Evaluation of Advanced Safety Perimeter Systems for Kansas Temporary Work Zones

By

Christopher Novosel

Submitted to the graduate degree program in Civil, Environmental, and Architectural Engineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Master of Science.

Chairperson Dr. Steven Schrock

Dr. Thomas Mulinazzi

Dr. Robert Parsons

Date Defended: December 11, 2014

The Thesis Committee for Christopher Novosel

certifies that this is the approved version of the following thesis:

Evaluation of Advanced Safety Perimeter Systems for Kansas Temporary Work Zones

____

Chairperson Dr. Steven Schrock

Date approved: December 11, 2014

Abstract

Every year approximately 120 workers die in work zones, with approximately 60 percent of them as a result of intrusion accidents. Temporary work zones have a critical safety gap due to the expense and time needed to deploy positive protection systems, allowing intrusions to occur more easily. In order to help address this gap, the two safety perimeter systems currently on the market, the Intellicone and the SonoBlaster, were evaluated for their applicability for temporary work zones in Kansas. The SonoBlaster is entirely mechanical, channelizer-mounted and produces an air-horn-like alarm when tipped over. The Intellicone is electronic, with sensors mounted on channelizers, which transmit a warning signal to a site alarm that produces an electronic auditory and visual alarm.

Testing was conducted in two phases: closed-course testing and field testing. Closed-course testing evaluated the operational parameters of both systems, especially their alarm sound levels and sound distribution. The Intellicone was found to be relatively quieter, but more consistent in alarm sound level, while the SonoBlaster was found to be relatively louder, but with much greater variation. The activation angles for both systems were also tested, as well as the transmission distance and battery life of the Intellicone system.

Field testing was conducted at four active work zones, ranging from local roads to an interstate highway. Both systems were deployed at each location and set off, allowing workers to experience alarm activations as if intrusion accidents had occurred. Following testing at each location, an oral survey was administered to the workers regarding their opinions on each system's effectiveness, suitability, and safety benefits. The majority of workers felt both safety perimeter systems were good and would be useful in helping address safety concerns from intrusion accidents. However, the sound volumes were perceived to be too low, with the

Intellicone being too quiet and the SonoBlaster's sound being localized too far from where work was actually occurring in the work zone.

Both systems showed great promise, as well as having worker acceptance. There were some minor difficulties: system setup was more difficult for the SonoBlaster, while the Intellicone had a few technical glitches. However, this research demonstrated that such safety perimeter systems have great potential to be successfully deployed to increase worker safety.

Acknowledgements

Thanks so much to Dr. Steven Schrock, Dr. Thomas Mulinazzi, and Dr. Eric Fitzsimmons, who taught me much as an undergraduate and a graduate student, and for advising me throughout writing my thesis. Thanks as well to Dr. Robert Parsons, who generously offered his time to help me finish my degree. The help of my fellow graduate and student researchers was invaluable in helping this research come together.

Thanks to Highway Resource Solutions who generously provided the Intellicone products and support throughout our testing. Thanks as well to the City of Lawrence, especially Mike Perkins, Mark Thiel, David Cronin and the work crews who allowed us to field test beside them and who gave us their invaluable input. Thanks to KDOT, especially Howard Lubliner and Josh Welge for their willingness to deploy these systems in their work zones and their help in finding appropriate locations for the research. Thanks to Barclay Hornung and Comanche Construction, to RD Johnson Excavating and Sunflower Paving, and most especially to the work crews who allowed us to work side by side with them.

Thanks to my family, especially my parents, who were great supporters through my courses and writing my thesis. Most especially, thanks to my wonderful wife, who has stood by me in everything, including the pursuit of my Master's degree.

And thanks be to God, who has given me all that I have. To God alone be the glory.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

Crashes in work zones due to vehicle intrusions represent a serious safety hazard for work crews, with an average of 120 worker fatalities occurring every year in work zones (Pegula, 2013) and approximately 60 percent are due to intrusions (Geistlinger, 1996). In order to address this issue, positive protection systems are often used on long-term, stationary, or hazardous work zones to provide lateral buffer space, a vehicle barrier, and a safe means of escape for work crews. However, temporary work zones often do not require positive protection or the use of such a system on the ground that it would be inefficient due to the short duration or mobile nature of the work zone project. Safety devices for these work zones are limited to plastic channelizers and truck-mounted attenuators, protecting work crews by providing separation from open traffic.

In order to fill the gap of safety systems for these types of work zones where positive protection is not feasible, work zone safety perimeters have been proposed. Significant research and development of potential systems occurred in 1990s with the Strategic Highway Research Program (SHRP) Project H-109 (Stout et al., 1993), but results were inconclusive and their use since has been limited. Numerous limitations of then-current systems were identified as part of the research and field testing which took place around the country (Agent and Hibbs, 1996; Stout et al., 1993; Trout and Ullman, 1996; Krupa, 2010). Safety perimeter systems had significant problems with false-positives, unreliable communication, difficult or time-consuming setup, and poor training for work crews deploying the systems. In addition, many systems required ongoing adjustments in order to properly maintain the electronic or mechanical perimeter. Due to the issues encountered with the systems, nearly all of the then-existing systems were discontinued.

Problem Statement

There is a significant gap in current research on work zone safety perimeter systems as compared to positive protection systems and other safety devices intended to safeguard work crews. Work zone intrusions by vehicles represent a serious safety risk for workers in work zones not protected by positive protection systems. At the time of this research, only two safety perimeter systems were on the market. This research analyzed the efficacy, ease-of-use, and perceived usefulness of the Intellicone and SonoBlaster safety perimeter systems for the purpose of determining whether or not such a system could provide meaningful safety improvements for temporary work zones.

An electronic safety perimeter system has been developed in the United Kingdom (UK), taking advantage of recent technology, and has had some success in the UK. The Intellicone system (Figure 1) is a safety perimeter system that uses already-present plastic channelizers and cones with sensors. Work crews are alerted with both a visual and auditory alarm from a separate alarm unit which is placed near the work crew. The alarm activates when a channelizer or cone equipped with a sensor is knocked over, whether that be in the taper area, before the work zone, or adjacent to the work zone. The use of sensors on multiple channelizers increases the likelihood for an intruding vehicle to strike an equipped channelizer and activate the alarm. The placement of a separate alarm unit near the workers increases the likelihood for workers to hear and recognize the alarm.

Figure 1. Intellicone Alarm Unit

Figure 2. SonoBlaster with Channelizer

The SonoBlaster (Figure 2) is a mechanical device which attaches to plastic channelizers and activates when knocked over. The device uses a compressed CO_2 cartridge to emit an auditory alarm and alert workers to a vehicle intrusion. It can also be equipped on channelizers in tapers, and before and adjacent to work zones, providing multiple points of contact. The auditory alarm is emitted from the device attached the channelizer.

The research will evaluate the two systems currently on the market, specifically analyzing their effectiveness. Operational characteristics, as well as ease-of-use and perceived usefulness by work crews, will be evaluated and compared for both systems. Limitations and potential problems will also be considered.

Intellicone Description

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 sensors.

The sensors are constructed of plastic. The sensors are powered by two 6V 4R25 batteries in the base of the unit. The lamps are yellow LEDs. When turned on, 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 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 MHz 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.

The PSA unit is constructed of durable hard plastic and is rated at IP67, making it dust-proof and moderately water-resistant. The PSA is powered by an internal, rechargeable battery. A small display allows control over all user-selectable settings, along with a power button, several selection buttons, and an alarm reset button. It emits a loud, three-tone siren for a user-determined amount of time. It also houses a bright visual warning using red LED flashing in a user-selected pattern. These LEDs can also display green while the alarm is inactive or be turned off. Once the alarm receives a signal, both the auditory and visual alarms activate. It can then be reset using the reset button.

SonoBlaster Description

The SonoBlaster is an entirely mechanical device which emits an auditory alarm. The entire alarm is constructed of hard plastic, except for the CO_2 nozzle constructed of metal. It also operates attached to a channelizer, by using two small bolts on the back side of the alarm, which go through holes drilled in the channelizer.

In order to activate the unit, the nozzle/CO_2 canister cover is removed and the firing pin inside the nozzle cocked by inserting the provided plastic arming tool. The front knob is turned to 'Locked' (the knob must be in the 'Unlocked' position to cock), and a single-use small CO_2 cartridge is inserted into the nozzle. The cover is replaced, covering the nozzle and CO_2 cartridge completely. The channelizer should then be positioned as desired, and the knob turned back to 'Unlocked.' Once the CO_2 cartridge is inserted and the knob in the 'Unlocked' position, the alarm is armed. The alarm activates when tipped, using a small weight inside the device. The internal firing pin then punctures the CO_2 cartridge, and the escaping gas is routed to a horn, emitting an air horn-like sound. Once fired, the CO_2 cartridge is spent and must be removed and replaced.

Organization

This thesis is organized into six chapters. Chapter 1, Introduction, discusses the state of temporary work zone safety and the limitations of current safety measures. Key safety gaps are identified, the conceptual workings of safety perimeter systems are explained, and the two systems being research are described. Chapter 2, Literature Review, summarizes studies related to intrusion crashes in work zones, their causes and the resulting injuries and fatalities. Reviews of previous safety perimeter systems are also summarized, along with other relevant studies. Chapter 3, Methodology, details the procedures and tests done with both safety perimeter systems, both in the closed course and field study testing phases. Chapter 4, Data Collection, describes the specific circumstances of the testing and the observed results, focusing on unanticipated outcomes. Chapter 5, Data Analysis, presents the analysis and results of the closed-course tests and the reduction of the field testing data. Chapter 6, Findings and Discussion, discusses the findings, explains safety contributions, and provides future avenues for research.

Chapter 2 Literature Review

Crash, Injury and Fatality Statistics

Based on data from the Bureau of Labor Statistics, the fatalities at road construction sites were analyzed for 1995 to 2002 by Pegula (2004). A total of 844 worker fatalities occurred.

Table 1. Fatalities at Road Construction Sites, 1995-2002

Year	Fatalities	% Indexed vs 1995
1995	94	0.0%
1996	93	-1.1%
1997	94	0.0%
1998	113	20.2%
1999	124	31.9%
2000	106	12.8%
2001	118	25.5%
2002	102	8.5%
Total	844	

In this same time period, workplace fatalities overall have declined, while road construction site fatalities have fluctuated or risen. More than half of the fatalities (504 total) were from being struck by a vehicle or mobile equipment, with 446 fatalities attributable to highway vehicles, representing the type of fatality an intrusion would cause.

An analysis of fatalities at road construction sites was also performed by Pegula (2013) for the years of 2003-2010 using data from the Bureau of Labor Statistics Census of Fatal Occupational Injuries. During those years, 962 were killed at these sites, with no signs of increasing improvements since 2003. Of those, 87 percent were working at the site when killed (13 percent were drivers passing through).

Table 2. Fatalities at Road Construction Sites, 2003-2010

Year	Fatalities	% Indexed vs 2003
2003	110	0.0%
2004	119	8.2%
2005	165	50.0%
2006	139	26.4%
2007	103	-6.4%
2008	101	-8.2%
2009	116	5.5%
2010	106	-3.6%
Total	962	

During the analysis years, workers were just as likely to be killed by construction or maintenance equipment as by other vehicles (152 fatalities versus 153 fatalities). Significantly, of the 143 instances of being fatally struck by a backing construction vehicle, 25 collisions occurred when back-up alarms were specifically noted as being present and working (versus 14 noted as non-functioning). Of the total number of fatalities, 92 were workers involved in flagging or traffic control.

An in-depth analysis of 77 work zone crashes involving fatalities from February 2003 – April 2004 in the state of Texas was performed by Schrock et al. (2004). Data were collected through site visits of each crash following notification by the Texas Department of Transportation (TxDOT). Site visits were performed to better understand what effect the traffic control had on the crash, in order for improvements to be made. In the 77 fatal crashes, there were 88 total fatalities, including six contract workers and one TxDOT employee. At least one of the fatal crashes where a worker was killed was an intrusion incident. It was determined that the work zone had no influence (the crash did not involve the work zone or traffic control and likely would have occurred even if the work zone were not present) on 45 percent of the crashes, an indirect influence (the crash involved the work zone or traffic control even though both were properly set up) on 39 percent of the crashes, and a direct influence (the work zone was improperly set up resulting in the crash) on 8 percent of the crashes. Based on the research, it was believed that auditory signals or a warning system of some kind could be a useful countermeasure for work zone crashes.

Bryden et al. (2000) examined the database of 290 reported work zone intrusion crashes in New York from 1993 to 1998. Of these, about two-thirds (196) of the intrusions were full intrusions, that is, totally entering a construction area defined by channelizers or other devices. Another fifth (56) were intrusions into mobile work zones. The rest were either in buffers or access areas, or intrusions from debris thrown into the work zone (not from an intruding vehicle). When vehicles did intrude, they were most likely to hit other vehicles or equipment (153). Actually hitting a pedestrian only occurred about 10 percent of the time (26). Setup and removal operations account for 8 percent of the total (23), which though small, is probably an overrepresentation considering the small amount of time involved. Overall, intrusions are rare, accounting for about 9 percent of work zone crashes and 7 percent of serious worker injuries. Workers were only involved in about half of the intrusions (131) and a third of the total injuries (18 of 60). Both speeding and driver inattention are believed to be major factors in intrusion crashes.

Injury and crash data from the California Department of Transportation (CALTRANS) for 1998-2007 was analyzed by Wong et al. (2011), specifically looking at 19,228 reports regarding CALTRANS workers. There were 208 crashes where a vehicle entered a work zone and caused injuries or fatalities. Rear-end intrusions accounted for 65 percent of all intrusions, with sideswipe (15 percent) being the second most common. It was determined that 94 percent of the intrusion incidents "could not have been prevented by the employee injured." Mobile work zones accounted for 49 percent of intrusion crashes, with short-term stationary (more than one hour, less than one daylight period) having 29 percent, and short duration (less than one hour) having 9 percent of the crashes. The analysis indicated that time of day, location, duration, and activity type were the four most significant influences on injury severity, with non-peak, moving lane closure, short-duration stationary, with on-foot workers having the most severe injuries.

Geistlinger (1996) reviewed national work zone fatality information and found that between 600-900 workers die every year from injuries received in roadway-repair zones, with 59 percent dying from vehicle intrusions.

Inattentive drivers form the greatest risk to workers and intrusion alarms can help address this. Work zone alarm systems work by delineating the work zone through mechanical or electronic means and an intrusion sets off an alarm. Both systems have advantages, and companies produce both types. False alarms are an issue as workers may stop reacting to an overused alarm.

Intrusion Alarm Analysis

SHRP Project H-109, conducted by Graham, Hanscom, and Stout, et al. (1993) tested various traffic control devices for short-term work zones, which were subsequently tested on open highways. Workers were trained on how to use the systems they were setting up. An ultrasonic intrusion system and an infrared intrusion system were tested in Arizona, Iowa, and Missouri (ultrasonic system only). The infrared system gave no false alarms, while the ultrasonic system did give some under cold, humid conditions. This was modified and retested with no false alarms. Further testing of both units resulted in some false alarms so the communication system was upgraded to FM radio. It was recommended that both systems be mass produced for further testing.

Various work zone safety devices from the Strategic Highway Research Program were evaluated under the direction of the Kentucky Transportation Cabinet (Agent and Hibbs, 1996) through trial use. Intrusion alarms are designed to give advanced warning of intruding vehicles; five such systems - one microwave system, one infrared system, and three pneumatic tube systems - were evaluated. Modifications based on feedback from 11 different state, county, local and private agencies were made, mostly focused on simplifying setup and increasing the volume of the alarm. Generally, workers were not enthusiastic about the devices, though they were found to be durable. A definite recommendation was not possible due to the continuous modifications, but it was believed that they had potential for use on major projects, with cost being a limiting factor. More evaluation was recommended.

A study was performed by Trout and Ullman (1996) to determine if work zone traffic control devices and techniques in use around the country were applicable to Texas. Various state Departments of Transportation were contacted and ten devices were reviewed, including intrusion alarm systems. The alarm systems were microwave-, infrared-, or pneumatic-based and were intended to give workers additional seconds to get out of the way of an errant vehicle entering the work zone. All three types of alarms were found to have issues with false alarms and difficult setup. A microwave-based system was rejected by the Alabama, Colorado, Iowa, and Pennsylvania DOTs because of setup difficulties and false alarms both due to difficulties keeping the devices aligned. An infrared-based system was rejected by Colorado, Iowa, Missouri, New York, and Pennsylvania DOTs due to problems with false alarms, alarms set off by workers, beam alignment, and setup. A pneumatic-based system was rejected by the Alabama, Iowa, New

Hampshire, and Pennsylvania DOTs due to problems with setup, inconsistent activation, and lack of sufficient warning. No field testing was done on the devices by Trout and Ullman; all information was obtained from reviews of existing information. It was determined that the technology, reliability, and ease of setup would need to improve to be effective.

Several devices were investigated by Burkett et al. (2009), including intrusion alarms. Intrusion alarms are intended to be set up quickly and activated when a vehicle enters into a restricted area in a work zone in order to alert workers to the danger. They are less expensive and easier to set up than positive protection, so they can more easily be used with short duration work zones. Various technologies existed, each with its own issues. Tipping sensors attached to cones can be knocked over by wind, resulting in false positives, or small vehicles could pass by cones without striking them, resulting in no alarm when one should have been issued. Pneumatic tubes reduce the chance of false positives. Microwaves or other electronic barriers must maintain proper alignment at all times and are usually not destroyed when the barrier is breached. However, alignment can be difficult when the road is uneven or curved.

Various systems did exist, but at the time of writing were no longer produced due to technical issues, small markets, or general ineffectiveness. Only the SonoBlaster was currently available. Issues in the development of such devices were maximizing alarm time, reducing false alarms, and worker determination of the intrusion point. Ultimately, the devices were found to be impractical, both from a technical side and from a lack of worker acceptance (Burket et al., 2009).

Cambridge Systematics (Krupa, 2010), on behalf of the New Jersey DOT, evaluated the SonoBlaster Work Zone Intrusion Alarm. The device alerts both workers and the driver to an intrusion into the work zone. Field testing was conducting for the closing of a shoulder on a high volume four-lane divided highway in New Jersey. No intrusions occurred during the test period, so two impact simulations were conducted. The sound volume was sufficient for alerting workers at 200 feet, including those with ear protection, though effectiveness during jack hammer operation was not tested. Setup was difficult and the unit had issues with activating while supposedly not armed. As no intrusions actually occurred, worker acceptance could not be gauged. It was concluded that quality control, reliability, and cost issues outweighed the potential benefits.

Kochevar (2014) presenting for the FHWA gave information on intrusion alarms and their place in work zone safety. There is a definite need for intrusion alarms: from 1998 to 2001, fatalities and injuries in work zones increased 33 percent (772 to 1026) and 25 percent (39,000 to 53,000), respectively. Possible reasons for the increase include increased vehicle miles travelled (VMT), work zone inconsistency, distracted driving, and an increase in work at night. Intrusion alarm systems were also presented. The Safety Line SL-D12 was an infrared system consisting of a transmitter and receiver emitting a strobe light and a siren. The SonoBlaster was discussed. The Wireless Warning Shield (WWS) was also mounted on traffic control devices and activated if impacted. A signal was transmitted from the impacted device to personal body alarms which both vibrated and emitted an auditory alarm.

Other Related Studies

Phanomchoeng et al. (2010) studied auditory warnings that were being used to alert drivers on highways. It can be hard to pinpoint the location of normal sirens, and they can be heard by drivers, potentially causing disturbances. An alarm system was designed to warn workers and an intruding vehicle from a considerable distance without being disturbing to nearby traffic. Several technologies were tried, with a panel of loudspeakers selected as the best technology. Normal loudspeakers produced poor directional sound while other systems were too expensive and difficult to set up. The selected array produced a noticeable alarm inside the vehicle at several hundred feet, but with sufficient sound drop off in adjacent lanes.

Summary

Past reviews of work zone intrusion alarms have found many of the devices to be unreliable, difficult to setup, and prone to false alarms. Specifically, several important considerations were revealed through this literature review:

- There are, on average, 120 worker fatalities a year, with around two-thirds resulting from intrusion incidents.
- False alarms were a major issue for most of the systems tested, making them unreliable indicators of intrusions.
- Setup of the majority of the systems was difficult, requiring continued work to maintain the perimeter of the systems.

The information from the literature reported herein was useful in developing the methodology for this research, which is found in Chapter 3.

Chapter 3 Methodology

Research was conducted in two main phases: 1) closed-course testing, and 2) field testing. The closed-course testing was designed to determine the operational limits of both sensors, including the sound levels and activation conditions of both alarms, as well as battery life and transmission distance of the Intellicone alarm. Field testing focused on ease-of-use, false alarm rate, and worker perception of the alarms.

Closed Course Testing

Intellicone Alarm Sound Levels

To test the sound level of the Intellicone alarm, the PSA unit (Figure 3) was set up in the corner of an outdoor test area, along with the sensor attached to a channelizer. The outside test area consisted of the University of Kansas band practice facility, which had the advantage of being in a relatively remote part of campus and had permanent yard line markers for ease of measurement. The sensor was activated along with the alarm unit, and the sensor was tipped by pushing the cone completely over, activating the PSA unit auditory alarm for 10 seconds.

Figure 3. Intellicone Alarm Unit with Marked Directions

Sound levels from the alarm were measured using a sound meter at a distance of 10 feet from the unit, with the sound meter being held approximately 4 feet off the ground. Sound levels were also measured in four directions 90° apart from the PSA unit, by rotating the unit 90° after each test, then measuring the sound levels again at the same distance but for each of the four directions. Direction 1 was directly in line with one of the three equally spaced speakers, direction 2 was 30° right of a speaker, direction 3 was equally spaced between two speakers, and direction 4 was 30° left of a speaker (Figure 4). This was to determine if the sound from the alarm was directional or omnidirectional. Once all four directions were measured, the process was repeated at distances of 20 feet, 30 feet, 40 feet, 50 feet, 100 feet, 200 feet, 300 feet, and 400 feet and 500 feet (Figure 5).

