bed of the experimental trials for the testing of the Intellicone alarm system.



**Figure 4-1** Test Bed for Experimental Trials

A video recorder and time lapse camera were positioned to record the experimental trials. Three sets of experimental trials were conducted for each of the technologies. In the first set, a worker was made to stand at 9 meters from the alarm speaker as shown in Figure 4-2. A member of the research team drove a vehicle at the speed of 40 kilometers per hour (25 miles per hour) and a rod protruding from the vehicle was made to hit the cone on which the impact sensor was mounted to activate the alarm. This technique was used for Intellicone and SonoBlaster testing while the vehicle crossed over the air pressure hose to trigger the alarm during the testing for the Traffic Guard Worker Alert System. Figure 4-2 shows the layout of the experimental trials site for the testing of Traffic Guard Worker Alert System.



**Figure 4-2** Layout of the Experimental Trials Site

The sound level was measured from the alarm speaker to the worker's location using a sound meter and the process was repeated for a total of 15 trials. The worker's reaction time as well as the time taken for the vehicle to come to a complete stop after the impact were then extracted from the video recording. The stopping distance was also measured and computed using the vehicle speed and stopping time after the activation of the alarm. The worker stood 15 meters and 30 meters away from the alarm speaker for the second and third sets of experimental trials respectively while the vehicle was driven at 72 kilometers per hour (45 miles per hour) for both sets of experimental trials. The same procedure used for the first set of experimental trials was used for the remaining two sets. Attempts to test the SonoBlaster were unsuccessful as the unit did not provide the warning alarm when the cone on which it was mounted was impacted by the traveling vehicle.

## 4.2 Experimental Evaluation Results

The data analysis, results, and discussion of the experimental trials are presented in this section. The analysis of the sound level provided by the two intrusion alarm technologies is presented and discussed. The worker's reaction to the alarm technologies are assessed and discussed. The reaction of the vehicle driver was also evaluated in terms of the vehicle stopping time and the vehicle stopping distance. The implication of the experimental outcomes for work zone safety is also discussed.



### 4.3 Sound Levels of the Intrusion Alert Technologies

The sound levels of the two alarm systems measured at different distances from the alarm source with the aid of a sound meter are presented in Figure 4-3. The sound meter used to measure the sound level of the alarms was calibrated using the sound decibel levels of three common noise sources. The sound levels of a handsaw, electric drill, and hair drier were used. The alarm duration of Intellicone was 60 seconds which was much longer than that produced by the Traffic Guard Worker Alert System which lasted for just 5 seconds. The sound levels were determined by extracting the sound level at the start of the alarm, the lowest and peak sound levels as well as the sound level at the end of the alarm from the graphed sound profile. These sound level points for 15 trials were used to compute the average sound level of each of the two technologies at distances of 3 meters, 9 meters, 15 meters, and 30 meters from the alarm speaker. The results showed that the sound levels provided by these two systems were very close at the different distances as illustrated in Figure 8 with the Intellicone generally having a higher sound level than the Traffic Guard Worker Alert System.

