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# Reducing Highway Construction Fatalities Through Improved Adoption of Safety Technologies

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# REDUCING HIGHWAY CONSTRUCTION FATALITIES THROUGH IMPROVED ADOPTION OF SAFETY TECHNOLOGIES

## Work Zone Intrusion Alert Technology

Submitted to:
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# 1. Abstract

Highway construction is commonly associated with high rates of worker accidents. These high rates are often linked to the requirement of work in close proximity to live traffic and heavy duty construction equipment. Existing transportation research shows that technological solutions, like Work Zone Intrusion Alert Technology (WZAIT) improve work zone safety. However, few organizations in the highway construction industry have adopted these safety technologies. Industry actors report concerns about technology effectiveness, cost implications adopting new technology, and lack of technology feature-synergy. Few studies have explored strategies for improving work zone safety technology adoption, implementation, and eventual diffusion across the highway construction industry. To fill this gap in research and practice, this study attempts to develop tools and identify effective processes that could be used to improve the adoption of work zone safety technologies using work zone intrusion technology as a case study.

## 2. Key Findings

I. Technological, individual, organizational, and external factors determine the extent to which WZIT adoption is successful and sustained.

II. WZIAT financial benefits outweigh associated costs if the technologies can prevent between 12.6% and 34% of the intrusion accidents that lead to injuries and fatalities.

III. Twenty-one factors influence WZIAT adoption (Table 4). These factors are largely technology-related and were identified through literature review and interviews with subject matter experts employed at contractor firms and departments of transportation.

IV. Lack of shared language/meaning/criteria between end users (construction companies) and technology manufacturers/salespeople. Each group provided different safety technology feature importance ratings.

V. Labor cost associated with WZIAT contributes a significant fraction of total implementation cost.

VI. The most important technology-based factors were

- worker comprehension of warning signal,
- adequate coverage distance, and
- few or no false negative and false positive.

VII. Ease of use and subjective norm are strong predictors of a worker's intention to accept and implement a work zone intrusion alert technology

# 3. Introduction

**Work Zone Injuries and Fatalities**

The construction industry has the highest worker fatality levels in the United States. Within construction, highway construction accounts for 16% of these fatalities (BLS 2017). On average, this translates to 121 annual work zone fatalities between 2005 and 2014, with one fatality every 15 hours and one work zone incident-related injury occurring every 16 minutes (FHWA 2017). Factors such as driver distraction, weather, and roadway conditions have been identified as major causes of work zone accidents. The volume of highway construction and maintenance projects is expected to increase as economic growth spurs public and private investment. This means there are more work zones and increased probability of harm to workers and motorists.

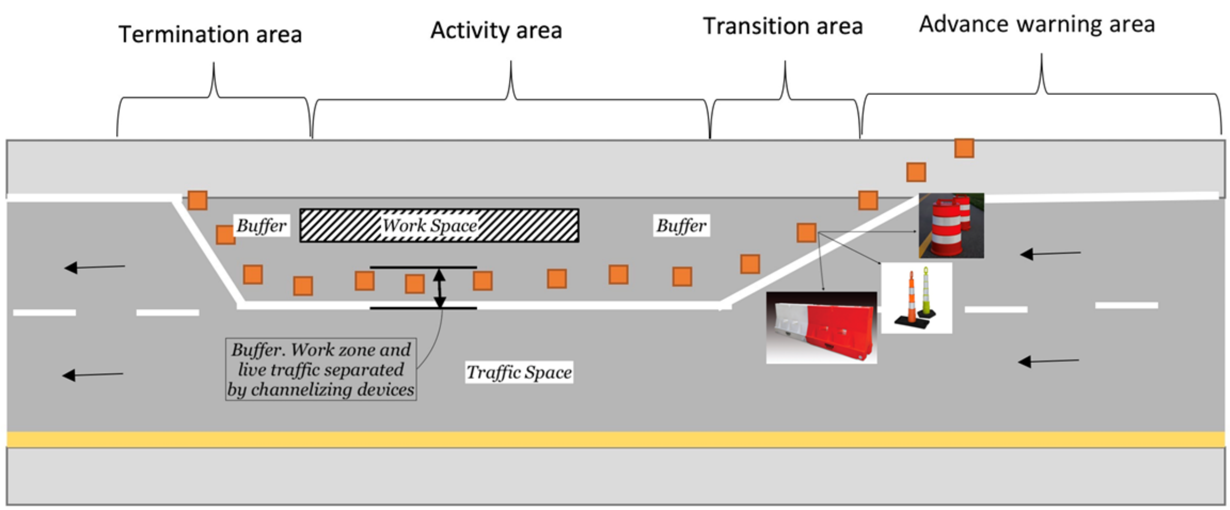


**Figure 1. Basic highway construction work zone layout (Adapted from ITSI, 2011)**

For this report, a work zone accident is any incident that occurs within a work zone. This includes work zone approach and exit. Existing research shows that most crashes occur within the "activity area" (Garber and Zhao, 2002), which is where most construction workers are located. Activity areas include "work", "traffic", and "buffer" zones. Vehicle intrusion past the channelizing devices (picture inserts in Figure 1) is a primary cause of worker fatalities.