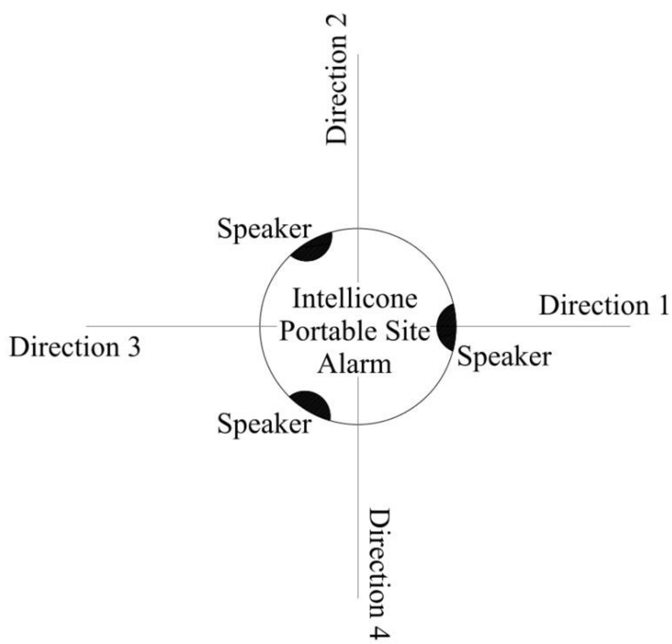


Figure 4. Intellicone Portable Site Alarm Speaker Orientations

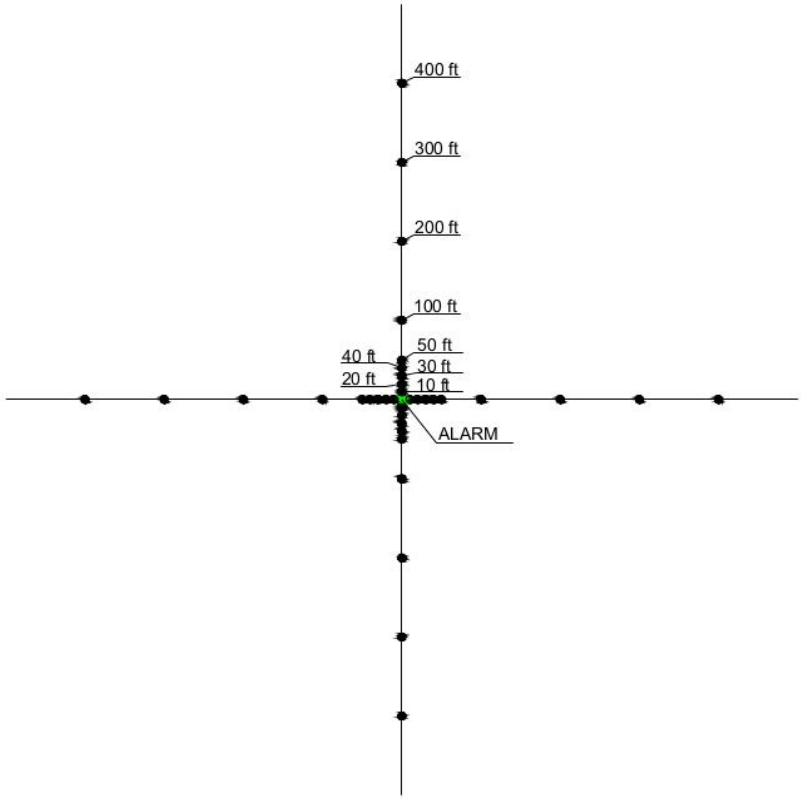


Figure 5. Intellicone Alarm Sound Level Testing Layout

As part of the sound level testing, frequencies were also measured in order to make a comparison with the SonoBlaster Alarm. Frequency measurements were made at 100 feet.

SonoBlaster Alarm Sound Levels

To test the sound level of the SonoBlaster, it was attached to a traffic delineator cone according to instructions from the manufacturer (Figure 6). The SonoBlaster and cone were then set up in the corner of the outdoor test area. The SonoBlaster was cocked with the cocking pin and the unit was turned to the 'Locked' position. It was loaded with an approved CO_2 cartridge, oriented properly, and then turned to the 'Unlocked' position. The cone was then tipped by pushing the cone completely over, activating the SonoBlaster alarm.

Figure 6. SonoBlaster Attached to Channelizer

The SonoBlaster has a unidirectional alarm, so it was first tested at a distance of 200 feet, with the alarm facing different directions to determine which orientation would result in the loudest alarm sound level and the quietest alarm sound level. Actual activation in a work zone would result in a random orientation, therefore measuring these loudest and quietest orientations gave the best and worst case scenario for alarm sound levels. Five alarm orientations were tested: directly away from the sound meter, perpendicular (sideways) from the sound meter, directly towards the sound meter, towards the ground, and up into the air. These orientations were then measured at distances of 10 feet, 20 feet, 30 feet, 40 feet, 50 feet, 100 feet, 200 feet, 300 feet, and 400 feet and 500 feet. As part of the sound level testing, frequencies were also measured in order to make a comparison with the Intellicone alarm. Frequency measurements were made at 100 feet.

Alarm Sound Levels with Construction Equipment

Alarm sound levels for both the Intellicone and the SonoBlaster were also tested in the presence of construction equipment, specifically, an idling backhoe. As depicted in Figure 7, the sound meter was set in three separate locations relative to the backhoe: inside the cab of the backhoe, 30 feet directly out from the side of the backhoe, and 100 feet directly out from the side of the backhoe. In addition to these three placements of the sound meter, which were intended to simulate workers at various distances from construction equipment, three different distances were used for the alarm units: 10 feet, 100 feet, and 200 feet, all perpendicularly away from the backhoe and sound meter, in line with the sound meter. Sound levels for the SonoBlaster were measured with the alarm oriented directly towards the sound meter.

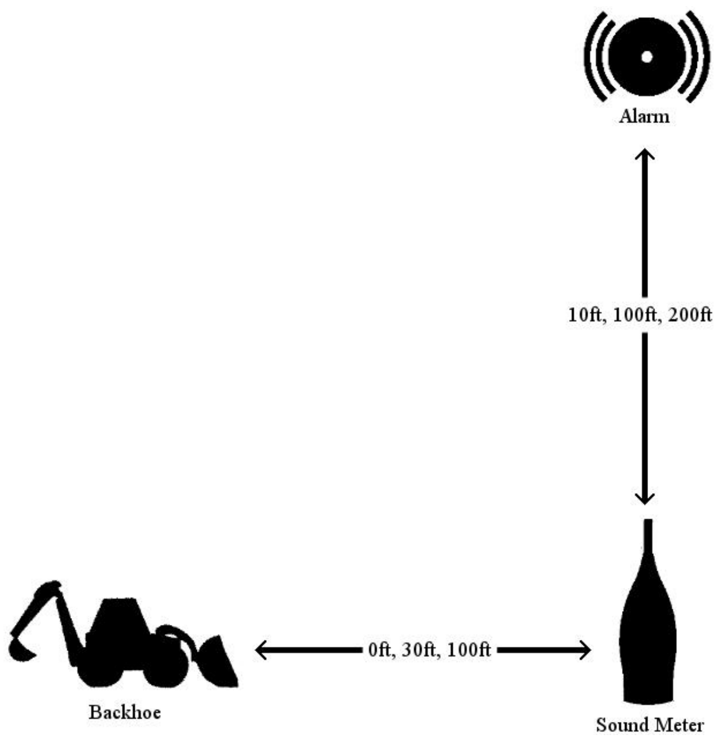


Figure 7. Layout for Alarm Sound Level Testing with Construction Equipment

Alarm Activation Angle

Both the SonoBlaster unit and Intellicone sensor were tested to determine the angle at which the unit activates its alarm. The SonoBlaster was attached to a channelizer and cocked without a CO_2 installed. The cone and SonoBlaster assembly was then slowly tipped over by hand until the firing pin could be heard firing. This was video recorded and at the moment of firing, a still photograph was extracted from the video, and the angle between the SonoBlaster and the ground was measured (Figure 8). This process was repeated a total of ten times. The unit was then rotated so the SonoBlaster was tipping on its second axis, and the process was repeated.

For the Intellicone system, the sensor unit was attached to the top of a channelizer with the alarm unit on the ground next to the cone. The assembly was then slowly tipped by hand, just as the SonoBlaster was, until the alarm unit was activated, and the angle was measured from a photograph extracted from the video recording. This was also repeated ten times and for both axes.

Figure 8. Intellicone Alarm Activation Angle Measurement

Battery Life

Battery life for the Intellicone system was measured as the time until failure, where failure was defined as the device no longer functioning. The SonoBlaster system is entirely mechanical and does not operate on batteries. Intellicone sensor battery life was measured by inserting two fresh batteries into a cone sensor and allowing them to run continuously until the sequential light no longer blinked. Three units were tested in an indoor environment.

Battery life for the portable site alarm unit was measured by fully charging the unit, and then allowing it to run continuously until it was no longer on. The battery life of the alarm was tested both with the green LED status lights on (Figure 9) for the duration of the test and with the green LED status lights off (Figure 10) for the duration of the test. Whether the green LED lights were on or off had no effect on the ability of the alarm unit to receive and display alarms. The alarm unit was tested three times with the LEDs on and three times with the LEDs off in an indoor environment.

Figure 9. Intellicone with Green LED Activated

Figure 10. Intellicone with Green LED Deactivated

Effective Transmission Distance

Two effective transmission distances for the Intellicone system needed to be determined: one for the transmission between the PSA unit and the sensor unit and one for transmission between two sensor units. The methodology for this test was based on similar research conducted at the Transportation Research Laboratory (TRL) in the UK (Beard et al., 2013).

The first transmission distance determined was between the PSA unit and the sensor unit (Figure 11). First, a sensor was activated 50 feet from the PSA unit. It was assumed that at this distance, there would be 100 percent transmission. The sensor was activated by quickly tipping the channelizer and attached sensor completely over to a 90° angle, which was found to be most reliable.

Figure 11. Intellicone Transmission Distance Testing

This was repeated 10 times and a transmission percentage was established. If the transmission percentage was not 100 percent, the distance was decreased in 10-feet increments until 100 percent transmission was achieved. The distance was then increased in 50-feet increments until the longest distance with 100 percent transmission and the distance with 0 percent transmission were found.

Sensor-to-sensor transmission distance was tested in a similar way. The PSA unit and sensor were set up such that no signal from this first sensor could reach the PSA unit, using the data from the first test. A second sensor unit was set up in between these with the distance varying from the first to second sensor. Because the distance from first sensor to PSA unit remained at the 0 percent distance or greater, its activation did not activate the PSA unit. And because the distance from the second sensor to the PSA unit remained under the 100 percent distance or less, its activation always activated the PSA unit. Activation of the PSA unit by activating the first sensor therefore only tested the transmission success rate between the first and second sensor.

The beginning distances used between the sensors and between the PSA unit were based on data from the first test. The sensor was activated by quickly tipping the channelizer and attached sensor completely over to a 90° angle. This was repeated 10 times and a transmission percentage was established.

If the transmission percentage was less than 100 percent, the distance was decreased in 50-feet increments until 100 percent transmission was achieved. Once 100 percent transmission was achieved, the distance between the sensors was increased in 50-feet increments, testing 10 times as each distance, until 0 percent transmission was achieved.

Field Testing

Field testing of the two alarm systems took place in two stages. The first stage was a preliminary field evaluation of the Intellicone in order to determine if there was a significant rate of false alarms due to normal traffic or stationary operation. If any such problem existed it could adversely affect the work in any work zone used for field testing and would adversely affect the research. The Intellicone system was deployed in an active work zone for 12 hours over the course of two days but the PSA unit was not near the work crew. The PSA and sensors were recorded using a video camera in order to determine the cause of any false alarms which occurred. If any such false alarms did occur, the alarm rate per vehicle volume would be determined from the video.

Phase 1 Testing

Working with the City of Lawrence Public Work Department, a suitable work zone was selected on Bob Billings Parkway between Kasold Drive and Monterey Way (Figure 12). Bob Billings Parkway is a four-lane principal arterial road (KDOT June 2013) with an ADT of approximately 11,500 vehicles on the portion under construction (KDOT August 2013). The posted speed limit is 40mph.

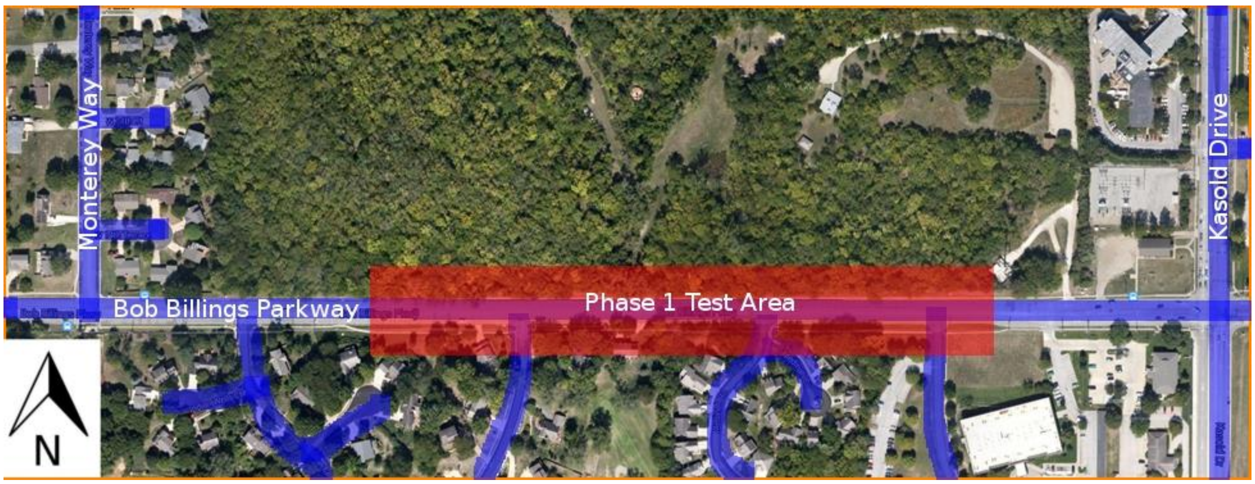


Figure 12. Phase 1 Test Area

Asphalt was being patched in the eastbound lanes by a seven person crew. Diesel trucks, a skid steer loader, jackhammers, an asphalt roller, and a vibratory plate compactor were all in use. Both eastbound lanes were closed and traffic was diverted to the westbound lanes, with one lane open in each direction. Traffic control consisted of standard 42" vertical channelizers to separate both the opposing traffic as well as the work zone from the flow of traffic (Figure 13). Two arrow boards were used upstream of the work zone in both directions in order to indicate that a merge was required for both eastbound and westbound traffic. The work zone was approximately 1000 feet long.

Figure 13. Phase 1 Test Area Traffic Control

The second stage of the field testing was the deployment of both the Intellicone and SonoBlaster systems at four separate work zones, for the purpose of determining the cause and rate of any false alarms and to survey the perceptions of the work crews to the alarms. The Intellicone and SonoBlaster systems were deployed in an active work zone for 12 hours over the course of two days with the PSA unit placed near the work crew. At the beginning of the first day of testing, the purpose of this research and the methodology of the field testing was explained to the workers present. The PSA and sensors were recorded using a video camera in order to determine the cause of any false alarms which occurred. If any such false alarms did occur, the alarm rate per vehicle volume would be determined from the video.

If, during the course of each day, either of the alarms were not activated, they were intentionally activated in order for the workers present to be able to hear the alarms. At the end of the second day of testing, an oral survey was administered, focusing on the workers' ability to perceive and recognize both alarms, the usefulness of such a system, and where such a system would be useful.

Test Site 1

Working with the City of Lawrence Public Works Department, a suitable work zone was selected for the first of four locations. The work zone was on Mississippi Street between 10th Street and 11th Street, at the intersection of Mississippi Street and Fambrough Drive (Figure 14). Mississippi Street north of Fambrough Drive is a two lane major collector (KDOT June 2013) with an ADT of approximately 4,000 vehicles on the portion under construction (KDOT August 2013). The speed limit is 30mph.

Figure 14. Location 1 Test Area

A storm sewer was being laid by an eight person crew, with the centerline of the storm sewer approximately 4 feet into the travelled way from the curb. Once the storm sewer was laid, concrete was poured over it, and then an asphalt wearing surface was placed. Diesel dump trucks, a skid steer loader, a backhoe, concrete trucks, an asphalt roller, and a vibratory plate compactor were all in use. The northbound lane and shoulder were closed, necessitating one-lane, two-way operation along the length of the operation. A single flagger was used to control traffic along the work zone as well as the intersection of Fambrough Drive and Mississippi Street, which is normally STOP-controlled along Fambrough Drive. Traffic control consisted of standard 42” vertical channelizers to separate the work zone from the flow of traffic (Figure 15). The work zone was approximately 350 feet long.

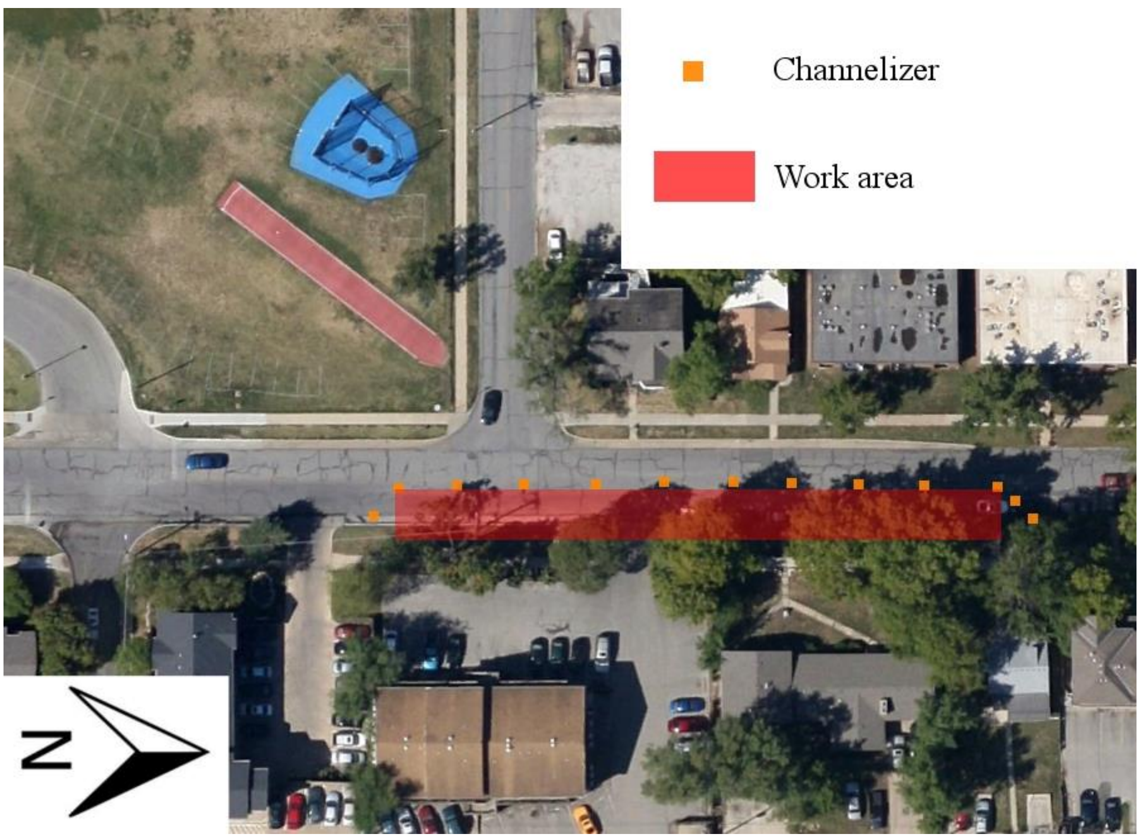


Figure 15. Location 1 Test Area Traffic Control

Test Site 2

Working with the Kansas Department of Transportation, a suitable work zone was selected for the second location. The work zone was on I-435 North on the 87th Street bridge in Lenexa, Kansas (Figure 16). I-435 is a six-lane interstate highway with an ADT of approximately 68,000 vehicles (8 percent trucks) on the portion under construction (Parsons Brinckerhoff et al. 2013). The speed limit is 70mph.

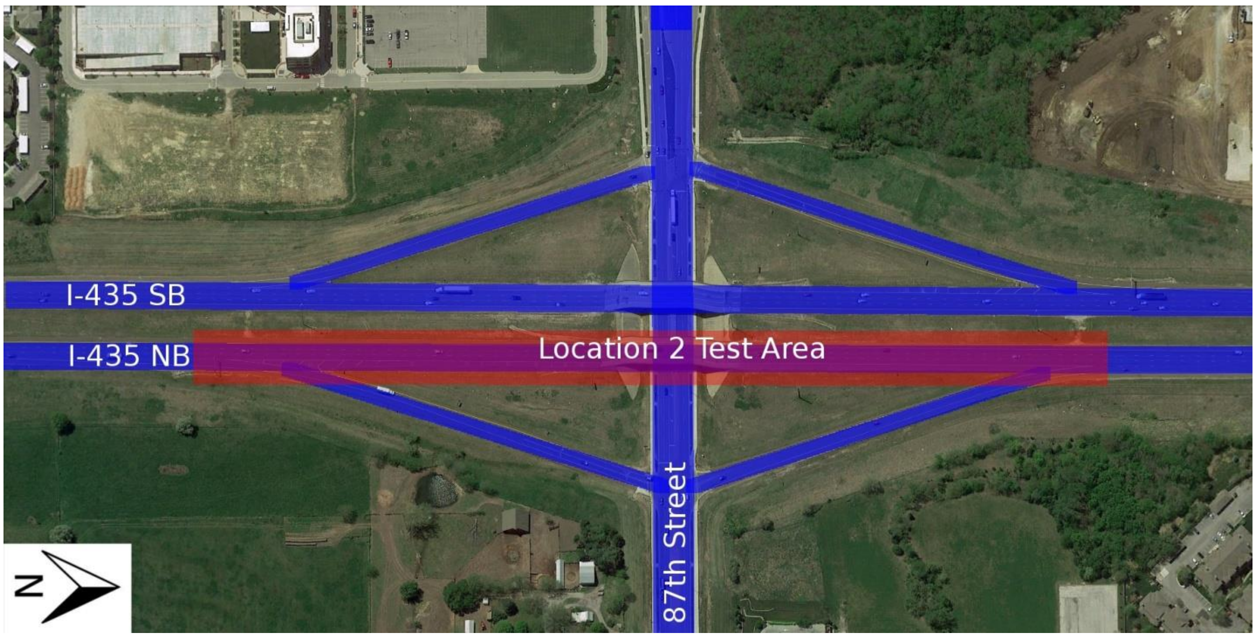


Figure 16. Location 2 Test Area

Bridge repair work was being completed, including removal and replacement of the concrete wearing surface, partial- to full-depth repairs of the bridge deck, repair of the bridge parapet, and partial repair of the bridge abutment. Diesel trucks, a skid steer loader, a backhoe, jackhammers, a chipping hammer, concrete saws, and a sandblaster were all in use. Workers were wearing in-ear hearing protection. The two outside northbound lanes and outside shoulder were closed, with two lanes of traffic shifted onto the inside lane and inside shoulder. Traffic control consisted of standard 42" vertical channelizers to merge vehicles into the shifted lanes, with temporary lane markings to delineate the lanes, DMS signs to communicate information upstream of the work zone, an arrow board, and concrete barriers to separate the work zone from the flow of traffic (Figure 17). The work zone was approximately 1200 feet long with the primary work and test area being approximately 600 feet long centered on the bridge. Similar repair work and traffic control was also being completed on the southbound bridge, though actual construction and repair work was not being done at the same time.