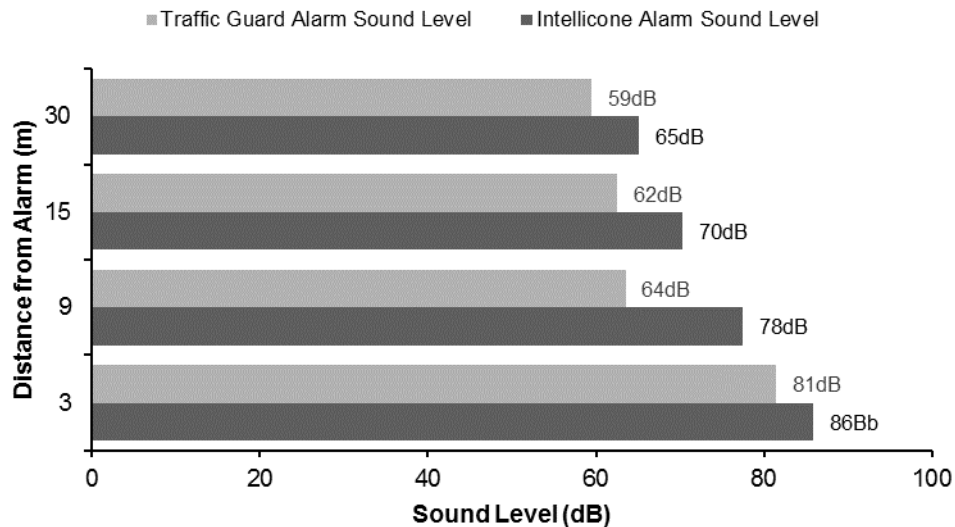


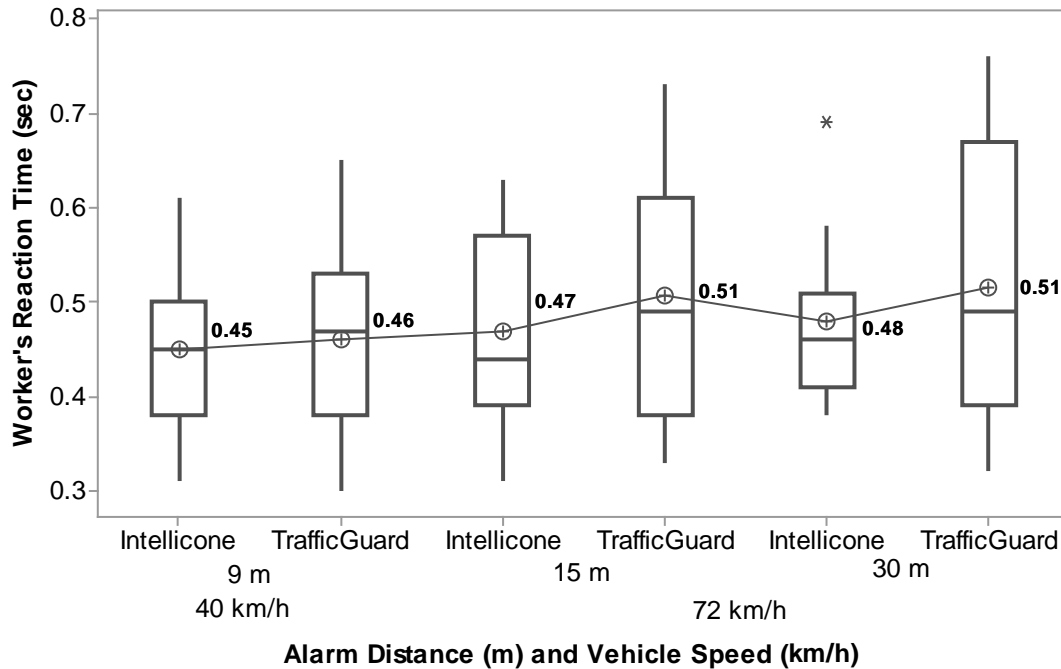
Figure 4-3 Sound Level of Intellicone and Traffic Guard Alerts

As expected, the sound level decreased as the distance of the sound meter from the alarm speaker increased with the Intellicone Alarm still having the louder sound level throughout the distances. The sound levels of the two alarm technologies were also tested with construction equipment (a back hoe was in use on a construction site near the test area). Although dependent on the distance of the construction equipment from the alarm source, the sound level of the two alarm technologies was found to be distinct and higher than the sound produced by the backhoe.

### 4.4 Worker's Reaction to the Intrusion Alert Technologies

The results of the worker's reaction to the alarm produced by the two systems tested are presented in Figure 4-4. The results indicate that worker reacted to the alerts provided by both alarm

technologies. The worker reacted a little faster to the Intellicone alarm than the Traffic Guard alarm even as the distance of the alarm from the worker as well as the vehicle speed varied. The shorter reaction time recorded for Intellicone could be because of the higher sound volume produced by the Intellicone alarm which may have also been amplified by the sound made from the collision of the intruding vehicle with the cone on which the impact activated sensor alarm was placed.