Figure 2 shows that worker “runover” by intruding vehicles or construction equipment is the primary cause of work zone fatalities. Other causes include collision between vehicles and mobile equipment, and incidents in which workers are caught between or struck by construction equipment.

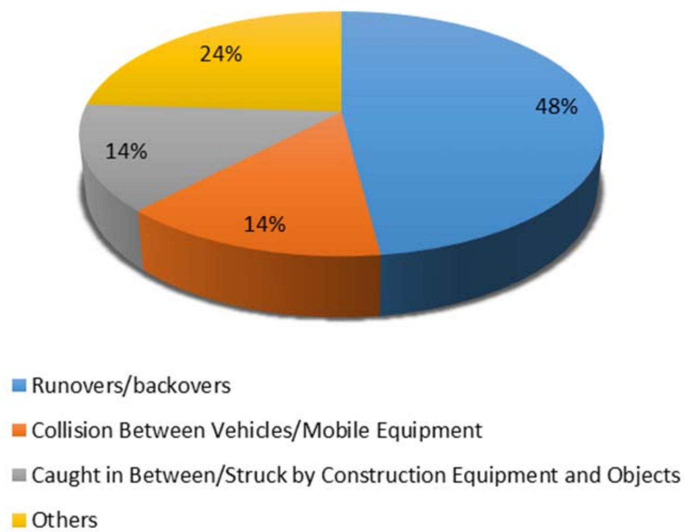


**Figure 2. Distribution by cause of fatality between 2005 and 2014 (n=1209) (Adapted from FHWA 2017)**

### How does Technology affect Work Zone Safety?

Recently, the Federal Highway Administration (FHWA) and other agencies impacted by work zone injuries and fatalities introduced several programs to help curb work zone fatality rates. Examples of such programs are the National Work Zone Awareness Week and Turning Point. While post-program assessments indicate work zone fatalities have decreased, annual motorist-induced deaths have remained relatively stagnant (Bello 2009; Sant 2014). In response, regulatory, industry, and other agencies across the United States have encouraged highway construction stakeholders to adopt work zone safety. This approach is bolstered by research that shows synergy between technology use and improved worker safety.

In preparing this report, the Oregon State University team undertook a detailed literature review of over 132 articles. There was a marked increase – by about 700% – in work zone safety technology (WZST) research between 2002 and 2012. There has also been an increase in WZST production. As a result, there is a need to assess why adoption is significantly lower than WZST research and development.

Existing research has looked at WZST performance as a means of assessing the adoption challenge. This includes work to assess effectiveness of proximity warning systems (Park et al. 2015), truck-mounted attenuators (Ullman and Iragavarapu 2014), and portable changeable message signs (Gambatese and Zhang 2016). However, other studies show that WZST adoption is persistently low because 1) it is difficult to quantify the holistic benefits of certain technologies using a direct measure of effectiveness (DMOE), 2) return on investment (ROI) and benefit-cost analyses (BCA) are often negative or inconclusive, and 3) there are conflicting opinions about WZST usefulness and ease of use (Fyhrie 2016; Edera et al. 2013; Huebschman et al. 2003). While responses to challenges like ROI are focused on management, DMOE and opinions about ease of use and usefulness call for employee/worker focused strategies. The following section is focused on a WZST – Work Zone intrusion alert technology (WZIAT) – that has not successfully diffused across the highway construction industry.

## Work Zone Intrusion Alert Technology

Work zone intrusion alert technologies (WZIATs) are alert-producing devices used to warn workers within an activity area of an impending accident caused by a vehicle intruding into the work zone. The objective is to secure additional time for workers to react when an intrusion occurs. First introduced to work zones in 1995, WZIAT was the product of a Strategic Highway Research Program (SHRP) sponsored study (Agent and Hibbs 1996). Since the SHRP program, several WZIATs have been developed, evaluated by departments of transportation (DOTs), and implemented in work zones on a number of highway projects.

There are currently four commercially available WZIATs. Table 1 is a summary of these WZIATs, including attributes extracted from past research (Wang et al. 2011; ELWC 2015; Highway Resource Solution 2015; Gambatese et al. 2017; Marks et al. 2017).

In addition to the WZIATs listed in Table 1, Oldcastle Materials recently introduced an alert technology named Advanced Warning and Risk Evasion (AWARE). The system relies on position and orientation sensors and radars to constantly monitor the work zone. While initially intended to alert drivers of their intrusion into a work zone, the system is also beneficial for alerting workers of intruding vehicles. AWARE is undergoing testing and is not current commercially available (http://artisllc.com/highway-safety/; http://theasphaltpro.com/oldcastle-aware-system/).