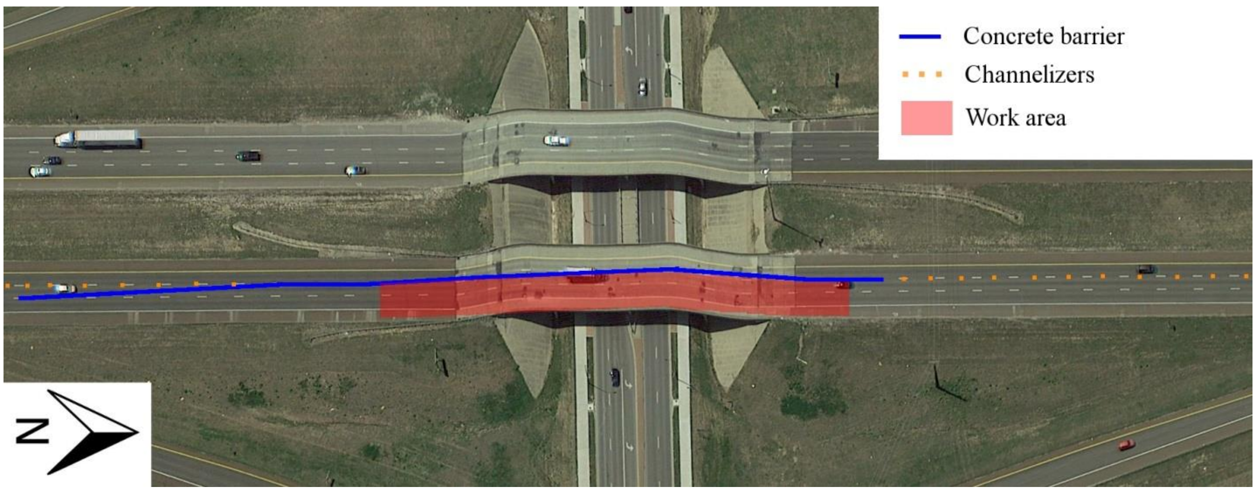


Figure 17. Location 2 Test Area Traffic Control

Test Site 3

Working with the City of Lawrence Public Works Department, a suitable work zone was selected for the third of the four locations. The work zone was on Wakarusa Drive between Bob Billings Parkway and north of Inverness Drive (Figure 18). Wakarusa Drive is a four-lane principal arterial (KDOT June 2013) with an ADT of approximately 14,000 vehicles on the portion under construction (KDOT August 2013). The speed limit is 45mph, though it had a posted speed limit of 20mph while under construction.

Complete pavement reconstruction as well as the addition of bike lanes was being completed. Diesel dump trucks, a skid steer loader and a backhoe were all in use. The northbound lanes and shoulder were closed, with both directions of traffic shifted to the southbound lanes, necessitating a single lane of traffic in each direction. Traffic control consisted of standard 42" vertical channelizers to separate the work zone from the flow of traffic and 28" tubular markers were used to separate opposing streams of traffic (Figure 19). A DMS sign was located in the taper section to direct northbound traffic to the proper access for nearby businesses. Several Type 3 barricades were also used in the taper section to block the lanes of traffic. The work zone was approximately 2500 feet long, with the southern half of the work zone being used for this research.

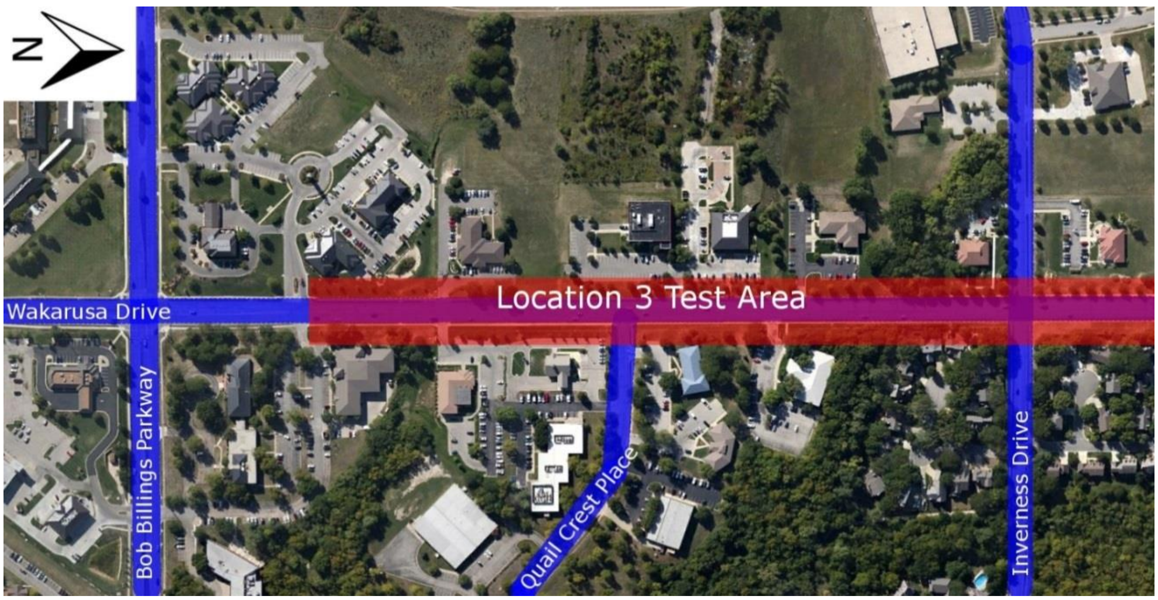


Figure 18. Location 3 Test Area

Figure 19. Location 3 Test Area Traffic Control

Test Site 4

A suitable work zone was selected for the last of the four locations. The work zone was on I-70/US-24/US-40 Eastbound at Exit 422A in Kansas City (Figure 20). I-70 at the location of the research is a four-lane interstate highway, with additional lanes on I-670 which diverges from I-70 approximately 0.25-mile upstream of the work zone, as well as additional acceleration and deceleration lanes. On the portion under construction, it has an ADT of approximately 35,900 vehicles (20 percent trucks) (Parsons Brinckerhoff et al. 2013). The speed limit is 55mph.

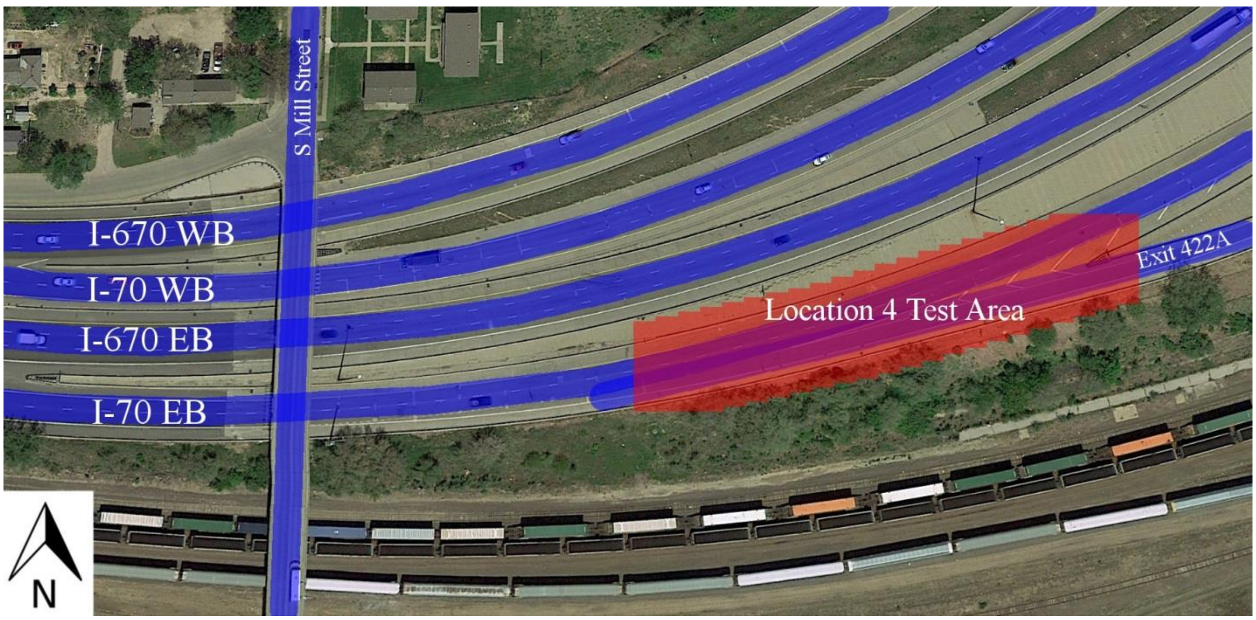


Figure 20. Location 4 Test Area

The I-70 Exit 422A gore area crash cushion was being replaced by an eight person crew. Several large diesel trucks and two skid steer loaders were in use. The southern-most, right through lane as well as the exit were closed, with only the left-hand through lane open in the area in question. Traffic patterns were normal on I-670 and I-70 Westbound. Traffic control consisted of standard 42” vertical channelizers to separate the work zone from the flow of traffic (Figure 21). The work zone was approximately 600 feet long.

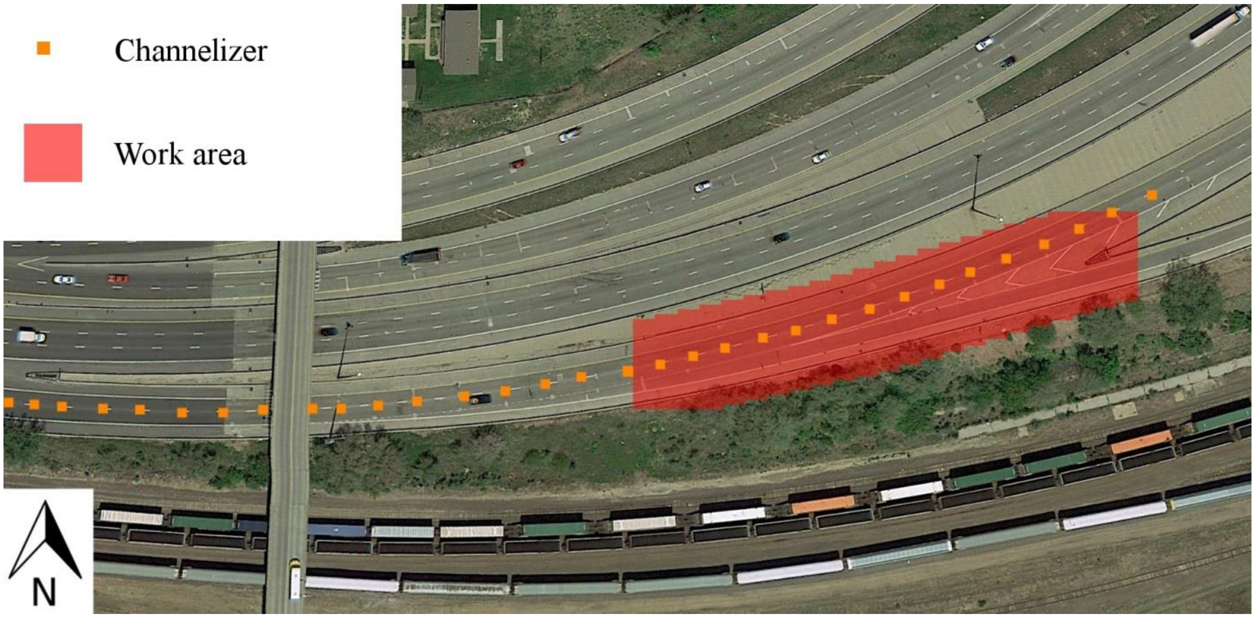


Figure 21. Location 4 Test Area Traffic Control

Survey Methodology

After testing at each of the locations, the following questions were asked:

1) How easy or hard was it to hear the alarms when they activated?
2) How close were you to the intrusion alarms when they activated?
3) When the alarm activated, what was your response?
4) If a real intrusion did or had occurred, how do you believe having an alarm deployed would affect the outcome, if at all?
5) What would be your overall rating of the alarm systems?
6) In what types of work zones do you feel this system would work well?
7) How would having the intrusion alarm deployed affect your feelings of safety in the work zone? Less safe, somewhat less safe, neither less safe nor more safe, somewhat more safe, more safe
8) Any additional comments?

Chapter 4 Data Collection

Closed-Course Testing

Intellicone Alarm Sound Levels

Sound levels were tested in an outdoor environment with the units set up on the ground in the corner of a level 360 foot by 160 foot asphalt test area (Figure 22). Sound levels were tested on a windy day using a sound meter with attached wind shield. The weather was cloudy and the temperature was approximately 50°F. Observations of sound levels indicated that wind did not affect the sound levels recorded due to the substantial difference in sound levels between the wind and the alarm.

Figure 22. Intellicone Alarm at Sound Level Testing Area

While the sound level tests were being conducted, there were several construction vehicles in the area when the close distance tests were being conducted. Monitoring the sound meter as levels were being read indicated that this did not affect the sound level readings of the alarm at all. However, the construction vehicles returned while the 400 foot tests were being conducted and engine and mechanical noises from the vehicles were observed to be louder than the alarm levels, so the tests were ended after all 400 foot tests were completed, without testing sound levels at 500 feet. It was noted, however, that even though noise from the construction vehicles was louder, the alarm could still be clearly perceived due to its unique high-frequency noise, which was qualitatively different than the mechanical noises from the equipment. It was also observed that the alarm sound level is fairly consistent while it is playing. A graph of a typical alarm sound level profile is displayed in Figure 23.

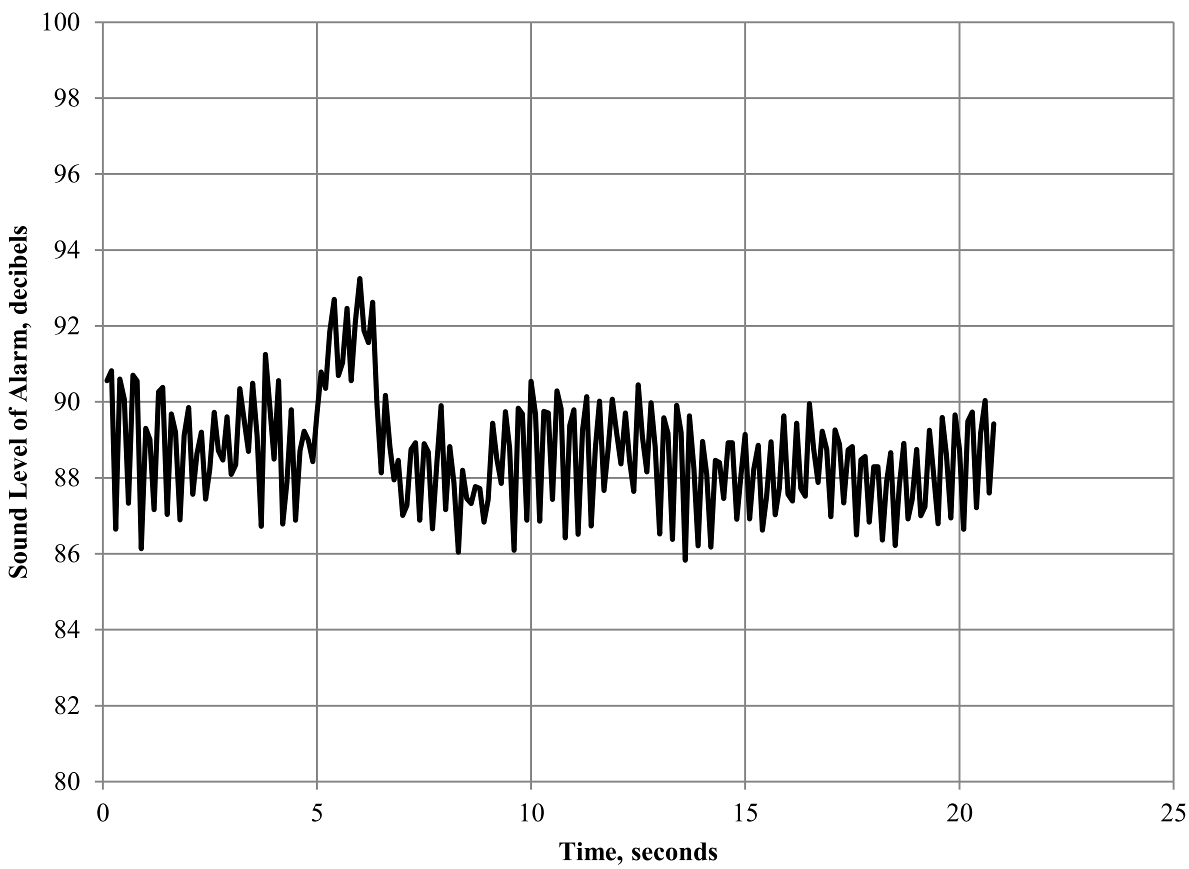


Figure 23. Intellicone Alarm Sound Profile

As part of the frequencies testing it was observed in the field that measurements at 100 feet did not give clearly defined differentiation with ambient sound frequencies. Therefore, frequency was measured again at 25 feet.

All sound level readings were conducted with a calibrated Bruel & Kjaer Type 2270 sound meter with a Type 4189 Bruel & Kjaer microphone, using the vendor supplied wind shield. Data were analyzed using a Bruel & Kjaer BZ5503 Measurement Partner Suite.

SonoBlaster Alarm Sound Levels

Sound levels were tested in an outdoor environment with the units set up on the ground in the corner of a level 360 foot by 160 foot asphalt test area. Sound levels were tested on a windy day using a sound meter with an attached wind shield. The weather was cloudy and the temperature was approximately 55°F. Observations of sound levels indicated that wind did not affect the sound levels recorded due to the substantial difference in sound levels between the wind and the alarm.

From the SonoBlaster orientation measurements, it was determined that directly towards the sound meter (Figure 24) resulted in the loudest alarm and towards the ground (Figure 25) resulted in the quietest alarm. These orientations were then measured at distances of 10 feet, 20 feet, 30 feet, 40 feet, 50 feet, 100 feet, 200 feet, 300 feet, and 400 feet and 500 feet.

Figure 24. SonoBlaster Oriented Towards Sound Meter

Figure 25. SonoBlaster Oriented Downward

While the sound level tests were being conducted, there were several construction and personal vehicles in the area. Monitoring the sound meter as levels were being read indicated that this did not affect the sound level readings of the alarm at all. Wind was also not a significant factor in any of the sound level readings. Several tests of ambient noise levels were conducted as a comparison.

During the testing several phenomena were observed. First, as the SonoBlaster uses compressed CO_2 to generate an air horn like alarm, the compressed CO_2 cartridges can become quite cold during firing, to the point where ice begins to condense on the cartridges – even though the test was conducted in approximately 55°F temperatures. This did not appear to be an issue. However, as the socket for the cartridges is also metallic and the cold, compressed CO_2 was pushed through it, the nozzle became very cold and condensed water and then created ice. During the testing, which took place over a two-hour window, larger amounts of frost gradually accumulated on the exterior of the nozzle (Figure 26).

Figure 26. Ice Accumulation on SonoBlaster Nozzle

By the end of testing, for the 300 foot to 500 foot test distances, ice began to accumulate inside the nozzle, between the CO_2 cartridge and the firing pin. In several instances this resulted in false negatives, that is, the unit was cocked and properly set up, but did not sound an alarm upon activation. It is believed that the firing pin impacted the ice before the CO_2 cartridge and, therefore, did not have enough force to properly puncture the cartridge.

This is unlikely to be an issue when used in the field as an individual unit will not be fired so many times in such a short period. It could be an issue in already cold or wet weather conditions if water were to get into the nozzle, or if the unit were fired, either as part of a test, accidently, or legitimately, and then the cartridge was replaced. In that situation, it is possible for the ice buildup to occur suddenly and this could result in false negatives. In order to fix the problem, the research team simply cocked the unit twice, and the plastic cocking mechanism was sufficient to puncture the ice, allowing the firing pin to puncture the CO_2 cartridge properly upon alarm activation.

More significant was the alarm time inconsistency. When the CO_2 cartridge was punctured and the alarm sounded, the alarm did not activate for a consistent length of time. For the orientation with the unit pointed towards the sound meter, the SonoBlaster was on the top side of the cone after the cone was pushed over. In this orientation, the alarm sounded for between 40 and 80 seconds. However, in one test, the alarm only sounded for 3 seconds before going silent. In addition, once the cone was reoriented upright, the alarm went off again, as all the CO_2 had not been and was not able to be expelled in that orientation.

When the alarm was tipped such that the SonoBlaster was facing downward, the alarm sounded for much less time – usually between 5 and 15 seconds, though once it sounded for 30 seconds. Also in this orientation, what appeared to be smoke was emitted from the bell of the horn. It is believed that this was CO_2 either itself condensing, or condensing water vapor around it. If this is the case, then the short alarm time could be explained by excessive amounts of CO_2 being emitted by the cartridge somehow due to the orientation of the alarm as it activated. This would result in both the observed condensation and short alarm time.