**Figure 4-4** Results of Worker's Reaction Time

The average reaction time expectedly increased as the distance of the worker from the alarm increased as indicated in Figure 9. This implies that the closer the worker is to the alarm, the shorter the reaction time (i.e. the faster the worker reacts to the alarm). The results also indicate that the reaction time increased slightly with increase in the speed of the intruding vehicle by a margin of 0.02 - 0.05 second with the Traffic Guard Worker Alert System having the higher margin. Although, the Traffic Guard Worker Alert System provided an extra Personal Safety Device (PDS) which gives the worker an additional vibratory alarm when a vehicle runs over the hose, this PDS was not found to be effective because the vibratory alert had delays ranging from 1 to 2.5 seconds with an average delay of 0.37 second over the 15 trials performed in the experiment.

#### 4.5 Response of Vehicle Driver to the Intrusion Alert Technologies

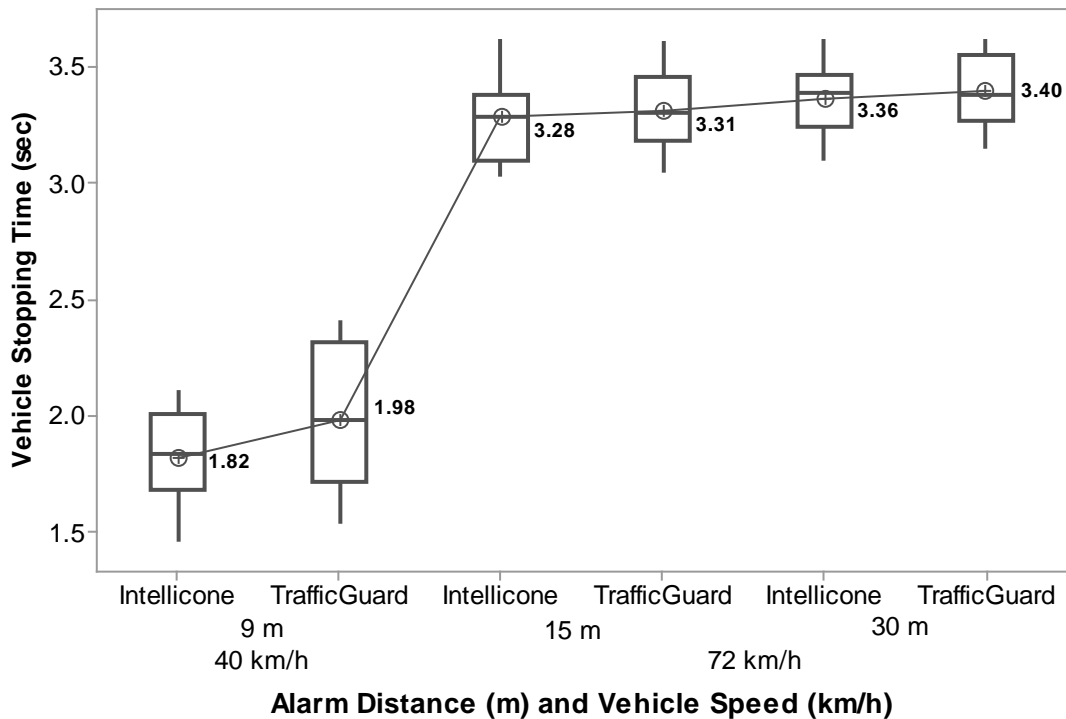
The vehicle driver's response to the intrusion alarm technologies were evaluated in terms of the amount of time it took the driver to bring the alarm to a complete stop after hearing the sound from the alarm and possible also observing the visual alert. The distance covered during this time was also measured and computed to establish the relative dynamic position of the intruding or errant vehicle from pedestrian workers at work zones. The vehicle stopping distance was computed using Eq. (1).

$$S_D = 0.224vt \tag{1}$$

Where  $S_D$  is the vehicle stopping distance in meters (m),  $v$  is the vehicle speed in miles per hour (mph), and  $t$  is the vehicle stopping time in seconds (sec).