For both orientations, the peak sound level was within the first second of firing, with a uneven drop-off in sound levels after that, usually down to a level about 25 decibels lower by the end of the alarm. In addition, it was observed qualitatively that there was natural variation in the sound level of the alarm, even at a consistent distance and orientation to the SonoBlaster. A typical alarm sound profile is shown in Figure 27. A sound profile of the alarm firing oriented downward is shown in Figure 28.

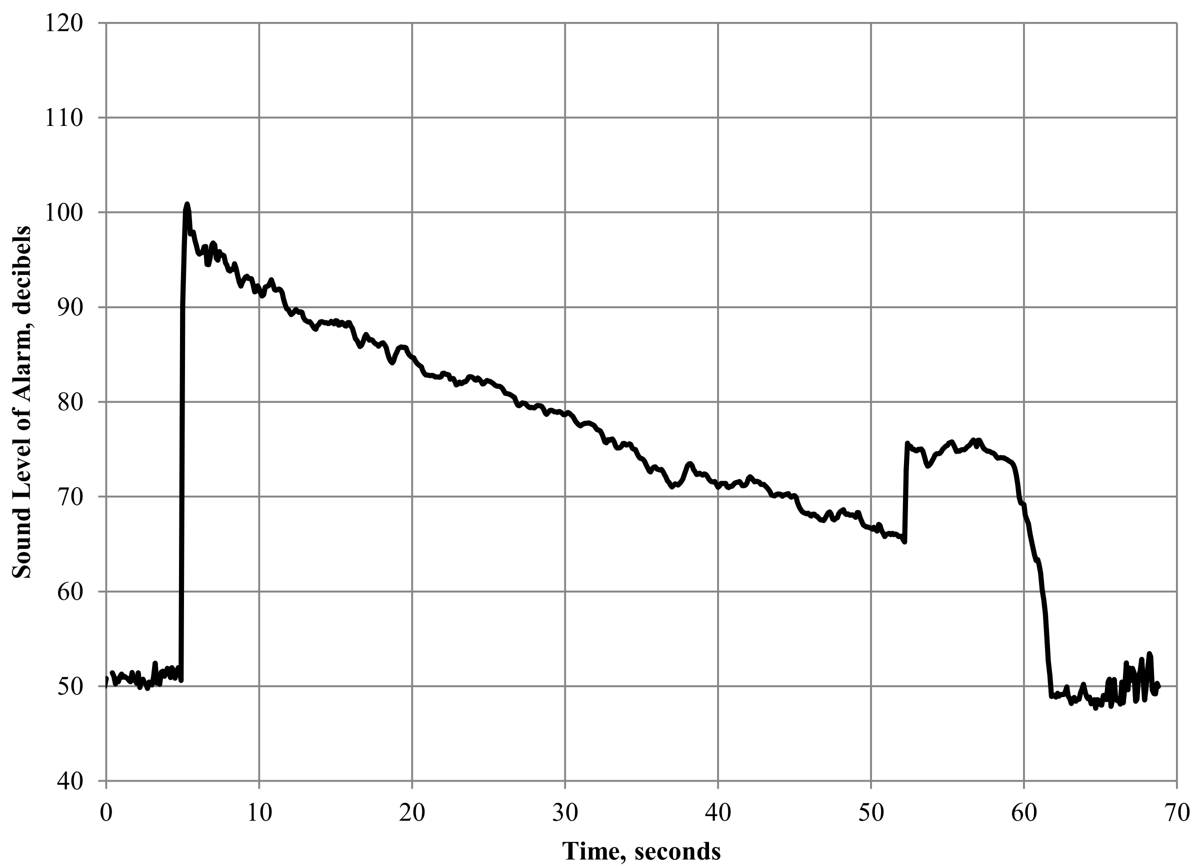


Figure 27. SonoBlaster Alarm Sound Profile (Oriented Toward Sound Meter)

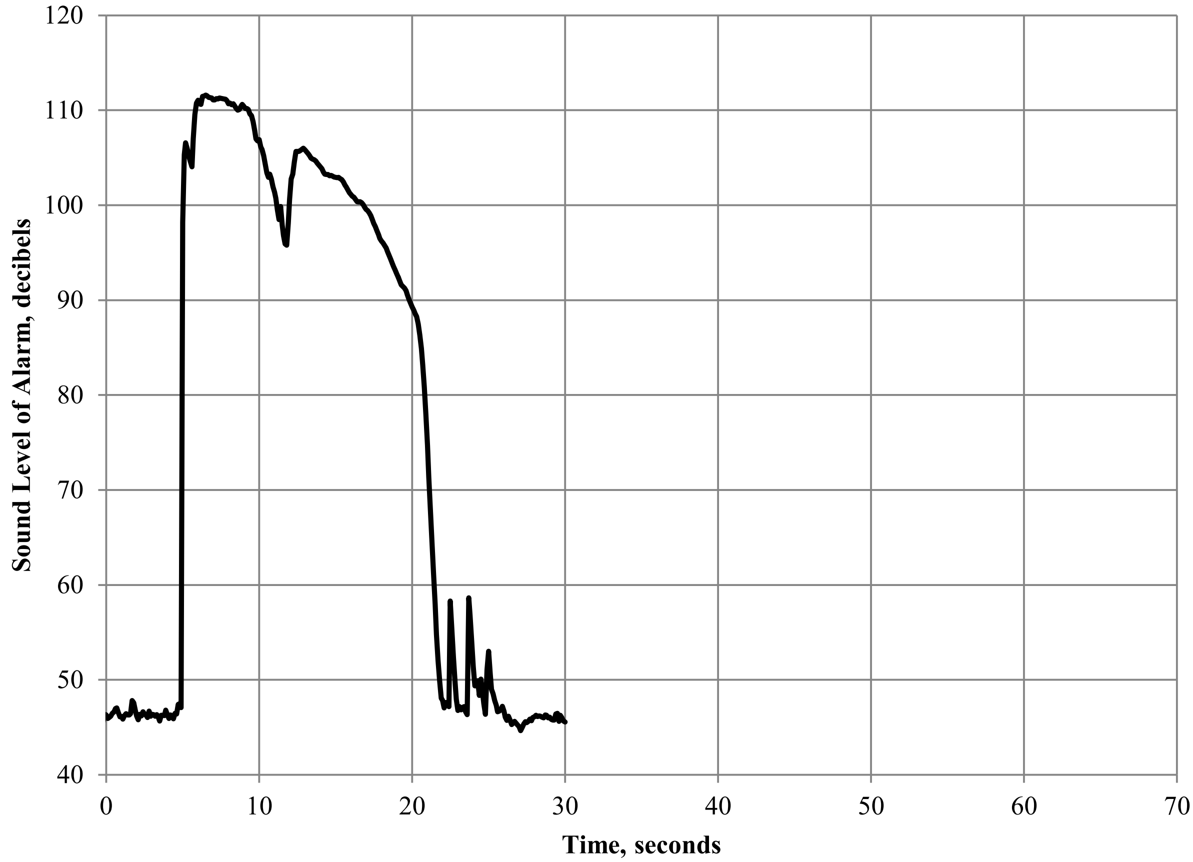


Figure 28. SonoBlaster Alarm Sound Profile (Oriented Downward)

Alarm Sound Levels with Construction Equipment

Sound levels were tested in an outdoor environment with the units set up on the ground in a level 360 foot by 160 foot asphalt test area. Sound levels were tested on a calm day using a sound meter with an attached wind shield. The weather was cloudy and the temperature was approximately 65°F.

During the testing, it was observed that for both the Intellicone system and the SonoBlaster, the alarms were impossible to distinguish from the noise of the backhoe while inside the backhoe at the distances of 100 feet and 200 feet. Furthermore, the SonoBlaster alarm was observed to qualitatively sound similar to noise generated by the idling backhoe, making it difficult to distinguish from the noise of the backhoe after several seconds of the alarm firing, even when it was still louder than the backhoe. However, this did not prevent the ability to distinguish the SonoBlaster alarm from the backhoe noise when the alarm first sounded and was loudest, as the difference in sound levels was noticeable.

Alarm Activation Angle

The SonoBlaster tilt test was performed in an outdoor environment on Thursday, May 1, 2014 at 9:00 a.m. The weather was partly cloudy with moderate winds, and a temperature of approximately 55°F. The cone was sitting on level ground.

The Intellicone tilt test was performed in an outdoor environment on Friday, May 2, 2014 at 10:00 a.m. The weather was sunny, and a temperature of approximately 70°F. The cone was sitting on level ground.

Battery Life

Sensor battery life was measured with three sensors in an indoor environment, beginning at 10:00 a.m. on Friday, April 4, 2014, and checked once every weekday. Two units stopped functioning between the 11th and 12th day checks. The third unit stopped functioning between the 13th and 14th day checks.

Battery life for the portable site alarm unit was measured with the LEDs on in an indoor environment beginning Saturday, June 7, 2014, and checked once every hour. In the first test, the unit lasted 23 hours. In the second and third tests, the unit lasted 21 hours and 24 hours, respectively. The alarm unit was then tested three times with the LEDs off in an indoor environment beginning Monday, June 16, 2014, and checked once every hour. In the first test, the unit lasted 62 hours. In the second and third tests, the unit lasted 48 hours and 56 hours, respectively.

Effective Transmission Distance

Transmission testing for both between the PSA unit and the sensor unit and between the two sensor units was performed in an empty asphalt parking lot (Figure 29) approximately 825 feet long on Wednesday, June 11, 2014 at 10:00 a.m. The weather was sunny, and a temperature of approximately 90°F. The cone was sitting on level ground.

Figure 29. Intellicone Transmission Distance Test Area

For testing between the PSA and a single sensor, the beginning distance used was 50 feet. This distance resulted in 100 percent transmission and the distance was increased in 50 feet increments until 100 percent transmission was not achieved at 400 feet. The distance was increased in 50 feet increments until 0 percent transmission was achieved at two 50 feet increment distances in a row, at 650 feet and 700 feet.

For transmission testing between two sensors, the beginning distance used was 350 feet between the sensors with 350 feet between the second sensor and the PSA unit (Figure 30). Because the distance from first sensor to PSA unit remained at 700 feet, its activation did not activate the PSA unit. And because distance from the second sensor to the PSA unit remains under 350 feet, its activation always activated the PSA unit.

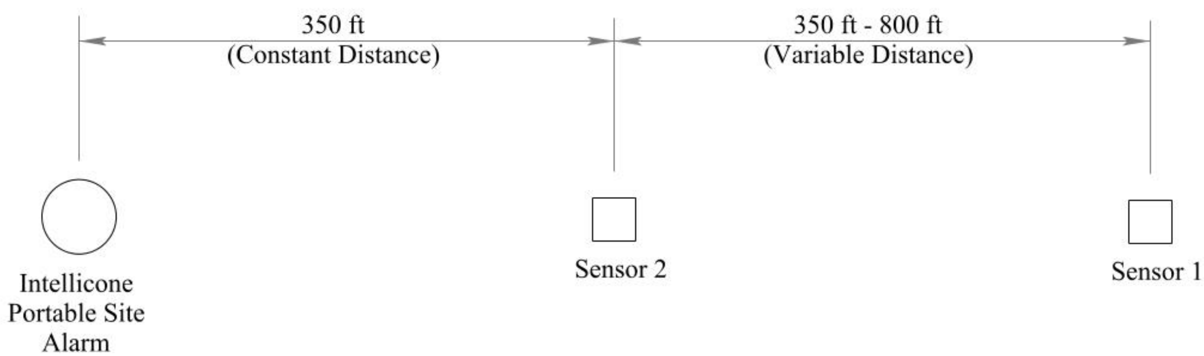


Figure 30. Intellicone Sensor to Sensor Effective Transmission Distance Testing Layout

The distance between the sensors was increased in 50-feet increments, as 100 percent transmission was achieved at the beginning distance. The distance was increased until there was 800 feet between the sensors, as the primary distance of interest was the longest distance with 100 percent transmission, and at longer distances, the level asphalt surface could not be maintained between both sensors and the alarm unit.

When transmission testing was first attempted, there were numerous issues with failed alarm activations occurring when the sensor was tipped over, coupled with numerous activations occurring when the cone and attached sensor were stood up from being tipped over. Intellicone was contacted and advised of the issue. New sensors were modified to reduce the possibility of these false positives; both the orientation of the antenna and the activation algorithm were altered. These new sensors were used for all transmission testing. There were no instances of failed alarm activations. There was one activation which occurred when the sensor was righted again, which was greatly limited compared to the previous units.

Field Testing

Phase 1 Testing

Phase 1 testing for the Intellicone false alarm rate was begun on Thursday, July 17, 2014 at 1:00 p.m. until 5:00 p.m. and continued on Friday, July 18, 2014 at 8:00 a.m. until 2:00 p.m. Testing time totaled 10 hours. The Intellicone PSA unit and four channelizer-mounted sensors were deployed, along with a SONY HDR-CX220 Handycam video camera. The four sensors were deployed at the intersection nearest the upstream taper of the work zone but still within the work zone (Figure 31).

Figure 31. Phase 1 Test Area Equipment Setup

The sensors were deployed along the downstream edge of the intersection on channelizers (Figure 32). The video camera was deployed on a tripod approximately one foot above the ground on the upstream edge of the intersection behind the arrow board, with the PSA unit set up several feet downstream of the camera. The video camera had a view of the PSA unit, all four sensors and both streams of traffic.

Figure 32. Phase 1 Intellicone Sensor Deployment

There were no false alarms, actual alarms, or false negatives during the testing period. While the proper activation of the alarm was not tested, the system otherwise performed as expected.

Test Site 1

Phase 2 testing at location 1 was begun on Wednesday, July 23, 2014 at 7:00 a.m. until 1:00 p.m., continued on Thursday, July 24, 2014 from 8:00 a.m. to 11:00 a.m., and finished on Friday, July 25, 2014 from 8:00 a.m. to 11:00 a.m. Testing time totaled 12 hours. Testing took place over the course of three days because the work crew finished on the second day, Thursday, at 11:00 a.m., waiting for concrete to cure. Therefore, only three hours of video and observation were completed, necessitating finishing the final three hours on a third day, Friday.

The Intellicone PSA unit and four channelizer-mounted sensors, the channelizer-mounted SonoBlaster alarm, and a SONY HDR-CX220 Handycam video camera were deployed (Figure

33). Three of the four Intellicone sensors and the SonoBlaster alarm were deployed at the north, downstream end of the work zone. This was determined to be the most useful location for deployment as a flagger was controlling traffic at the intersection of Mississippi Street and Fambrough Drive, very near the south, upstream end of the work zone.

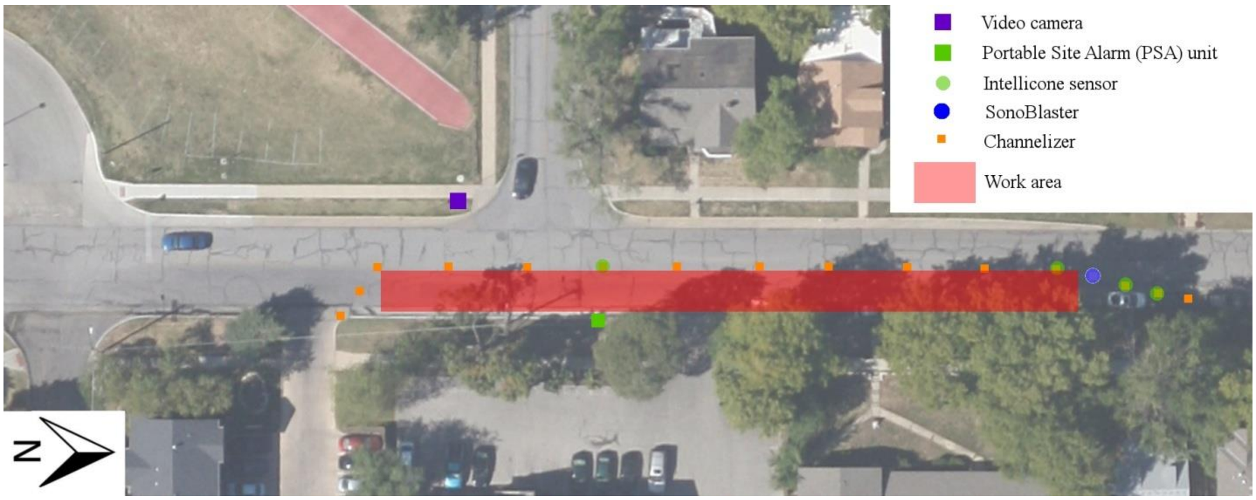


Figure 33. Location 1 Test Area Equipment Setup

The sensors were deployed on the channelizers in the taper section, with the SonoBlaster alarm also deployed in the taper (Figure 34). The final fourth and final Intellicone sensor was deployed on a channelizer nearest the active work in the work zone, which was directly in line with the intersection of Mississippi Street and Fambrough Drive (Figure 35). The PSA unit was set up approximately three feet from the curb off the road, near to the center of the work activity. The video camera was deployed on a tripod approximately one foot above the ground on the upstream side of the work zone, on the southwest corner of the Mississippi Street and Fambrough Drive intersection. The video camera had a view of the PSA unit, all four sensors and the traffic.

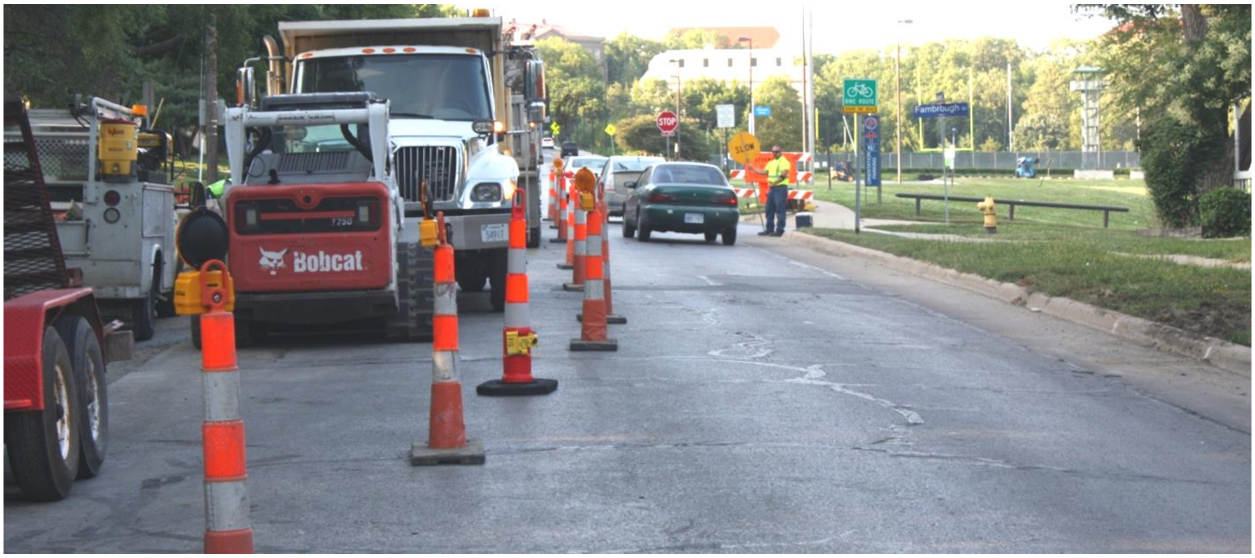


Figure 34. Location 1 Taper with Equipment

During testing, both the Intellicone alarm and the SonoBlaster were activated. On the first day of testing the Intellicone alarm was set off at approximately 10:30 a.m. when a channelizer and attached sensor were backed over by a truck exiting the work zone. The Intellicone alarm was set off a second time at 11:10 a.m. when the site foreman intentionally tipped a channelizer and attached sensor to demonstrate the system to utility workers who were present. The SonoBlaster alarm was intentionally activated at 1:30 p.m.

Figure 35. Location 1 Intersection and Work Area with Equipment

On the second day, the Intellicone alarm was activated at approximately 10:00 a.m. as a channelizer and the attached sensor were dragged out of the way of a front loader entering the work zone. No activations occurred on the third day of testing.

Test Site 2

Following testing, an oral group interview was conducted with seven of the workers present during the three days at the location.

Testing at location 2 was begun on Monday, July 28, 2014 at 8:00 a.m. until 2:00 p.m., and finished on Tuesday, July 29, 2014 from 8:00 a.m. to 2:00 p.m. Testing time totaled 12 hours. The Intellicone PSA unit and four channelizer-mounted sensors, the channelizer-mounted SonoBlaster alarm, and a SONY HDR-CX220 Handycam video camera were deployed (Figure 36). Three of the four Intellicone sensors and the SonoBlaster alarm were deployed at the south, downstream end of the work zone. This location was the primary hazard area for intrusion incidents, especially with the only opening in the downstream side of the concrete barriers being approximately 150 feet farther south.

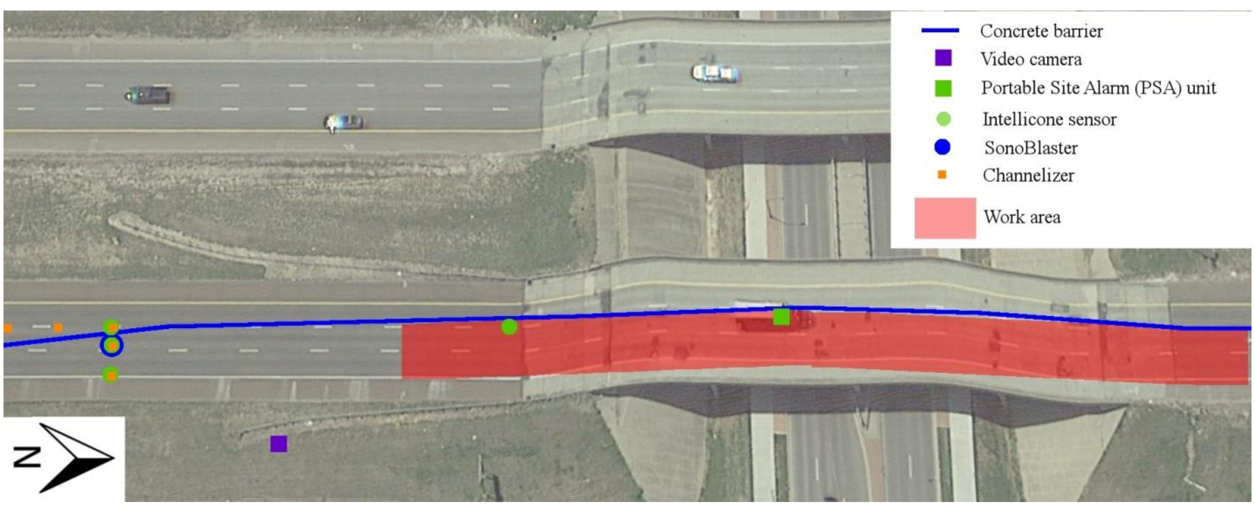


Figure 36. Location 2 Test Area Equipment Setup

The sensors were deployed on channelizers at the end of the concrete barrier taper section. One sensor was deployed on the traffic side of the concrete barrier, about two feet from traffic. The other two sensors were deployed on the work zone side of the concrete barrier, about 11 feet apart, parallel with the first sensors, forming a line across the roadway (Figure 37). The SonoBlaster alarm was deployed on the work zone side channelizer nearest traffic which also had the Intellicone sensors on it. The final fourth and final Intellicone sensor was deployed as a relay on the ground next to the concrete barrier, approximately halfway between the sensor line and the PSA unit, as the distance between the sensor line and the PSA unit was approximately 400 feet, which is greater than the distance of 100 percent transmission for the Intellicone system. The PSA unit was set up next to the concrete barrier, near to the center of the work activity (Figure 38). The video camera was deployed on a tripod approximately five feet above the ground on the downstream side of the work zone behind the metal railing. The video camera had a view of the sensor line and the SonoBlaster alarm, as well as the traffic, but not the PSA unit or the relay sensor.

Figure 37. Location 2 Sensor Line

Figure 38. Location 2 Intellicone Portable Site Alarm Deployment near Work Activity

During testing, the Intellicone alarm was successfully intentionally activated several times. On the first day of testing, the Intellicone alarm was intentionally activated at 1:15 p.m. At the time, the workers were approximately 150 feet away, using jackhammers and wearing in-ear hearing protection. On the second day of testing, the Intellicone alarm was activated four times. At 10:10 a.m., the alarm was activated while the workers were using jackhammers and wearing in-ear hearing protection, approximately 100 feet away. At 11:10 a.m., the alarm was activated while the workers were approximately 200 feet away using jackhammers and wearing in-ear hearing protection. One worker was approximately 150 feet away and using a chipping hammer, also while wearing in-ear hearing protection. At 12:45 p.m., the alarm was activated while three workers were using jackhammers 150 feet away, one was using a concrete saw 100 feet away, and one was using a chipping hammer 50 feet away. All the workers were wearing hearing protection. At 1:30 p.m., the alarm was activated while one worker was using a concrete saw approximately 100 feet away. Four workers were standing approximately 200 feet away, loading equipment onto a pickup truck. Traffic was heavy at the time and moving at free-flow speeds.

The SonoBlaster alarm was not activated on either the first or second day of testing. During testing, subcontractor workers were performing repairs on the bridge abutment, which lay in between the location of the SonoBlaster and the general contractor workers, with whom the research was being conducted. The abutment repairs were covered by a tarp and therefore, the nature of the work and the tools being used were unknown. From the noise generated by the repairs, it appeared to be saws as well as other power tools. Given the extremely loud nature of the SonoBlaster alarm at short range, it was possible that activation of the alarm may have presented a safety risk to the subcontractor workers who were not informed of the nature of the research or aware of what the alarm represented. Therefore, the SonoBlaster was not intentionally activated at the second location.

Following testing, an oral group interview was conducted with five of the workers present during the two days at the location.

Test Site 3

Testing at location 3 was begun on Wednesday, August 13, 2014 at 8:00 a.m. until 2:00 p.m., and finished on Thursday, August 21, 2014 from 7:00 a.m. to 5:00 p.m. Testing time totaled 16 hours. The Intellicone PSA unit and four channelizer-mounted sensors, the channelizer-mounted SonoBlaster alarm, and a SONY HDR-CX220 Handycam video camera were deployed (Figure 39). The four Intellicone sensors and the SonoBlaster alarm were deployed at the south, downstream end of the work zone. This location is the primary danger area for intrusion incidents, as the road reconstruction was being completed on the northbound lanes.

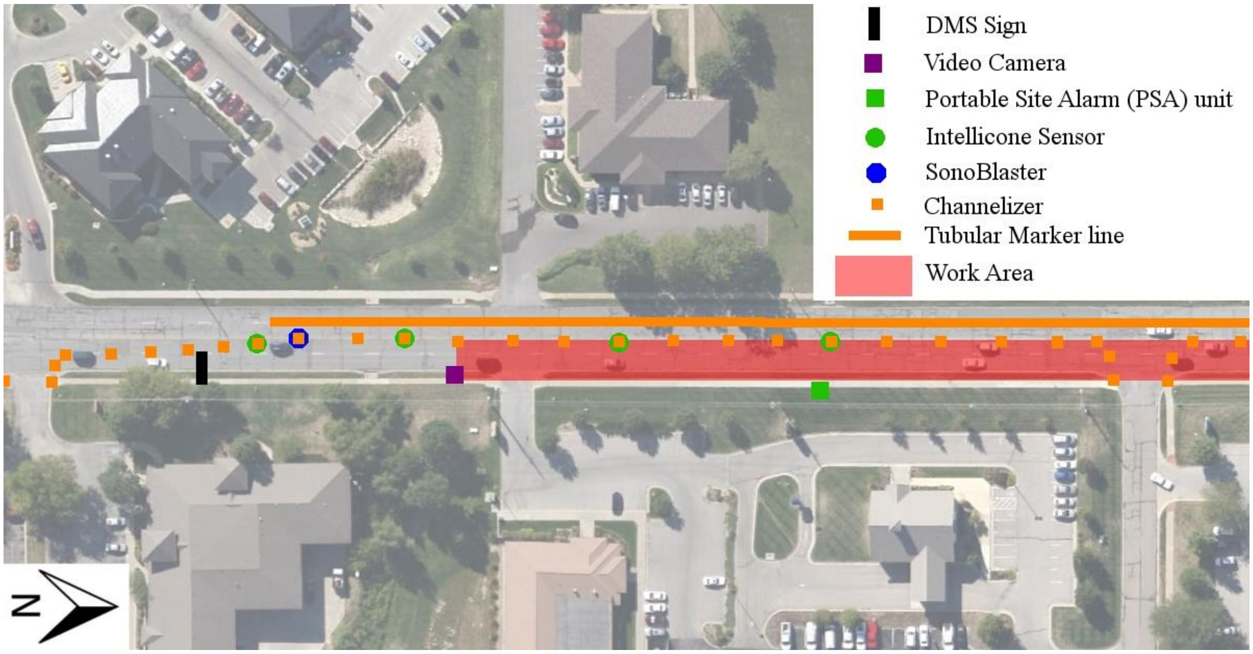


Figure 39. Location 3 Test Area Equipment Setup

The sensors were deployed on channelizers. One sensor was deployed on a channelizer in the taper section. The other three sensors were deployed on channelizers along the work zone (Figure 40), approximately 200 feet apart, which is within the 100 percent transmission distance for the sensors. The SonoBlaster alarm was deployed with the Intellicone alarm in the taper section. The PSA unit was set up on the ground just outside the work limits, near to the center of the work activity (Figure 41). The video camera was deployed on a tripod approximately three feet above the ground on the downstream side of the work zone behind Type 3 barricade. The video camera had a view of three of the four Intellicone sensors, as well as the traffic, but not the PSA unit or the taper section. There was no location where all of the equipment could be recorded simultaneously.

Figure 40. Location 3 Sensor Line

Figure 41. Location 3 Intellicone Portable Site Alarm Deployment near Work Activity

During the first day of testing, only two workers were present in the work zone and not in the area being studied; therefore neither of the alarms were intentionally activated. However, the systems were still active and the Intellicone system experienced a false negative during the testing period. At approximately 10:00 a.m., one of the cones with attached sensor deployed along the length of the work zone was knocked over as a result of a car hitting the base of the channelizer, tipping the channelizer over (Figure 42). However, the Intellicone alarm did not activate.

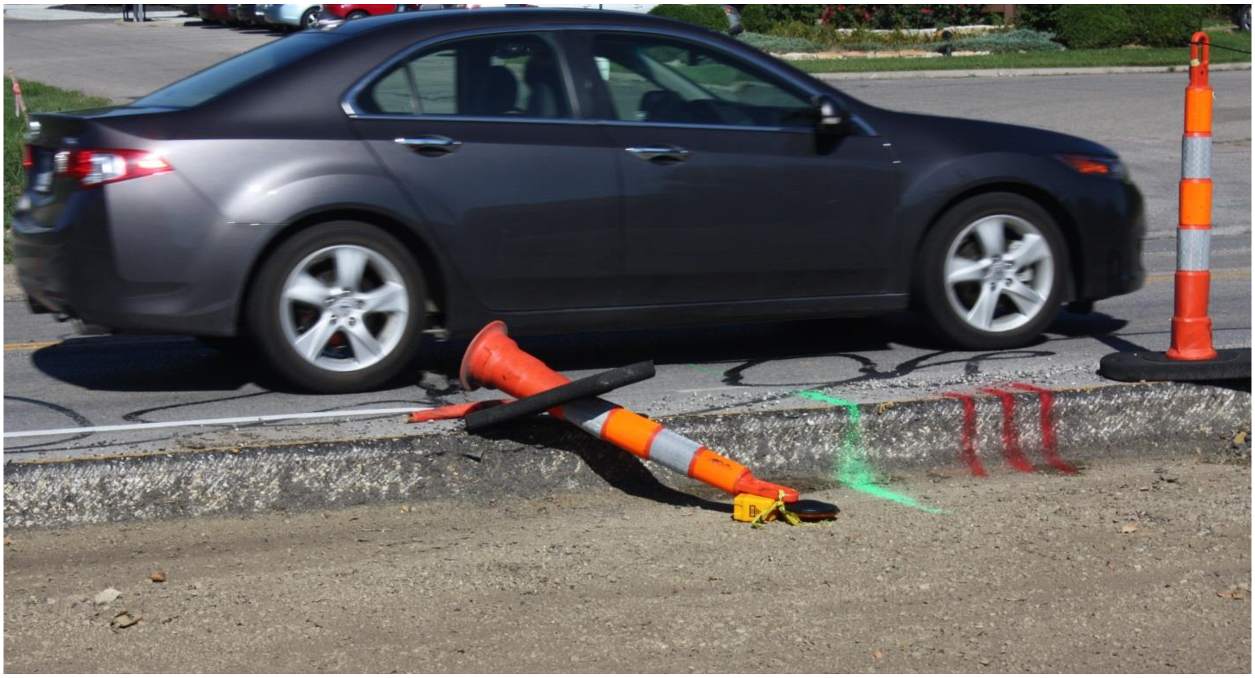


Figure 42. Location 3 Intellicone Sensor on Ground

During the second day of testing, the Intellicone alarm was intentionally activated at 10:30 a.m. while the workers were between approximately 200 feet and 350 feet away, not working with any machinery. At 1:45 p.m. the SonoBlaster alarm was intentionally activated while the workers were between approximately 300 feet and 500 feet away. No vehicles were operating in the work zone at the time. At 2:40 p.m., the Intellicone was activated when a skid loader backed over a channelizer and attached sensor in the taper area. Workers were approximately 350 feet away from the Intellicone PSA unit in both directions of the work zone.

Following testing, an oral group interview was conducted with three of the workers present during the second day at the location.

Test Site 4

Testing at location 4 took place on Tuesday, October 7, 2014, beginning at 10:00 a.m. and ending at 2:00 p.m. on the same day. Testing time totaled 4 hours. The Intellicone PSA unit and two cone-mounted sensors, the channelizer-mounted SonoBlaster alarm, and a SONY HDR-CX220 Handycam video camera were deployed (Figure 43). The cone-mounted Intellicone sensors were different model sensors than used at the previous three locations. The sensors used slid on to the top of 36" cones. They functioned identically to the channelizer-mounted sensors, except that they came off the cone if the cone was struck instead of remaining on the channelizer if the channelizer was struck. The two Intellicone sensors and the SonoBlaster alarm were deployed at the west, upstream end of the work zone. The previous day, the work crew experienced an intrusion incident in a different work zone with similar geometric characteristics, and based on that, the location for the sensors was selected.

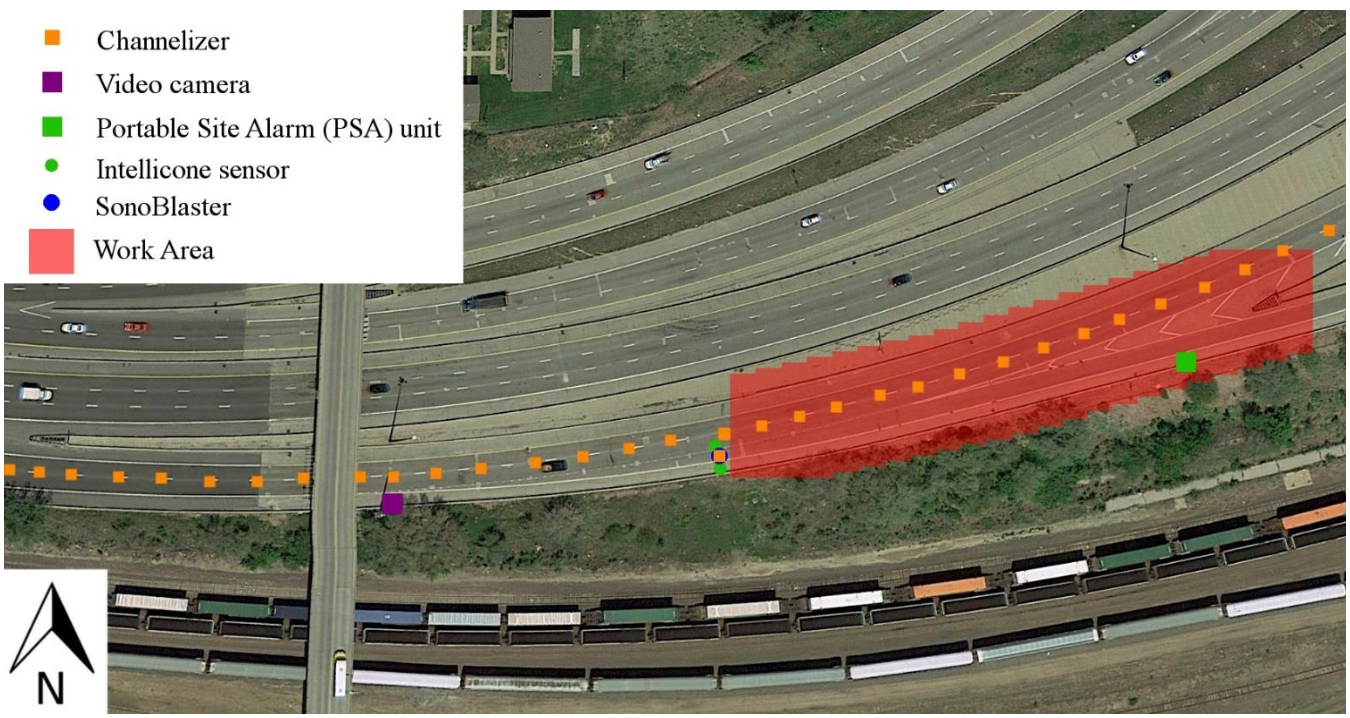


Figure 43. Location 4 Test Area Equipment Setup

The sensors were deployed on cones approximately 250 feet upstream from the gore area. The sensors were placed in a line approximately six feet apart across the closed right-hand through lane, with the SonoBlaster alarm set up in between the two Intellicone sensors (Figure 44). The PSA unit was set up on the ground about 12 feet away from the work activity (Figure 45). The video camera was deployed on a tripod approximately three feet above the ground on the downstream side of the work zone behind a concrete barricade. The video camera had a view of the sensor line, the SonoBlaster alarm, and the traffic, but not the PSA unit. There was no location where all of the equipment could be recorded simultaneously by a single video camera.

Figure 44. Location 4 Sensor Line

Figure 45. Location 4 Intellicone Portable Site Alarm Deployment near Work Activity

During testing, the Intellicone alarm experienced a single false positive. At approximately 10:15 a.m., a fast moving truck passed close to one of the traffic cones, causing it to move, resulting in activation of the alarm. While this does not represent an actual intrusion, the sensor did correctly activate upon movement.

In addition to the false positive, the Intellicone alarm was intentionally activated at 11:30 a.m. At the time, workers were approximately 15 feet away, using drilling machinery. The SonoBlaster alarm was also intentionally activated at 12:45 p.m. (Figure 46). Workers were approximately 250 feet away from the alarm and not using any powered machinery.

Following testing, an oral group interview was conducted with four of the workers as well as the site supervisor.

Figure 46. Location 4 Intentional Activation of SonoBlaster Alarm

Summary

This chapter presented information on the closed-course and filed testing conducted. The following highlights include:

- The SonoBlaster alarm was, on average, louder than the Intellicone alarm, while the Intellicone alarm was, on average, more consistent in volume and duration than the SonoBlaster alarm.
- Alterations to the Intellicone sensors successfully addressed problems with alarm activations when a sensor was righted after being tipped over.
- Field testing was conducted under a variety of field conditions spanning the breadth of potential field deployments for safety perimeter systems.
- The SonoBlaster had no false negatives or false positives during field testing.
- The Intellicone had one false negative and one false positive during field testing.

The next chapter will analyze the data obtained during closed-course testing as well as discuss the results of the oral interviews conducted during field testing.

Chapter 5 Data Analysis

The study design was presented in Chapter 3, with a discussion of the data collection presented in Chapter 4. In this chapter, the data analysis and the results of the analysis are presented and discussed.

Closed-Course Testing

Alarm Sound Levels

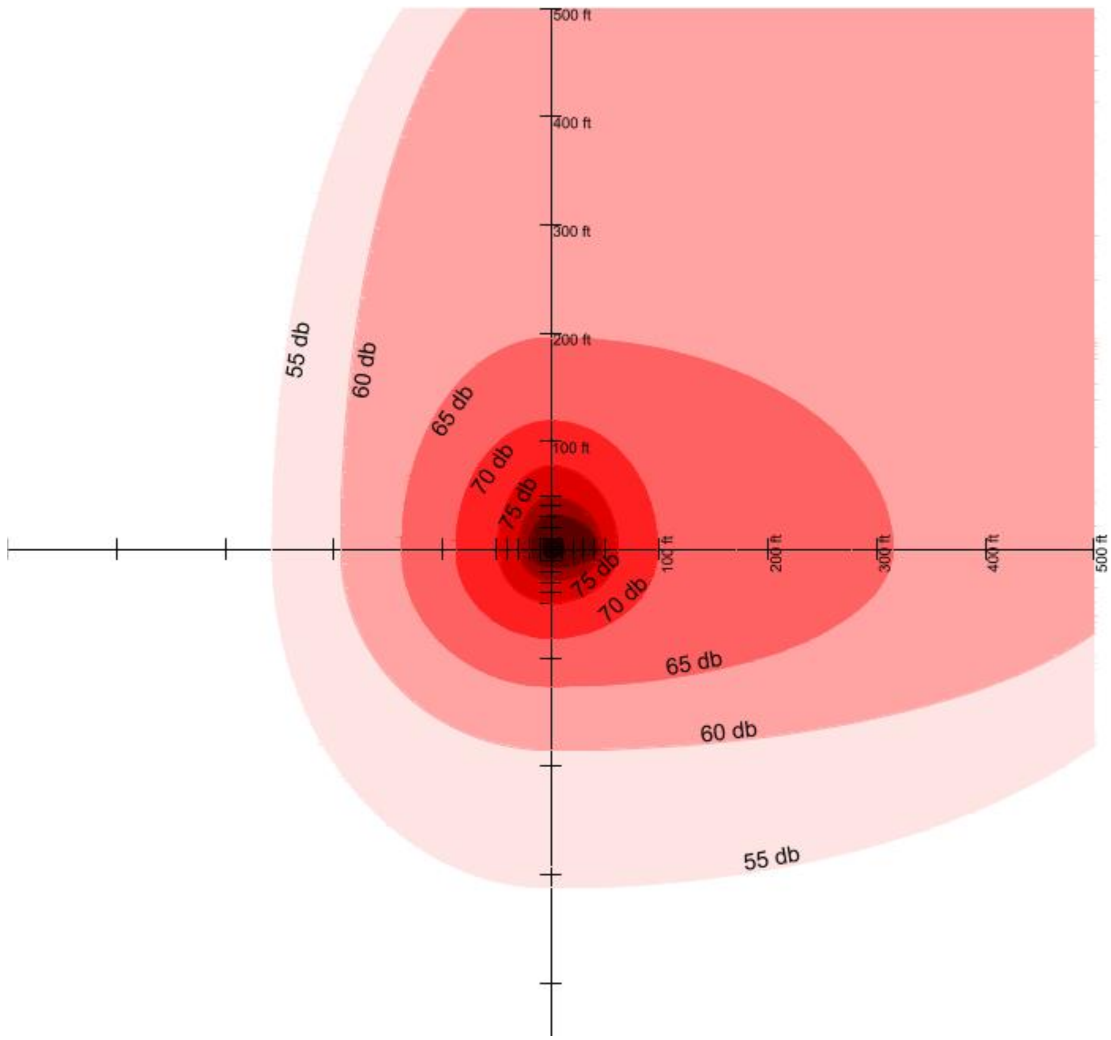


Figure 47. Intellicone Alarm Sound Levels

Sound level testing of the Intellicone Portable Site Alarm unit showed a maximum alarm sound level of around 90 dB at a distance of 10 feet. This decreases with distance down to