#### 4.6 Vehicle Stopping Time

The results of the vehicle stopping time at vehicle speed of 40 kilometers per hour and 72 kilometers per hour are presented in Figure 4-5. The results of the experimental trials show that the driver took a longer time to stop the vehicle when the Traffic Guard Worker Alert System was used than the Intellicone alarm. This could be because of the higher sound volume produced by the Intellicone alarm together with the impact sound when the cone is knocked down. The fact that the alarm is activated when the vehicle runs over the pneumatic trip hose in the Traffic Guard system without a loud impact sound may not give the driver that additional alert apart from the sound produced from the alarm and the directional light from the alarm system.



**Figure 4-5.** Results of Vehicle Stopping Time

The vehicle stopping time expectedly increased as the vehicle speed was increased from 40 kilometers per hour to 72 kilometers per hour with a difference ranging between 1.42 and 1.54 seconds for Traffic Guard and Intellicone respectively. The decision on the positioning of the alarm source should be carefully thought out because irrespective of how well the position of both the pedestrian worker and the vehicle is considered, it might be wiser to give more preference to the pedestrian worker for faster response. In this case, the worker’s response time is compared to the time taken by the driver to bring the vehicle to a complete stop. The results from the previous

section indicated that the worker took an average of 0.45 seconds to respond to the alarm provided by the Intellicone while it took the driver 1.82 seconds to bring the vehicle traveling at 40 kilometers per hour (i.e. 25 miles per hour) to a complete stop. This implies that the distance covered by the vehicle in 0.45 second (which is approximately equal to 2.52 meters) in the direction of the pedestrian worker should be less than the position of the worker. Similarly, in the case of the Traffic Guard system, the distance covered by a vehicle traveling at 72 kilometers per hour (i.e. 45 miles per hour) in 0.51 seconds (which is approximately 5.14 meters) in the direction of the pedestrian worker should be less than the position of the worker.

#### 4.7 Vehicle Stopping Distance

Figure 10 illustrates the results of the vehicle stopping distance at vehicle speed of 40 kilometers per hour and 72 kilometers per hour when the two alarm systems were used one after the other. The experimental findings indicate that a longer distance was covered before the vehicle was brought to a complete stop when the Traffic Guard Worker Alert System was used than when the Intellicone alarm was deployed as depicted in Figure 4-6. This again could be because of the louder sound produced by the Intellicone system.

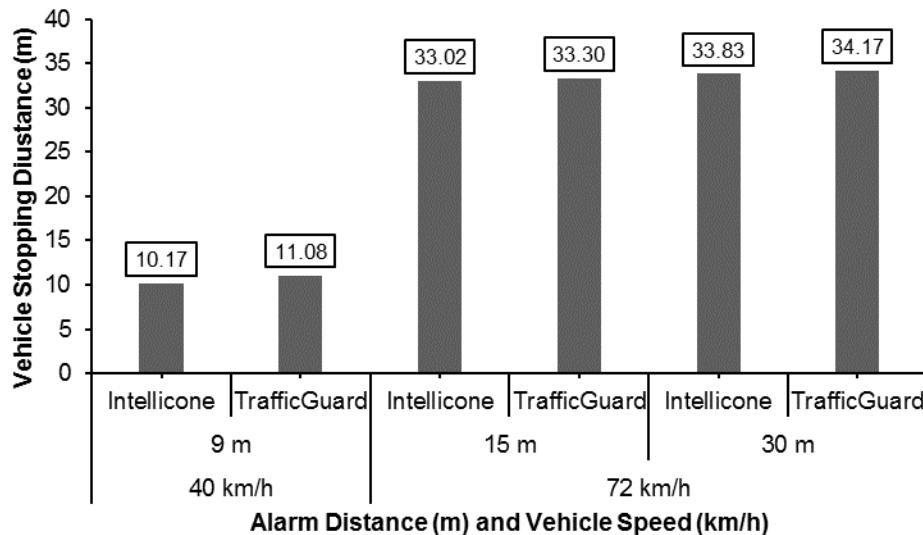


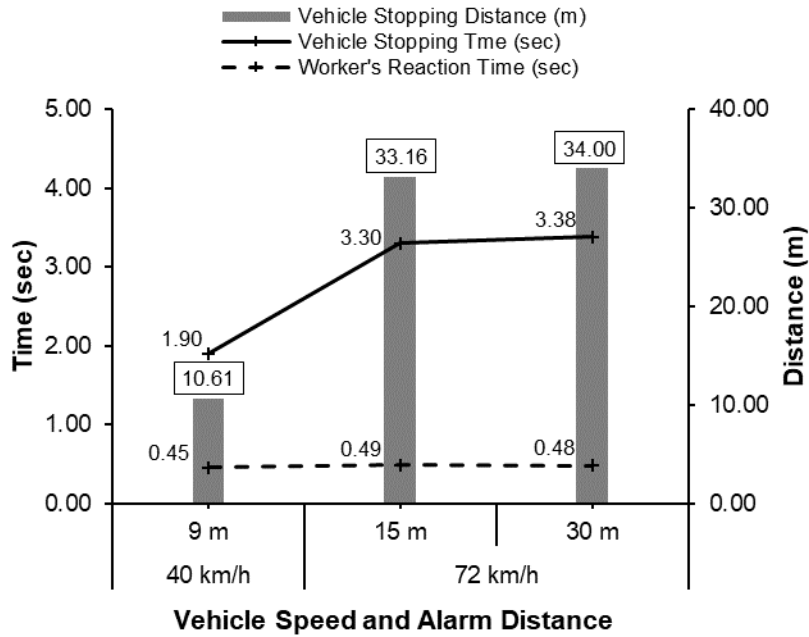
Figure 4-6 Results of Vehicle Stopping Distance

The consideration of these vehicle stopping distances is paramount in the planning of the layout for the implementation of these intrusion alarm technologies. These distances with an extra factor of safety may perhaps be set as the minimum allowable distance between the intrusion sensor and the pedestrian workers.

#### 4.8 Implication of the Experimental Findings for Work Zone Safety

The results of the experimental investigation imply that warning alerts can be provided to the workers and vehicle drivers around work zones when hazardous situation occurs. This can be observed in the experimental results as depicted in Figure 4-7. On the average, it took a worker less than 1 second to respond to warning alerts produced by the tested intrusion sensing

technologies. This result is satisfactory but cannot be considered in isolation because the response of the vehicle driver is very vital in determining if the pedestrian worker is fully protected from being hit by the vehicle.



**Figure 4-7** Summary of Experimental Results

The minimum stopping distance for a vehicle is determined by the effective coefficient of friction between the tires and the road, and the driver’s reaction time in a braking situation assuming proper operation of brakes on the vehicle. Using the results of this experimental evaluation, the work area should not be less than 10.61 meters away from the intrusion sensing device while it should be a minimum of 34.00 meters if the posted vehicle speed is 72 kilometers per hour (i.e. 45 miles per hour). These results would have been compared to the posted stopping distances obtained from past transportation studies but there is no uniformity in the values determined as these values vary from one document to the other.

Though the experimental findings may not be generalized because other factors not investigated may also influence the responses of workers and vehicle drivers warning alerts, it is relevant to note that these results can be used in planning the work zone layout when some of these technologies are deployed to mitigate injuries and fatalities.

## Chapter 5 Recommendation

Based on results of the review and experimental evaluation, the research team has several recommendations for selecting and implementing work zone sensing technology. The research team recommends implementing the Intellicone for longer tapers in construction highway work zones where traffic barrels or other longer term temporary devices are implemented. The Traffic Guard Worker Alert System is recommended for short tapers and short term or mobile highway work zone projects. For long term highway work zone projects requiring heavy pieces of construction equipment, the AWARE System is recommended. This system requires the most infrastructure but provides the best opportunity for alerting highway work zone personnel during a work zone intrusion. More information on implementation is provided in the implementation guide. Table 5-1 presents a guide when selecting work zone intrusion detection devices.