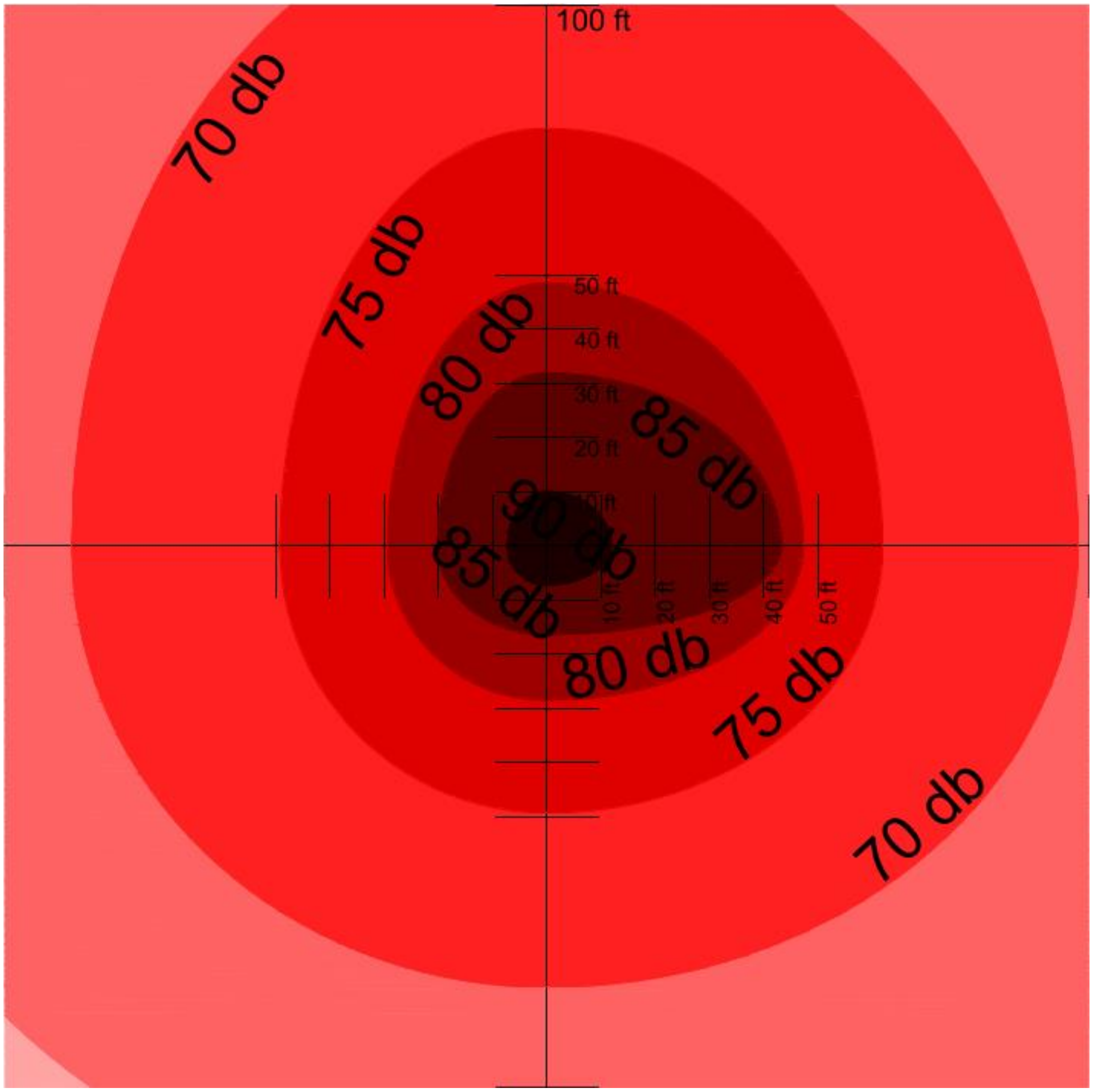


Figure 48. Intellicone Alarm Sound Levels under 100 Feet

approximately 55-60 dB at a distance of 400 feet, as shown in Figure 47 and Figure 48. The alarm was found to have limited directionality, with directions 1 and 2, in line with a speaker and 30° to the right of a speaker, having the highest sound levels. However, this directionality is primarily evident at distances greater than 200 feet from the alarm; at distances less than 200 feet, the alarm, while not perfectly omni-directional, is relatively omni-directional, with the range between highest and lowest sound levels for any given distance being about 5.5 dB, on average. At 300 feet and 400 feet, the range is 14.0 and 10.6 dB, respectively.

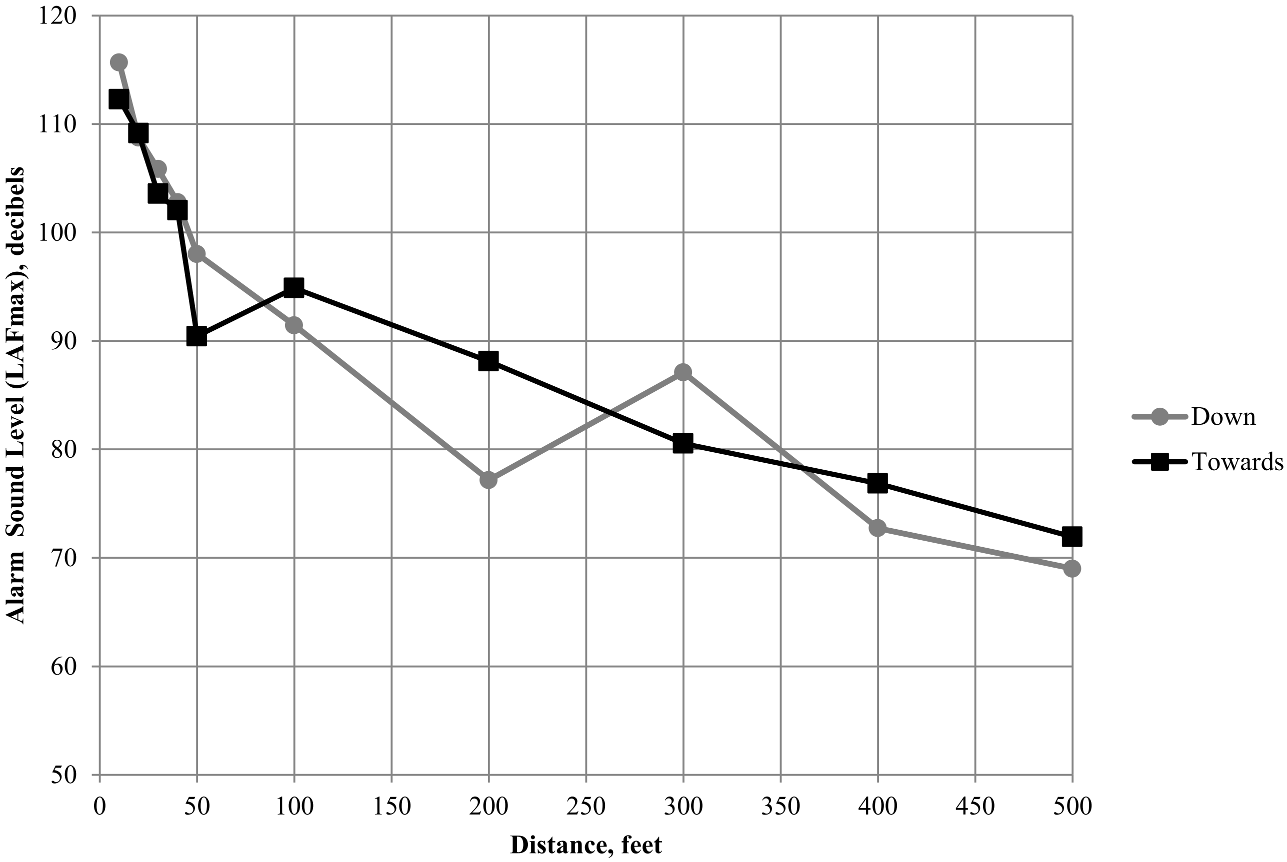


Figure 49. SonoBlaster Alarm Sound Levels

Sound level testing of the SonoBlaster Alarm showed a maximum alarm sound level of around 115 dB at a distance of 10 feet. This decreased with distance down to approximately 70 dB at a distance of 500 feet, as shown in Figure 49. The alarm was found to have limited directionality, with the alarm generally loudest when pointed directly towards the sound meter. As indicated in Figure 20, however, there were instances when the SonoBlaster was pointed directly down and it was louder than while point towards the sound meter. This is believed to be a result of the inconsistencies in the sound emitted by the SonoBlaster; the CO_2 cartridges do not create a consistent sound level for the alarm. Because the cartridges are single use only, multiple tests using the same cartridge were not possible, resulting in this slightly inconsistent data.

However, while the maximum sound level only shows limited directionality, the direction of fall had a strong influence on the amount of time the alarm sounded and the rate of noise dissipation of the alarm. As previously discussed, when pointing downward, the alarm sounds for a limited amount of time, usually 15 seconds or less, while when pointing towards the sound meter, with the SonoBlaster on its side, the alarm sounds for upwards of 60 seconds. A comparison of the two profiles is shown below (Figure 50).

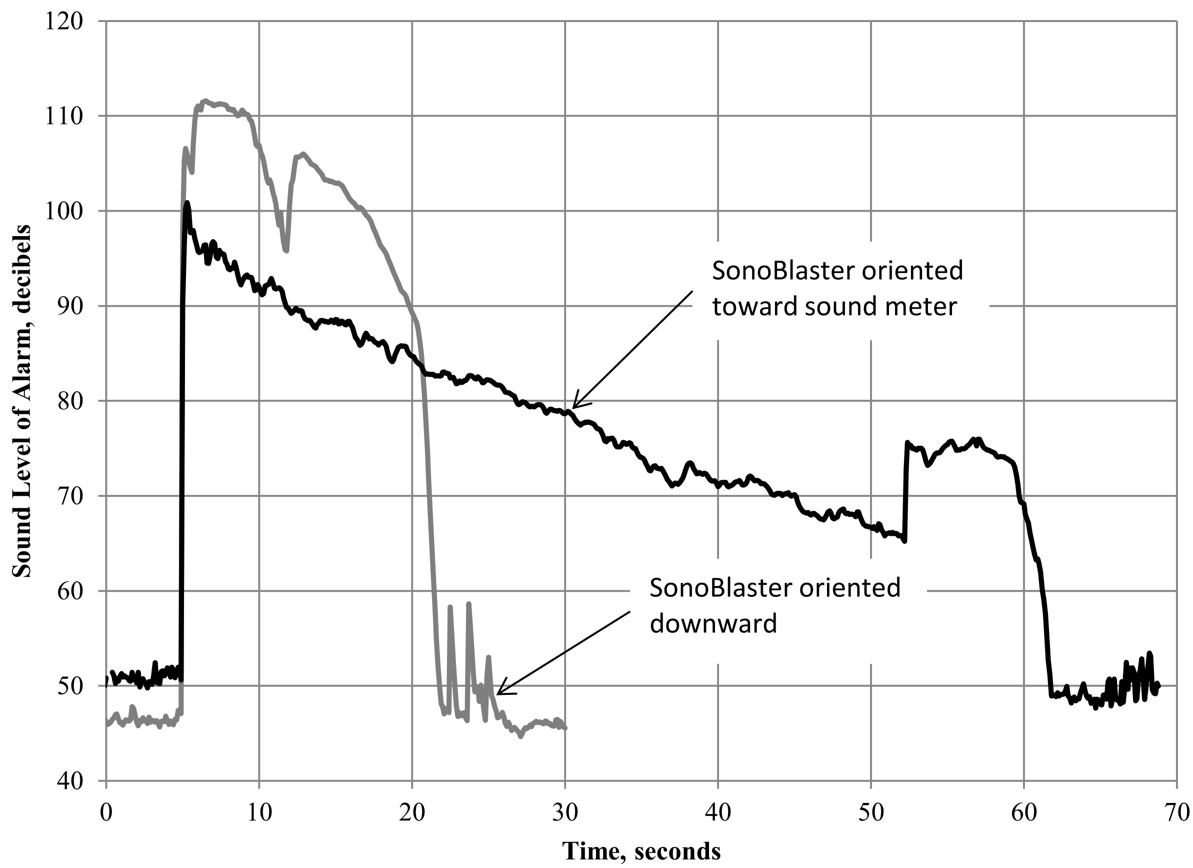


Figure 50. Comparative SonoBlaster Alarm Sound Profiles

In addition to measuring sound levels for the SonoBlaster and Intellicone alarm, the frequency ranges of both alarms were measured. As shown below in Figure 51 and Figure 52, the SonoBlaster's alarm has sound frequencies more spread out across the spectrum up to about 10 kHz. The Intellicone alarm has frequencies clustering primarily around 500 Hz, 1 kHz, 2.5 kHz, and 5.5 kHz.

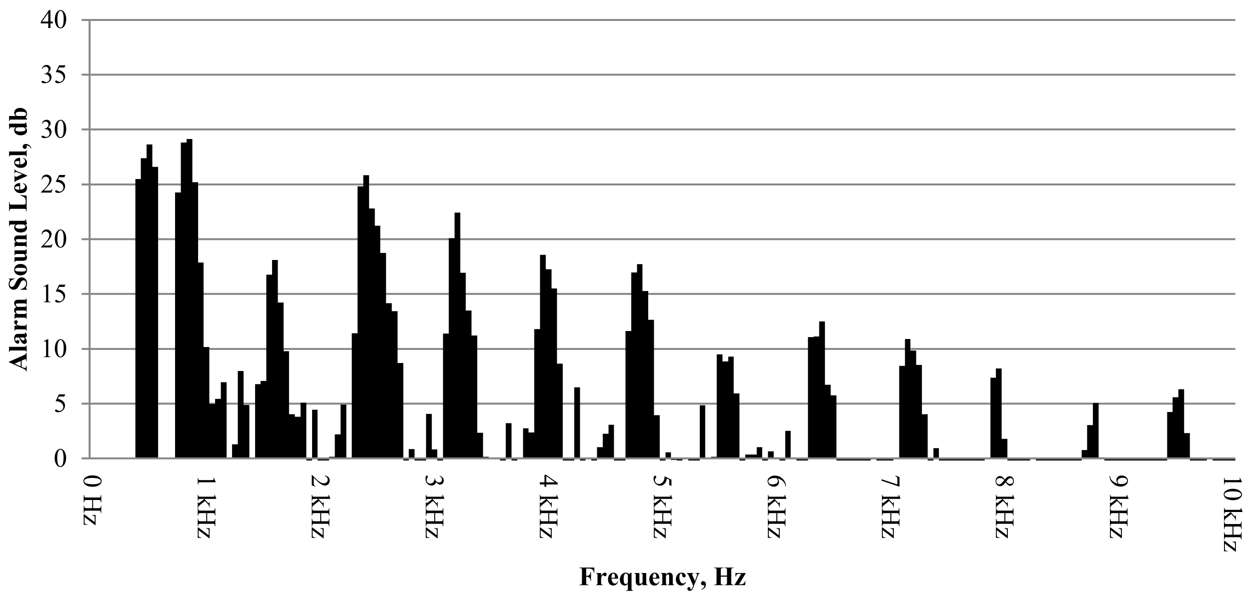


Figure 51. Frequency Distribution of SonoBlaster Alarm

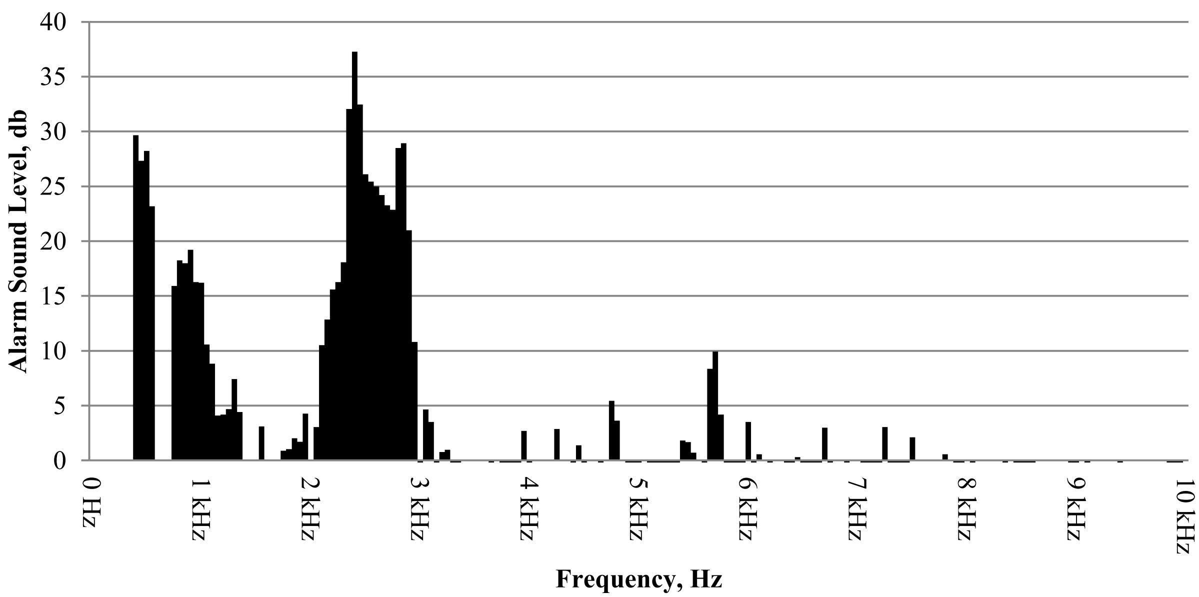


Figure 52. Frequency Distribution of Intellicone Alarm

Alarm Sound Levels with Construction Equipment

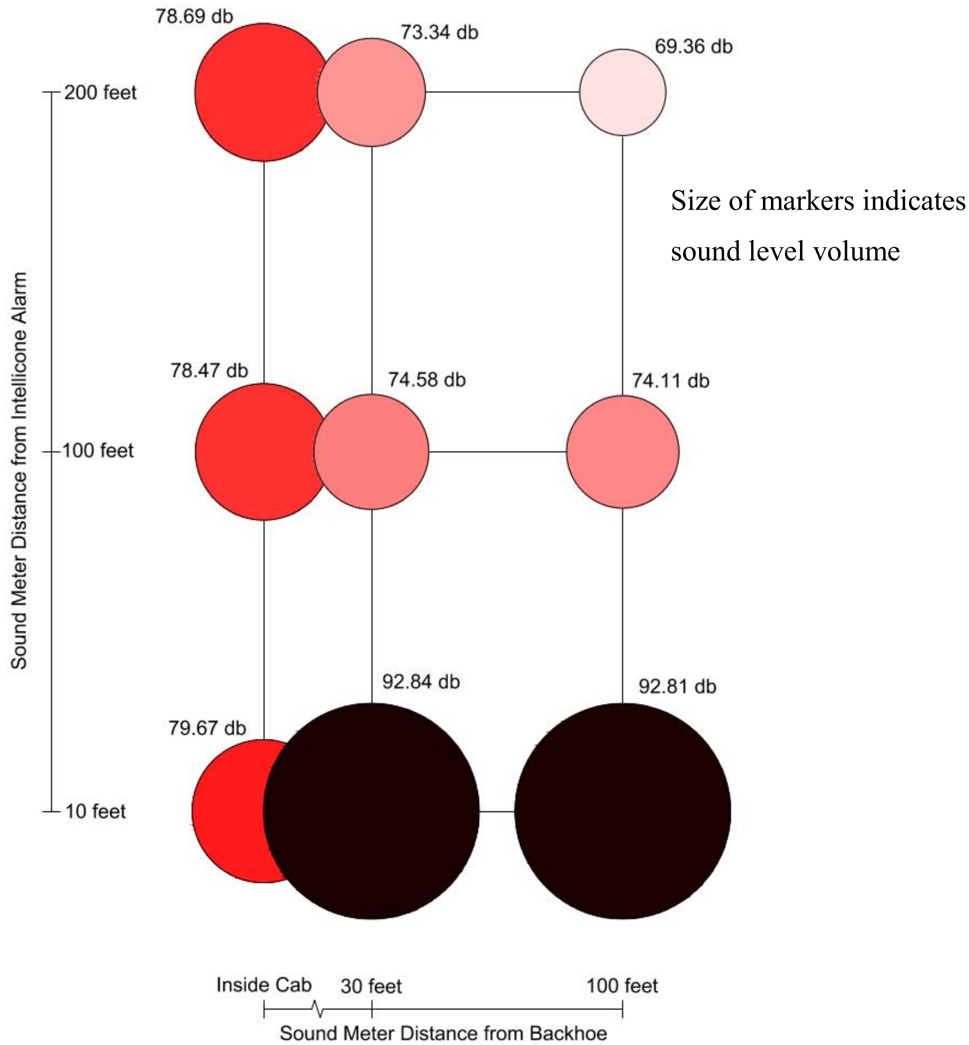


Figure 53. Intellicone Alarm Sound Levels in Presence of Construction Equipment

Sound levels for both alarms were also tested in the presence of construction equipment (an idling backhoe). For the Intellicone (Figure 53), while the sound meter was inside the cab of the backhoe, there was no perceptible difference in the maximum sound level between the idling backhoe and the alarm, thus at all three alarm distances, the maximum sound levels were nearly identical, reflecting the sound level of the idling backhoe and not the alarm. However, as previously discussed, the unique tone of the Intellicone alarm could be heard while inside the cab at distances of 10 feet and 100 feet, even though the sound level was not louder. Outside the cab of the backhoe, distances from the backhoe (30 feet versus 100 feet) did not make a substantial difference in the sound level of the alarm, and the alarm was louder than the idling backhoe at all distances.