**Table 5-1** Selection Guide for Work Zone Intrusion Detection Devices

Situations	Intellicone	Traffic Guard Worker Alert System	AWARE
Longer than one day	X		X
One day or shorter		X	
Mobile operation			X
Taper longer than or equal to 1,500 ft.	X		X
Taper shorter than 1,500 ft.		X	

## **Chapter 6**

### **Conclusion**

The limited work space and ever-changing nature of highway construction work zones make the work environment very dangerous for pedestrian workers (Gambatese and Lee 2016, Fyhrie 2016). Active sensing and alert devices are not readily available in highway work zones and in transportation infrastructure construction and maintenance. The applicable intrusion technologies for work zone safety were reviewed in this paper. Commercially available technologies were evaluated using experimental trials. Out of the seven applicable intrusion technologies reviewed, only four are commercially available. The findings of this review indicate that a few states have had difficulty in using most of the early intrusion alarm systems despite the efforts made by the device manufacturers to improve these systems. Some of the shortcomings of the technologies are lengthy set up time, false alarms, misfires and alignment difficulties. This has continued to hinder the wide-spread application of these technologies for work zone safety. For instance, there were challenges with the use of SonoBlaster which led to the inability of the research team to evaluate the technology along with the Intellicone and Traffic Guard Worker Alert System evaluated.

The results of the experimental evaluation of the Intellicone and Traffic Guard systems indicate that the two technologies produce more than one type of alerts which can be used to warn workers when vehicle intrudes the work zone. The findings also indicate that workers and vehicle drivers responded to the warning alerts provided by this technology as observed in the reaction times obtained in the experimental trials. As expected, worker's reaction time was on average less than 1 second while the vehicle stopping time was less than the posted stopping time for vehicle traveling at the same speed used in this experimental evaluation.

The performance of the two technologies evaluated by the research team was satisfactory in terms of power consumption as no issues were encountered with batteries running down. The batteries supplied the required power throughout the duration of the experiments. The technologies were relatively easy to set up and no cases of false alarms were experienced while testing the Intellicone and Traffic Guard systems.

## References

- Agent, K. and J. Hibbs. (1996). "Evaluation of SHRP work zone safety devices." *Research Report No. KTC-96-30*, Kentucky Transportation Center, Lexington, KY.
- Andrijcic, E., Y. Y. Haimes, and T. Beatley. "Public policy implications of harmonizing engineering technology with socio-economic modeling: Application to transportation infrastructure management." *Transportation Research Part A: Policy and Practice* 50 (2013): 62-73.
- Astro Optics (2017). "Traffic Guard Worker Alert System." *Astro Optics, LLC*.  
<http://www.astrooptics.com/products/traffic-guard-worker-alert-system>
- Bathula, M., Ramezanali, M., Pradhan, I., Patel, N., Gotschall, J., and Sridhar, N. (2009). "A sensor network system for measuring traffic in short-term construction work zones." *Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 5516 LNCS, 216-230.
- Benekohal, R., ahim, Kaja-Mohideen, A. and Chitturi, M. (2004). "Methodology for estimating operating speed and capacity in work zones." *Transportation Research Record: Journal of the Transportation Research Board*, 1883(1), 103-111.
- Bryden, J. and Mace, D. (2002). "Guidelines for design and operation of nighttime traffic control for highway maintenance and construction." *NCHRP Report 476, Transportation Research Board*. Washington, D.C.
- Burkett, G. and Her, V. (2009). "Development of new kinds of mobile safety barriers." *AHMCT Research Center*, California Department of Transportation, Davis, California.
- Carlson, P., Fontaine, M. and Hawkins, H. (2000). "Evaluation of traffic control devices for rural high-speed maintenance work zones." *Texas Transportation Institute*, The Texas A&M University System, College Station, Texas.
- Chambless, J., Ghadiali, A., Lindly, J. and McFadden, J. (2002). "Multistate work-zone crash characteristics." *Institute of Transportation Engineers*. 72(5), 46.
- Cleaver, L. (2016). "Oldcastle Materials Creates AWARE to Save Lives." Oldcastle Materials, <<http://www.forconstructionpros.com/article/12181842/oldcastle-materials-creates-aware-to-save-lives>> (Feb. 8, 2017).
- Duranton, G. and Turner, M. (2012). "Urban growth and transportation." *The Review of Economic Studies*, 79(4), 1407-1440.
- Federal Highway Administration (FHWA). (2016). "NCHRP Report 350: Devices in Work Zones." *U.S. Department of Transportation*,



<[https://safety.fhwa.dot.gov/roadway\\_dept/policy\\_guide/road\\_hardware/nchrp\\_350/](https://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/nchrp_350/)> (Feb. 8, 2017).