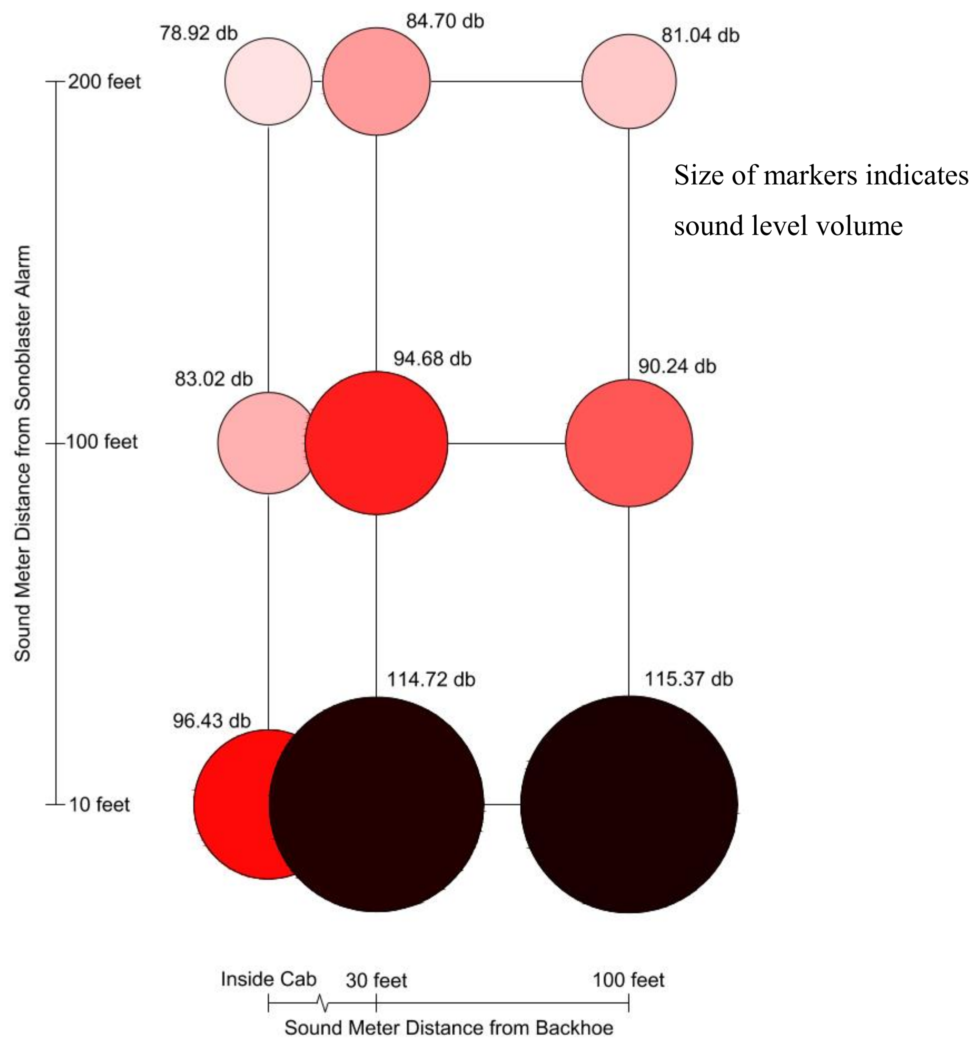


Figure 54. SonoBlaster Alarm Sound Levels in Presence of Construction Equipment

For the SonoBlaster (Figure 54), the sound level of the alarm was substantially louder than the Intellicone and could be heard even when measured inside the cab of the backhoe. When the alarm was placed at 100 feet and 200 feet away from the backhoe though, the alarm was only slightly louder than the sound from the idling backhoe. Furthermore the tone of the SonoBlaster alarm was similar enough to the sound of the idling backhoe that distinguishing the alarm from the backhoe when the alarm was at 100 feet and 200 feet was difficult. Outside the cab, distance from the backhoe (30 feet versus 100 feet) did not make a substantial difference in the sound level of the alarm, and the alarm was louder than the idling backhoe at all distances. Differences in sound levels between being 30 feet from the backhoe versus 100 feet, with the alarm at 100 feet and 200 feet from the sound meter are likely due to inconsistent alarm noise from the CO_2 cartridges.

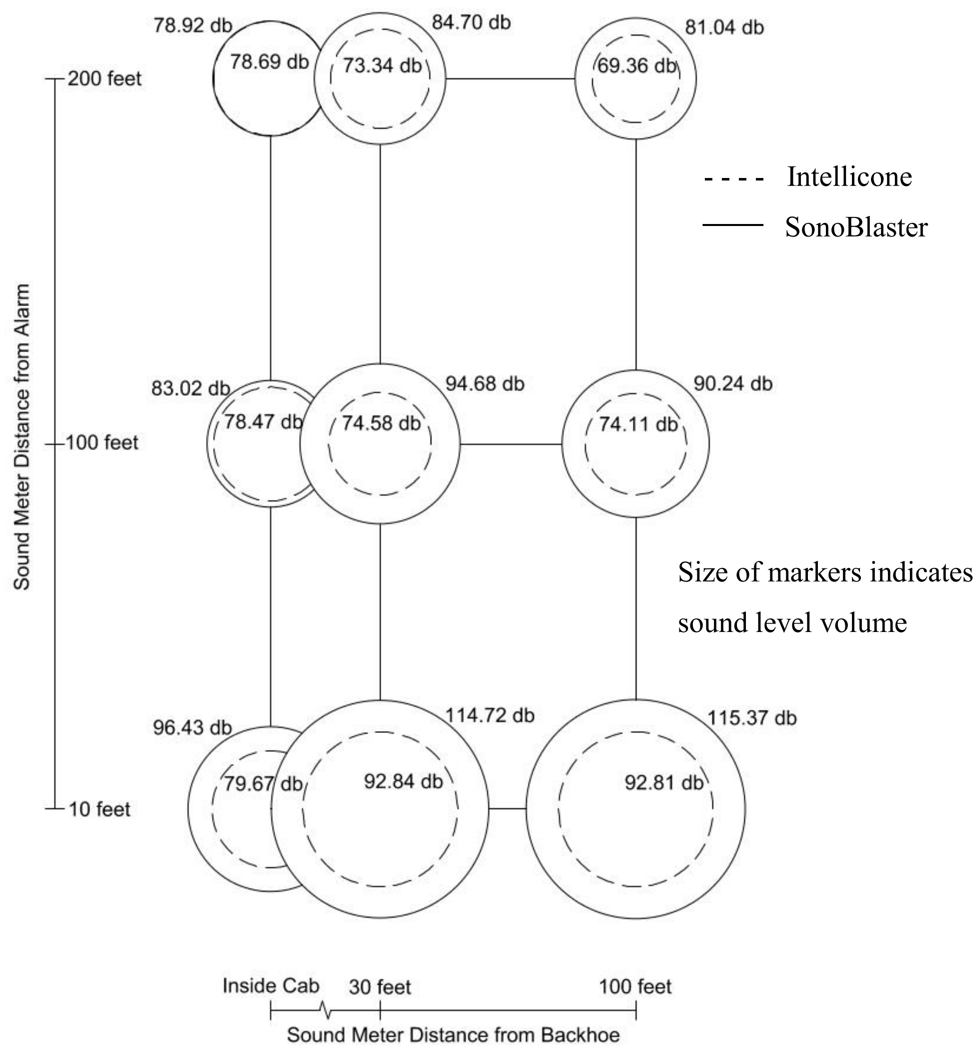


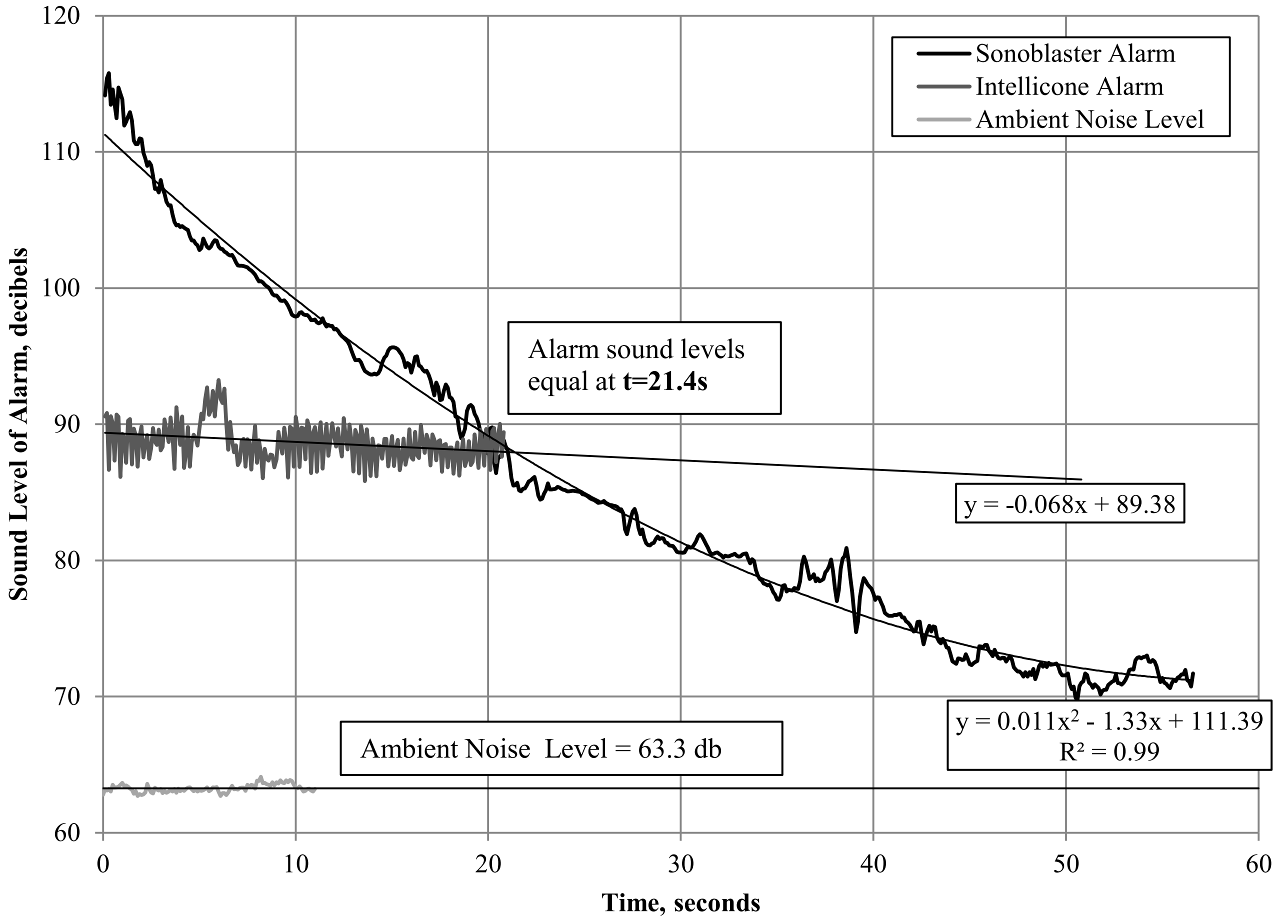
Figure 55. Comparative Alarm Sound Levels in Presence of Construction Equipment

A comparative look at the sound levels of both alarms in the presence of the backhoe (Figure 55) demonstrates the consistency with which the SonoBlaster alarm was louder than the Intellicone alarm, even with construction equipment. Both units though have much lower sound levels within the cab of the backhoe, and unless the alarm is right next to the backhoe when activated, the sound level was nearly identical to the ambient noise from an idling backhoe. Outside the cab, both alarms were louder than the idling backhoe and sound levels were not hampered by the presence of the backhoe.

Practically, this suggests that the difference in volume between both the SonoBlaster and the Intellicone alarms and construction vehicle noise is large enough that the alarms will be audible over the sounds of construction vehicles. This does not necessary extend to construction vehicle noises when they are performing construction activities, such as actively using a hoe or front loading scoop. It also indicates that unless the construction vehicles are close to the intrusion alarms when activated, it is unlikely the operators will be able to hear the alarm.

Alarm Sound Level Profile Comparisons

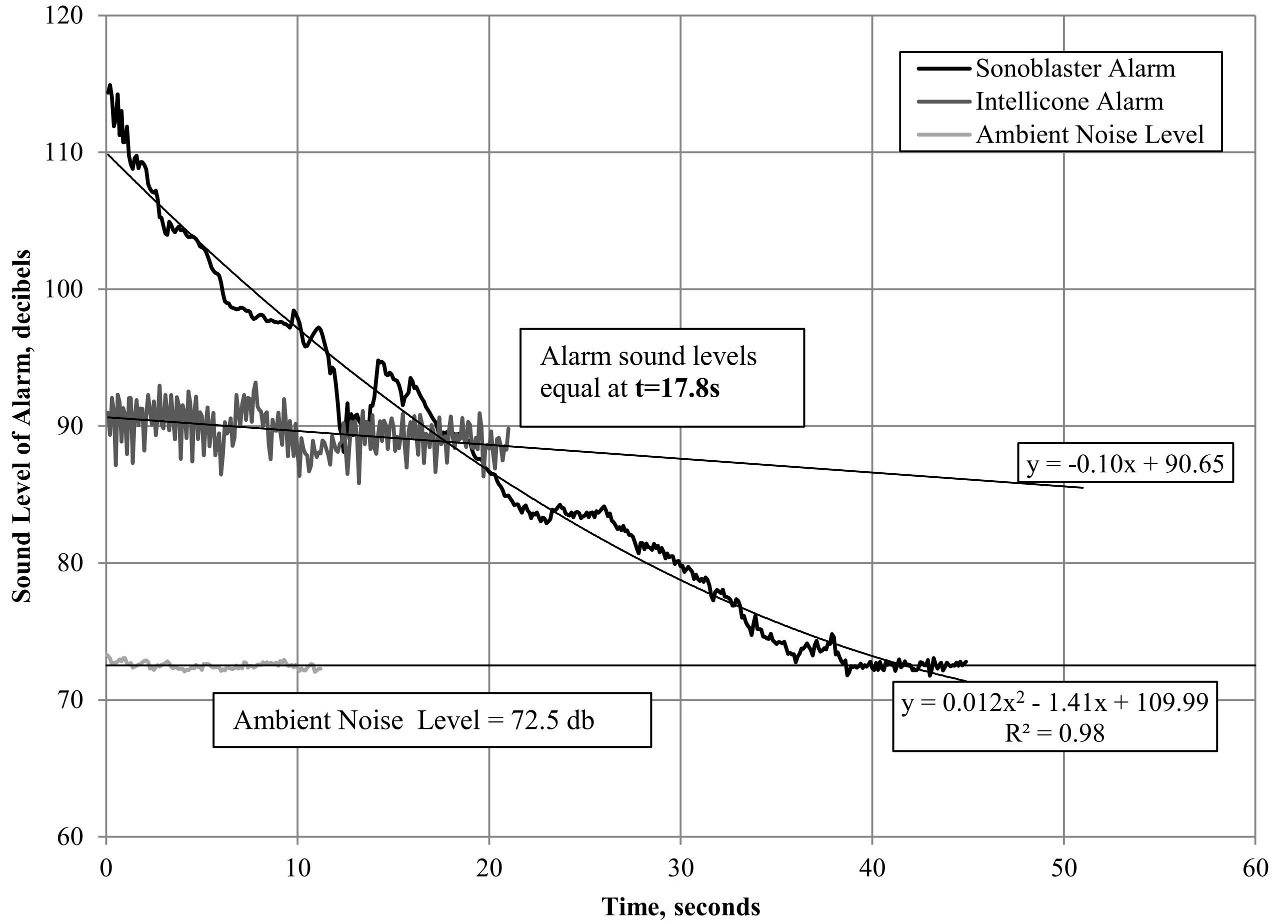
In addition to comparing the sound levels of both alarms, the sound level profiles of both alarms were compared for several identical alarm setups. The profiles were fitted to equations of best fit and analyzed to determine when the alarm sound levels were equal. Two representative cases of five are shown (Figure 56 and Figure 57). While the mean of the time when the Intellicone sound level became louder than the SonoBlaster sound level is 27.8 seconds, the two cases shown are the best samples taken and indicate that the sound levels likely intersect closer to 20 seconds.



Sound sampling rate at 0.1 seconds

Figure 56. Comparative Sound Level Profile

Also, only the clearest samples were used, using only alarm profiles from the SonoBlaster with the alarm pointed towards the sound meter. From previous testing it was evident that this configuration produced the steadiest decline in sound level. In the field, the alarm sound level intersection would likely be less than 20 seconds, especially considering that many SonoBlaster trials did not last 20 seconds.



Sound sampling rate at 0.1 seconds

Figure 57. Comparative Sound Level Profile

This comparison of the sound profiles indicates that practically, the SonoBlaster alarm will be a louder alarm than the Intellicone alarm at the same distance away from each alarm for the first 20 seconds. Given the setup parameters of both alarms, workers near taper areas and sensor lines are more likely to hear the SonoBlaster alarm, because of the SonoBlaster proximity. It also indicates that, if the Intellicone alarm duration is set up for longer than 20 seconds, it may be more likely to be heard than the SonoBlaster. Overall though, for work near the alarms, the SonoBlaster will likely always be louder for workers to hear.

Alarm Activation Angle

The activation angle of the Intellicone sensor was found to be 19.2° from horizontal for the sensor unit tilting on its side. The activation angle for tilting downward on its face was found to be 19.3° from horizontal.

The activation angle of the SonoBlaster alarm was found to be 11.3° from horizontal for the sensor unit tilting on its side. The activation angle for tilting downward on its face was found to be 4.8° from horizontal.

While there is some difference between the alarm activation angles for both alarms, all of the angles are small enough that the channelizer mounted with each alarm will need to be knocked over for the alarms to activate. Therefore, it is likely that both alarm systems will operate and activate identically with regards to activation angle. However, the small angles also suggest that channelizers should be able to be moved with the alarms on them without causing false alarms. Additionally, the alarms will need to be directly struck by an intruding vehicle to activate; being swiped or bumped by a car driving by would likely not result in the channelizer tipping to 20° or less. Wind, except in extreme cases, would also likely not be able to tip a channelizer over and activate the alarm.

Battery Life

The battery life of the Intellicone sensor units was found to be approximately 12 days. The battery life of the Intellicone alarm unit was found to be approximately 23 hours with the green LEDs on. The battery life of the Intellicone alarm unit was found to be approximately 55 hours with the green LEDs off.

While battery life may become an issue for long-term work zones where sensors with sequential lighting would be used constantly for 10 or more days, or in all day work zones where work would start during the day and go through the night, in general, for short-term or temporary work zones where intrusion alarms are most likely to be deployed, the battery life of the Intellicone alarm will be sufficient for work. The sensor battery life is likely enough to last for the duration of a short to medium term project, and the Intellicone PSA battery is sufficient to last all day and be recharged each night.

Effective Transmission Distance

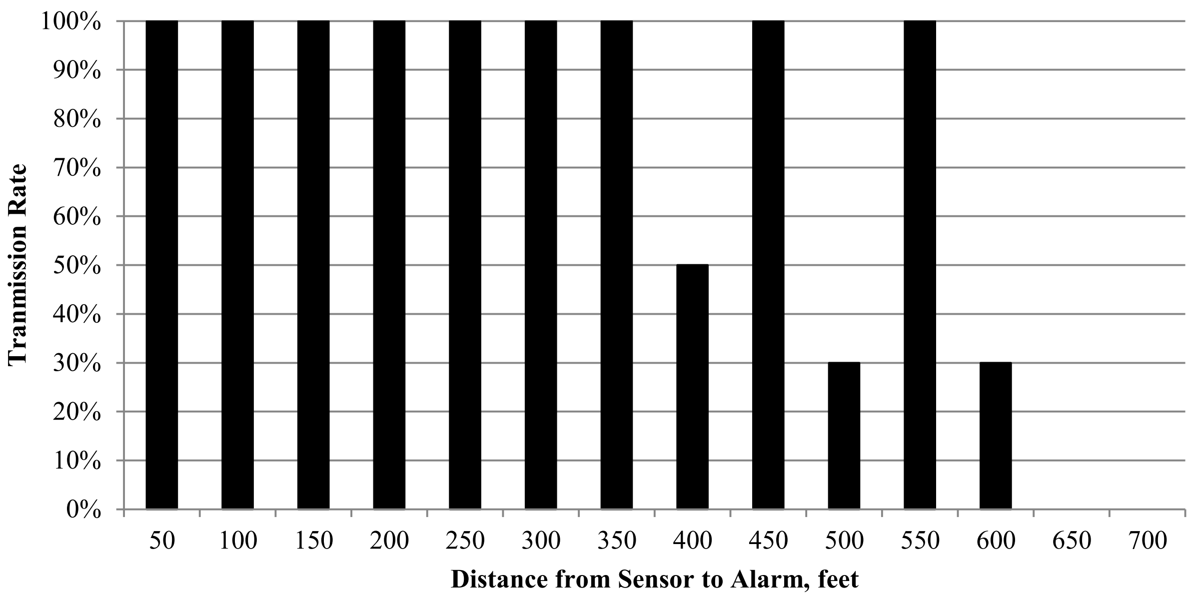


Figure 58. Intellicone Transmission Rate between Sensor and Alarm

Effective transmission distances for the Intellicone alarm were measured. For transmission between a sensor and the alarm (Figure 58), 350 feet was found to be the maximum distance with 100 percent transmission rate as well as for lesser distances up to 350 feet. While both 450 feet and 550 feet also had 100 percent transmission rates, the intermediate values at 400 feet and 500 feet did not. Thus, it is unlikely that perfect transmission truly occurs at either 450 feet or 550 feet. For 0 percent transmission, 650 feet was found to be the shortest distance at which no activation of the sensor successfully activated the alarm unit. It was found that transmission rates did not decrease in a consistent manner between 350 feet and 650 feet.