Fyhrie, P. (2016). "Work zone intrusion alarms for highway workers: Preliminary investigation." *Caltrans Division of Research, Innovation and System Information*. California Department of Transportation.

Gambatese, J. and Lee, H. (2016). "Work zone intrusion alert technologies: Assessment and practical guidance." *SPR Research Program Second-Stage Problem Statement FY 2016*. ODOT Research Unit. Oregon Department of Transportation.

Givechi, M. (2015). "Cones sound a warning of work zone intrusion." *Kansas LTAP Newsletter*, Kansas University Transportation Center.

Hagan, M. (2004). "Work-zone safety ITS: technical analysis and system proposal." *Transportation Research Institute (UMTRI)*. University of Michigan, Ann Arbor, MI.

Hanscom, F., Graham, J. and Stout, D. (1993). "Highway evaluation of maintenance work zone safety devices." *Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents Conference*, Federal Highway Administration, Hague, Netherlands.

Hourdos, J. (2012). "Portable, Non-Intrusive Advance Warning Devices for Work Zones with or without Flag Operators." *Final Report*. Minnesota Department of Transportation Research Services. Minnesota Department of Transportation.

Intellicone (2016). "About." Intellicone, <<http://www.intellicone.co.uk/about>> (Feb. 7, 2017).

IntelliStrobe (2016). "W1-AG automated flagger assistance device." IntelliStrobe Safety Systems, <<http://flaggersafety.com/home.html>> (Feb. 7, 2017).

Khan, A. (2007). "Microsimulation of traffic in highway work zones for testing ITS-based traffic management measures." *11th World Conference on Transport Research*, Elsevier, Shanghai, China.

Khattak, A., Khattak, A. and Council, F. (2002). "Effects of work zone presence on injury and non-injury crashes." *Accident Analysis & Prevention*, 34(1), 19-29.

Kochevar, K. (2008). "Intrusion Devices - New and Emerging Technology in Worker Safety." Federal Highway Administration, <[http://ops.fhwa.dot.gov/wz/workshops/accessible/Kochevar\\_ID.htm](http://ops.fhwa.dot.gov/wz/workshops/accessible/Kochevar_ID.htm)> (Feb. 7, 2017).

Krupa, C. (2010). "Work Zone Intrusion Alarm Effectiveness." *Report NJ-2010-004*, New Jersey Department of Transportation.

- Li, Y. and Bai, Y. (2008). "Development of crash-severity-index models for the measurement of work zone risk levels." *Accident Analysis & Prevention*, 40(5), 1724-1731.
- Lin, P., Kang, K. and Chang, G. (2004). "Exploring the effectiveness of variable speed limit controls on highway work-zone operations." *Intelligent Transportation Systems*, 8(3), 155-168.
- Liu, Y., Li, C., He, Y., Wu, J. and Xiong, Z. (2007). "A perimeter intrusion detection system using dual-mode wireless sensor networks." *Communications and Networking in China*, IEEE, 861-865.
- Martin, J., Rozas, A. and Araujo, A. (2016). "A WSN-Based intrusion alarm system to improve safety in road work zones." *Journal of Sensors*, MDPI.
- Meng, F. and Spence, C. (2015). "Tactile warning signals for in-vehicle systems." *Accident Analysis and Prevention*, 75 (2015) 333–346
- Mohan, S. and Gautam, P. (2002). "Cost of highway work zone injuries." *Practice Periodical on Structural Design and Construction*, 7(2), 68-73.
- National Work Zone Safety Information Clearinghouse (NWZSIC). (2016). "Fatalities in Motor Vehicle Traffic Crashes by State and Work Zone (2014)." U.S. Department of Transportation Federal Highway Administration, <<https://www.workzonesafety.org/crash-information/workzone-fatalities/workzone-fatalitiesmotor-vehicle-traffic-crashes-2014/>> (February 3, 2017).
- Novosel, C. (2014). "Evaluation of advanced safety perimeter systems for Kansas temporary work zones." *MS. Thesis*, Civil, Environmental, and Architectural Engineering, University of Kansas, Lawrenceville, KS.
- Noyce, D. and Smith, C. (2003). "Driving simulators for evaluation of novel traffic-control devices: Protected-permissive left-turn signal display analysis." *Transportation Research Record: Journal of the Transportation Research Board*, 1844(1), 25-34.
- Ozbay, K., Bartin, B., Yang, H. and Chien, S. (2012). "Traffic control and work zone safety for high volume roads: Final report." *Center for Advanced Infrastructure and Transportation (CAIT) Rutgers*, The State University of New Jersey. New Jersey Department of Transportation.
- Phanomchoeng, G., Rajamani, R. and Hourdos, J. (2010). "Directional sound for long-distance auditory warnings from a highway construction work zone." *IEEE Transactions on Vehicular Technology*, 59(5), 2266-2276.
- Pratt, S., Fosbroke, D. and Marsh, S. (2001). "Building safer highway work zones: Measures to prevent worker injuries from vehicles and equipment." *No. DHHS (NIOSH) Publication*, Center for Disease Control.

- Qiao, F., Jia, J., Yu, L., Li, Q. and Zhia, D. (2014). "Drivers' smart assistance system based on radio frequency identification: Enhanced safety and reduced emissions in work zones." *Transportation Research Record Report 2458*. Journal of the Transportation Research Board, 37-46.
- Sullivan, J. (2005). "Work-zone safety ITS: smart barrel for an adaptive queue-warning system." *Transportation Research Institute (UMTRI)*. University of Michigan, Ann Arbor, MI.
- Sun, B., Osborne, L., Xiao, Y. and Guizani, S. (2007). "Intrusion detection techniques in mobile ad hoc and wireless sensor networks." *IEEE Wireless Communications*, 14(5), 56-63.
- Trans Canada Traffic Inc. (2016). "Intellicone Traffic Management Unit." Intellicone, <<http://www.transcanadatrafic.ca/Intellicone-WorksitePack.html#>> (Feb. 4, 2017).
- Transpo (2010). "SonoBlaster Work Zone Intrusion Alarm." *Transpo Industries Inc.*, <<http://www.transpo.com/SonoBlaster.html>> (Feb. 4, 2017).
- Trout, N. and Ullman, G. (1997). "Devices and technology to improve flagger/worker safety." *Research Report 2963-1F*. Texas Transportation Institute, College Station, Texas.
- Tsai, Y. (2011). "Development of a sensing methodology for intelligent and reliable work-zone hazard awareness. *Final Report for Highway IDEA Project 139*. Transportation Research Board of the National Academics. Washington, D.C.
- Tsai, Y., Wang, C. and Wu, Y. (2011). "A vision-based approach to study driver behavior in work zone areas. *International Conference on Road Safety and Simulation*, Indianapolis, IN.
- Ullman, G., Finley, M., Bryden, J., Srinivasan, R. and Council, F. (2008). "Traffic safety evaluation of nighttime and daytime work zones." *Project. 17-30 Report*, Transportation Research Board, Washington, D.C.
- Wang, M. (2011). "Evaluation of innovative traffic safety devices at short-term work zones." *Report No. K-TRAN: KU-09-5*, Kansas Department of Transportation.
- Wang, M., Schrock, S., Bai, Y. and Rescot, R. A. (2011). "Evaluation of innovative traffic safety devices at short-term work zones." *Bureau of Materials and Research*, Kansas Department of Transportation.

# University Transportation Center for Alabama

## Executive Committee

**Dr. Jay K. Lindly, Director UTCA**  
The University of Alabama

**Dr. Steven Jones, Associate Director UTCA**  
The University of Alabama

**Dr. Fouad H. Fouad, Associate Director UTCA**  
The University of Alabama at Birmingham

**Dr. Houssam A. Toutanji, Associate Director UTCA**  
The University of Alabama in Huntsville

## Staff

**Ms. Connie Harris, Secretary UTCA**

## Contact Information

University Transportation Center for Alabama  
1105 Bevill Building  
Box 870205  
Tuscaloosa, AL 35487-0205  
(205) 348-9925  
(205) 348-6862 fax

[utca@eng.ua.edu](mailto:utca@eng.ua.edu)  
<http://utca.eng.ua.edu>