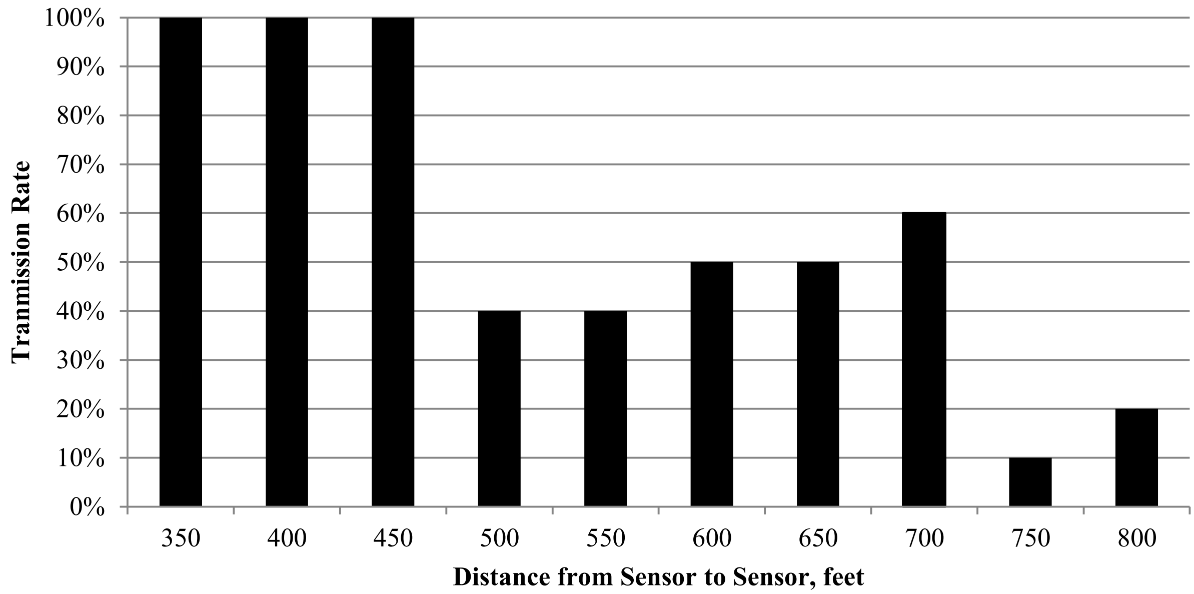


Figure 59. Intellicone Transmission Rate between Sensor and Sensor

For transmission distances between sensors (Figure 59), the longest distance with 100 percent transmission was found to be 450 feet. At distances above 450 feet, transmission rates ranged from 10 percent to 60 percent, but did not decrease in a consistent manner. No distance with 0 percent transmission rate was found, as the test area was not sufficiently long to test distances above 800 feet in a manner consistent with the previous test distances.

The effective transmission distances for both sensor-to-sensor transmission and sensor-to-alarm transmission demonstrate that multiple sensors will likely be needed along work zones of any appreciable length in order to properly transmit a signal to the alarm. This should also limit large gaps in the safety perimeter which could allow a vehicle to enter a work area without striking a sensor. In addition, the distances are considerably greater than the manufacturer recommended ~150 feet (50m), allowing for inexact distance placement between sensors. Furthermore, the effective transmission distance between sensor and alarm allows for moving the alarm within the work area during construction.

Field Testing

At location 1, an oral group interview was conducted with seven of the workers. When the Intellicone alarm was activated, the workers were between 20 feet and 150 feet away, with the majority being around 50 feet away. When the SonoBlaster was activated, the workers were approximately 200 feet.

- Four of the workers responded that both the Intellicone and SonoBlaster alarms were easy to hear. One of the four was inside the backhoe when the alarms were activated.
- When the alarm went off, all seven workers indicated they recognized both systems as intrusion alarms.
- The site foreman said he saw all the workers look upstream, towards the location of oncoming traffic when the Intellicone activated the first time on the first day.
- The workers believed that if an actual intrusion had occurred, having such an alarm would give them time to look upstream and react. They said that without such a system they would not know about an intrusion.
- They felt that ideally, the alarms would be placed “pretty far” away from the work zone, in order to give the workers time to react.
- Four of the workers rated both systems as good; one rated them as very good. The other two workers indicated their assent.
- They felt an intrusion alarm system would work well on highways, in locations with blind spots, near horizontal curves or hills, and on extremely long work zones.
- Were such a system in place, the workers felt it would make them feel somewhat safer.

- One worker, who was driving the truck which backed over the channelizer and attached Intellicone alarm, said that the alarm did not activate when the channelizer fell, but only activated once it was stood back up.

At location 2, an oral group interview was conducted with five of the workers. When the Intellicone alarm was activated, the workers were between 50 feet and 150 feet away, with the majority being around 100 feet away.

- Four of the workers responded that the alarm was difficult to hear; the worker who was closest to the Intellicone PSA unit heard the alarm activate three out of five times, one worker heard it twice, two workers heard it once, and one worker never heard it.
- When the alarm went off, three of the four workers indicated they recognized the alarms as intrusion alarms. One worker said he thought the alarm was a back-up alarm on a truck.
- The workers believed that if an actual intrusion had occurred, having such an alarm would allow them to react and see an intruding vehicle. Furthermore, they indicated that they had experienced intrusions into work zones they had worked at and felt such a system would be useful.
- They felt the Intellicone alarm was not good right now for the type of work zone they were in (lane closure on a major interstate highway), but that it was a good idea and just needed to be louder.
- The workers believed an intrusion alarm system would work well in residential or local areas which were quieter environments than the interstate, or in work zones which required a flagger.

- Were such a system in place, the workers felt it would definitely make them feel safer if it were louder, as it would give them time to know an intrusion was occurring and react.

At location 3, an oral group interview was conducted with three of the workers; the other workers declined to be interviewed. When the Intellicone alarm was activated, the workers were between 200 feet and 350 feet away, with the majority being around 300 feet away. When the SonoBlaster alarm was activated, the workers were between 300 feet and 500 feet away.

- Two of the workers responded that they heard the Intellicone alarm, but that it was difficult to hear; none of the workers heard the SonoBlaster alarm, but two of the three interviewed were not sure if they were present at the work zone when the alarm was activated, though the researcher believes they were.
- When the alarm went off, the workers who heard it indicated they recognized the Intellicone alarm as an intrusion alarm.
- The workers believed that if an actual intrusion had occurred, having such an alarm would be very helpful because they are not able to always keep an eye on the roadway. They also indicated that they had experienced intrusions into work zones in which they have worked.
- They felt the Intellicone alarm was somewhat good, but that it needed to be louder.
- The workers believed an intrusion alarm system would work well at intersections, on highways or other high speed roadway, or during night operations.
- Were such a system in place, the workers felt it would either not make them feel safer or only make them feel a little bit safer.

At location 4, an oral group interview was conducted with four of the workers; the other workers declined to be interviewed. When the Intellicone alarm was activated, the workers were between 15 feet and 30 feet away, with the majority being around 20 feet away. When the SonoBlaster alarm was activated, the workers were between 250 feet and 300 feet away.

- Three of the workers responded that they heard both the Intellicone alarm and the SonoBlaster alarm, and that neither alarm was difficult to hear. One worker responded that it was a little difficult to hear the Intellicone alarm, as he was drilling when it was activated, but that he was able to recognize it immediately and look for an intrusion.
- When the alarm went off, the workers who heard it indicated they recognized both the Intellicone alarm and the SonoBlaster alarm as intrusion alarms.
- The workers believed that if an actual intrusion had occurred, having such an alarm would be very helpful by giving them a few seconds to react to the situation. They also indicated that they had experienced an intrusion into the work zone they were working in on the prior day.
- They felt the Intellicone alarm was very good, and that was loud enough for the work zone they were in.
- The workers believed an intrusion alarm system would work well in any type of work zone, including at intersections and on highways, both during the day and night.
- Were such a system in place, the workers felt it would make them feel safer.

Discussion of Survey Comments

Intellicone

Overall, based on evaluations from the workers at the work zones where testing occurred, the Intellicone was relatively more difficult to hear due to its sound volume, even though it was recognizable as an alarm. Most of the workers wanted the alarm to be louder, especially in the two work zones with louder ambient environments from traffic and construction activities. Based on the researcher's experience with setting up and taking down the alarm systems, the Intellicone was easy to deploy at all three work zones which used the channelizer-mounted sensors. The biggest difficulty encountered during deployment was the varying conditions of the channelizers to which the Intellicone sensors were being mounted. The mounting hole used to bolt the sensor to the channelizer and the plastic piece which supports the sensor both vary based on the manufacturer of the channelizer. Furthermore, many of the channelizers are hit or run over and the plastic can be warped, marking the bolt more difficult to thread through the channelizer. The cone mounted Intellicone sensors were also easy to set up and take down.

SonoBlaster

Overall, based on evaluations from the workers at the work zones where testing occurred, the SonoBlaster was slightly easier to hear but still difficult due to its distance from workers. When loud enough to hear clearly, it was easily recognized as an alarm. It is possible, based on sound frequency profile, that when the sound level from the alarm is close to the ambient sound level of the traffic, that it might be mistaken for traffic. Based on the researcher's experience with setting up and taking down the alarm systems, the SonoBlaster was more difficult to deploy at all four work zones. Due to the SonoBlaster attaching to channelizers using bolts passing through drilled holes in the channelizer, the SonoBlaster had to remain attached to a single channelizer during the entire study; it could not be attached to channelizers already in use at the job sites, as the researchers did not want to alter contractors' work equipment. Furthermore, with the SonoBlaster mounted on the channelizer, the 30 pound base could not be removed; it had be carried and set up as a single unit, which was difficult due to the weight and bulk of the channelizer and the size of the second and third work zone locations. Additionally, the inconsistency of the SonoBlaster was of some concern as the duration and intensity of the alarm were dependent on how the alarm was oriented once the channelizer was knocked over, which cannot be controlled in the field.

General observations by the workers indicated that both systems were recognizable as an alarm when loud enough to hear, and therefore would function well as a warning system. All the workers felt an intrusion alarm system had potential to be useful by giving them knowledge of an incoming vehicle and time to react to the potential threat. Most of the workers felt such a system would make them feel safer, though by varying degrees. They believed an intrusion system like the two tested would be effective in three primary situations:

- On highways and high speed roadways, due to the high speeds and corresponding safety issues, as well as the difficulty in knowing if an intruding vehicle was coming.
- On local or residential roads, due to the lower ambient noise volume, allowing the alarms to be heard easier.
- On work zones during the night or with obstructions, such as horizontal or vertical curves, due to the difficulty in being aware of an intruding vehicle.

Chapter 6 Findings and Discussion

Limitations

The research had several key limitations. Most testing was conducted on a closed course so data gathered on transmission distances, activation angles, etc. do not account for key parts of the road and work zone environment, specifically: obstacles, construction equipment, road grades, or variations in weather, among other things. The presence of obstacles limiting a clear line of sight to the PSA unit is a potential reason for the failure of the Intellicone alarm to activate at Location 3. Furthermore, the closed course testing was limited in trials and not enough for a statistical analysis.

The open course testing was also limited in the amount of time so no actual intrusion events were witnessed. Reactions by workers to the intentional alarm activation were likely different than a totally unexpected, unanticipated alarm. Reactions could be slower, because of its unexpected nature, or quicker, because of the awareness that it is not a test. Furthermore, the work zones tested were during the day and stationary. The reactions and efficacy of the system may be different or impaired for night operations or moving operations. Furthermore, both Location 2 and Location 3 cannot be considered either short-term or temporary, and thus did not model the type of work zone where a safety perimeter system may be most likely to be used, though the Location 3 work zone did have a limited number of safety devices present, as a short-term or temporary work zone would. Both the Location 1 and Location 4 work zones were short-term.

Additionally, the amount of equipment used during testing was far less than what would likely be deployed in an actual work zone were either of the tested systems being used as a safety system. Both companies producing the Intellicone and SonoBlaster, respectively, call for the use of more equipment, especially SonoBlaster alarms and Intellicone sensors, to create a more complete safety perimeter.

Also, a critical finding in previous research indicated that ease of setup was a major issue for many of the early systems developed and tested during the 1990s (Graham et al. 1993; Agent and Hibbs, 1996; Trout and Ullman, 1996; Burkett et al. 2009; Krupa, 2010). However, during this study, the researcher set up and monitored the alarm systems during the field testing, so no information on how workers felt regarding the ease of use of the system was gathered. It is believed this may be especially significant in comparing the two systems tested, as the researcher noted a marked difference in ease of setup for the two systems.

Finally, there was limited testing of the SonoBlaster during the field evaluation, as it was never set off at Location 2 due to field concerns, and potentially only had one interviewed worker present at the Location 3 work zone when the alarm was activated. Only Location 1 and Location 4 had successful activations of the SonoBlaster alarm and workers interviewed regarding the alarm activation.

Future Research

Future research is needed, especially additional field testing of the Intellicone system and similar electronic safety perimeter systems if they become available. This study was a limited proof of concept study to determine if a system of this type could work in Kansas. Extensive field testing will also be needed to determine if the system actually results in safety benefits.

In addition, future research will need to be conducted to determine the best parameters for the deployment of any system. Research regarding the time needed for workers to get out of the way of an intruding vehicle would be particularly helpful in the development of such safety systems. The best location to deploy a perimeter in relation to the work zone and the best location to deploy the alarm unit within the work zone should also be research.

Additional research into the tone, duration and sound level of the alarm would also be beneficial in increasing the chances of workers hearing the alarm. Based on discussions with the designers from Highway Resource Solutions, it was indicated that the Intellicone alarm was designed with specific parameters for distance, volume, and hearing protection penetration. Research into these parameters would help develop more effective electronic alarms. Research into the type of ambient noise present at work zones would be useful in creating alarms which are distinct enough and loud enough to be heard.

As noted in the limitations of the study, additional research and surveys will be necessary to determine if the Intellicone system and SonoBlaster alarm are easy enough to set up and use so that contractors would be willing to use them.

Contributions to Highway Safety

This research provides an important first step in addressing the safety deficiency in short-term and temporary work zones. There are no current safety systems which are cost effective to be used consistently on short-term work zones, and only a few systems which are mobile enough to be used on temporary work zones. Safety perimeter systems offer the potential to provide safety for workers by alerting them to intrusion incidents in both short-term and temporary work zones. This research demonstrated the potential efficacy of such systems and that they can be adapted to work zones in Kansas.

Conclusion

There is a significant safety gap for short-term and temporary work zones. Both the Intellicone system and SonoBlaster alarm can help address this gap by providing safety perimeters. Field testing showed that there are some difficulties with both systems, mainly with the sound levels of the alarms. However, workers were generally positive about the systems and felt such a system would give them time to react to an intrusion incident. Additional extensive field research is certainly needed, especially allowing contractors to set up and use the system themselves. While both systems had issues, they each showed promise in making workers safer in work zones.

References

Agent, K. and J. Hibbs. "Evaluation of SHRP Work Zone Safety Devices." Research Report No. KTC-96-30, Kentucky Transportation Center, Lexington, Kentucky, December 1996.

Beard, G., K. Fernandez-Medina, and B. Lawton. "Safelane Signal Transmission Trials." Transport Research Laboratory Draft Project Report RPN2700, Transport Research Laboratory, Wokingham, Berkshire, United Kingdom, June 2013.

Bryden, J., L. Andrew, and J. Fortuniewicz. "Intrusion Accidents on Highway Construction Projects." Transportation Research Record 1715, Paper No. 00-0265, New York State Department of Transportation, Albany, New York, 2000.

Burkett, G., V. Her, and S. Velinsky. "Development of New Kinds of Mobile Safety Barriers." Research Report No. CA09-0920, Advanced Highway Maintenance and Construction Technology Research Center, Davis, California, February 2009.

Geistlinger, L. "A Cause for Alarm!." Roads & Bridges, Volume 34, No. 7, July 1996.

Graham, J., J. Hinch, and N. Lerner. "Maintenance Work Zone Safety." Research Report No. SHRP-M/FR-89-001, September 1991.

Hanscom, F., J. Graham, and D. Stout. "Highway Evaluation of Maintenance Work Zone Safety Devices." Proceedings of the Conference Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents, Hague, Netherlands, September 22-24, 1993.

Kansas Department of Transportation (KDOT). "Proposed Functional Classification Map of Lawrence Urban Area Boundary (UAB)." June 2013. http://www.ksdot.org/Assets/wwwksdotorg/bureaus/burTransPlan/maps/FunclassMaps/Urban/Lawrence.pdf. Accessed August 5, 2014.

Kansas Department of Transportation (KDOT). "Traffic Count Map of Lawrence." August 2013. https://www.ksdot.org/Assets/wwwksdotorg/bureaus/burTransPlan/maps/CountMaps/Cities/lawren13.PDF. Accessed August 4, 2014.

Kochevar, K. "Intrusion Devices – New and Emerging Technology in Worker Safety." Presentation given on unknown date. http://ops.fhwa.dot.gov/wz/workshops/accessible/Kochevar_ID.htm and http://ops.fhwa.dot.gov/wz/workshops/originals/Ken_Kochevar_ID.ppt. Accessed March 11, 2014.

Krupa, C. "Work Zone Intrusion Alarm Effectiveness." Research Report No. NJ-2010-004, Cambridge Systematics, Princeton Junction, New Jersey, September 2010.

Parsons Brinckerhoff, Olsson Associates, and Shockey Consulting. "5-County Regional Transportation Study Phase 2 Final Report." KDOT Project No: 106 KA-1277-02. April 8, 2013. http://kdotapp2.ksdot.org/5CountyStudy/get_more_info/reportsPhase2.aspx. Accessed August 5, 2014.

Pegula, S. "An Analysis of Fatal Occupational Injuries at Road Construction Sites, 2003-2010." U.S. Bureau of Labor Statistics, Monthly Labor Review, November 2013.

Pegula, S. "Fatal Occupational Injuries at Road Construction Sites." U.S. Bureau of Labor Statistics, Monthly Labor Review, December 2004.

Phanomchoeng, G., R. Rajamani, and J. Hourdos. "Directional Sound for Long-Distance Auditory Warnings From a Highway Construction Work Zone." IEEE Transactions on Vehicular Technology, Vol 59, No. 5, June 2010.

Schrock, S., G. Ullman, A. Cothron, E. Kraus, and A. Voigt. "An Analysis of Fatal Work Zone Crashes in Texas." Research Report No. FHWA/TX-05/0-4028-1, Texas Transportation Institute, College Station, Texas, October 2004.

Stout, D., J. Graham, and F. Hanscom. "Maintenance Work Zone Safety Devices Development and Evaluation". Research Report No. SHRP-H-371, Strategic Highway Research Program, Washington, DC, November 1993.

Trout, N., and G. Ullman. "Devices and Technology to Improve Flagger/Worker Safety." Research Report No. TX-97/2963-1F, Texas Transportation Institute, College Station, Texas, September 1996.

Wong, J., M. Arico, and B. Ravani. "Factors Influencing Injury Severity to Highway Workers in Work Zone Intrusion Accidents". Traffic Injury Prevention, Vol 12, No. 1, 2011.

Appendix A – Field and Interview Guide

Kansas Work Zones
Intrusion Alarm Effectiveness

Date

Interviewees

Work Zone

Project Purpose

The University of Kansas is researching the use of intrusion alarm systems for temporary work zones in Kansas to determine the effectiveness of the two available systems. It is being deployed in several work zones, after which, an evaluation will be conducted with work zone workers.

The study is seeking to determine the systems' effectiveness, ease-of-use, and perceived usefulness, as well as any limitations and potential problems.

Field observations will be made of system deployment at various work zones. Group interviews will also be conducted following the deployment and use of the system. The data collected will be synthesized in a final report which will summarize the findings.

Field Observations

Describe details of the work zone (type of roadway, number of lanes, rough traffic volume, work zone type, work being performed, equipment in use, size of work crew).
Describe the traffic management and any safety systems used (channelizers, message signs, etc.).
Describe the setup of the intrusion alarms (placement of alarm unit, number of sensors, spacing of units, and placement in relation to work zone activity).

Describe any work zone intrusions that occurred.
Describe any intentional alarm activations that occurred.
Describe any false alarms that occurred.

Describe worker reactions to alarm activation (who reacted, how quickly, what they did).

Describe any operational problems observed.

How easy is the alarm unit and sensor units to deploy and operate?
How long did total deployment of the system take?
How easy is the alarm unit and sensor units to take down and store?
How long did take down of the system take?

Questions for Workers
How easy or hard was it to hear the alarms when they activated?

How close were you to the intrusion alarms when they activated?

When the alarm activated, what was your response?

If a real intrusion did or had occurred, how do you believe having an alarm deployed would affect the outcome, if at all?

What would be your overall rating of the alarm systems?

In what types of work zones do you feel this system would work well?

How would having the intrusion alarm deployed affect your feelings of safety in the work zone? Less safe, somewhat less safe, neither less safe nor more safe, somewhat more safe, more safe

Any additional comments?

Appendix B - Summary of Field Interview Comments

Question	Location 1	Location 2	Location 3	Location 4
How close were you to the intrusion alarms when they activated?	Intellicone: 20ft-150ft, majority 50ft SonoBlaster: 200ft	Intellicone: 50ft-150ft, majority 100ft	Intellicone: 200ft-350ft, majority 300ft SonoBlaster: 300ft-500ft	Intellicone: 15ft-30ft, majority 20ft SonoBlaster: 150ft-300ft
How easy or hard was it to hear the alarms when they activated?	All 7 workers said both alarms were easy to hear.	4 workers said Intellicone was difficult to hear, 1 worker never heard it.	2 out of 3 workers said the Intellicone was difficult to hear, no workers heard the SonoBlaster though possibly only one was present.	3 workers said both alarms were easy to hear, 1 worker said Intellicone was difficult to hear.
When the alarm activated, what was your response?	All 7 workers said both alarms were recognizable.	3 workers recognized the alarm, 1 worker thought it was a back-up alarm.	2 workers who heard the Intellicone recognized it.	All 4 workers said both alarms were recognizable.
If a real intrusion did or had occurred, how do you believe having an alarm deployed would affect the outcome, if at all?	Alarm would give time to look upstream and react. Should be placed "pretty far" upstream.	Alarm would allow them to react and see an intrusion. They had experience with intrusions.	Alarm would be very helpful because they are not always able to keep an eye on the road. They had experience with intrusions.	Alarm would be very helpful by giving them time to react. They had experienced an intrusion on the prior day.
What would be your overall rating of the alarm systems?	4 workers rated both systems good. 3 workers rated them very good.	All 5 workers rate it bad for their work zone, though good idea (needed to be louder).	All 3 workers felt it was somewhat good, but it needed to be louder.	All 4 workers said the alarms were very good.
In what types of work zones do you feel this system would work well?	Highways, near blind spots, horizontal curves or hills, on long work zones.	Residential or local areas, quieter environments, where flaggers were required.	Intersections, highways, other high speed roadways, night operations.	Any type of work zone, intersections, highways, day or night.
How would having the intrusion alarm deployed affect your feelings of safety in the work zone?	Workers felt they would feel somewhat safer.	Workers felt they would definitely feel safer if they could hear it.	Workers felt they would only feel a little bit safer or not safer at all.	Workers felt they would feel safer.
Any additional comments?	Alarm activated when the channelizer stood back up.	SonoBlaster not activated due to safety concern.		