Despite the introduction of WZIAT over 20 years ago, there has been limited application of WZIAT in work zones (Wang et al. 2011; Gambatese et al. 2017). This phenomenon could be attributed to several factors such as reported inaccurate alarms, difficulty to install and retrieve devices, lack of evaluation protocol, non-existing business case analysis, and low product awareness (Fyhrie 2016; Wang et al. 2011).

**Table 1: Commercially-Available Work Zone Intrusion Alert Technologies**

| | Intellicone | Intellistrobe | SonoBlaster | Worker Alert System (WAS) |
|---|---|---|---|---|
| **Manufacturer** | Highway Resource Solution | IntelliStrobe Safety Systems | Transpo Industries | Astro Optics, LLC |
| **Website** | www.intellicone.co.uk | www.intellistrobe.com | www.transpo.com | www.astrooptics.com |
| **Accessories** | Lamps, motion detector, and portable site alarm | Flagger - W1-AG and Remote Control Radio-FC 401-1 | Single alarm unit | Pneumatic hose, flashing alarm light, personal vibrating and audio alert |
| **Alert Mechanisms** | Impact-tilt, wireless sensor activated alarm system | Pressured trigger pneumatic tube alarm system | Impact-tilt activated alarm system | Pressured trigger pneumatic tube alarm system |
| **Suggested Application** | Longer than one day, tapper shorter than 1,500 ft. | Along tapper | | One day or shorter, tapper shorter than 1,500 ft. |
| **Price estimate** | $2,000 each | $25,000 | $100 each | $600 each |
| **Type of Alarm** | Audio and visual | Audio and visual | Audio | Audio, visual, and haptic |
| **Sound level** | 75 dB @ 50 feet | 90 dB @ 50 feet* | 90 dB @ 50 feet | 80 dB @ 50 feet |
| **Deployment** | Install device on channelizer along taper and work zone | Place tube at the beginning of taper. | Attach device to channelizer along taper | Place tube at the beginning of taper. |

## 4. Study Goal and Objectives

The primary goal of this study is to reduce work zone incident (injury and fatality) occurrence and severity by identifying factors that drive work zone safety technology adoption in the highway construction industry. Previous research shows that technology utilization increases worker safety, so it is expected that proactive steps , like effective worker-centric safety technology adoption, will reduce work zone incident occurrence and severity. Objectives established for the study in order to meet the primary study goal include:

I. Investigate how safety technology affects workers and highway construction work zones;
II. Develop and evaluate a model for work zone safety technology acceptance; and
III. Develop proposed frameworks for determining financial implications of WZIAT adoption, and standardized protocols for evaluating WZST - including WZIAT.

## 5. Methods

A mixed-methods approach involving a combination of qualitative and quantitative methods was adopted to investigate the research objectives. Specifically, an extensive review of extant literature on WZST was conducted to identify and assess the effectiveness of the technologies currently used to protect workers in construction work zones. In addition to identifying the WZSTs, the literature review provided an opportunity to identify potential barriers and drivers of adopting WZST as well as key technology attributes that influence technology acceptance. A concurrent triangulation process which relied on a cross-sectional survey of, and in-depth interviews with, highway construction stakeholders was utilized to provide additional contextual information on factors that influence the acceptance of WZSTs. Lastly, a case study approach was adopted to provide observational data required to develop benefit-cost analysis (BCA) and return on investment (ROI) for work zone intrusion alert technologies.

## 6. Accomplishments and results, including their relevance and practical application

To ensure that the research objectives were sufficiently met, the following research questions were developed to guide the study:

I. What are the major causes of worker fatalities and how often do they occur?
II. What is the use frequency and perceived effectiveness of existing WZIT?
III. Are end-users receptive to the adoption of new work zone safety technology (WZIAT and other technologies)?
IV. What is the current process/protocol used for adopting work zone safety technology (WZIAT and other technologies)?
V. What factors impact the acceptance, use, and diffusion of technology in highway construction?
VI. Does safety climate impact safety behavior (decision to adopt a technology)
VII. To what extent does end-user (consumer) and safety technology manufacturer WZST expectations converge?
VIII. Does investment in WZIAT represent value for money for contractors and DOT's?

Answers to the research questions were distributed across five primary tasks which were successfully executed by the researchers. Each of the tasks and corresponding results are provided below.

**Task 1: Investigate the impact of safety technology on work zone construction workers**

Assessing and documenting the impact of safety technologies used in highway work zones was the primary objective of Task 1. In addition, identifying the major causes of worker fatalities in work zones and the enablers and barriers to adoption of work zone safety technology was conducted within this section. To achieve these objectives, the researchers relied on a systematic review process using a proven review framework (Hong et al. 2012; Yi and Chan 2014), a retrospective analysis of worker fatalities within FACE database, and interview results from a preceding study (Gambatese et al. 2017). In total, 132 articles on work zone safety technology assessment were identified through the systematic review process involving four databases.

Publication trends show that the number of studies focused on WZST evaluations has increased steadily over the past 25 years. At the same time, the number of fatalities in work zones has reduced progressively. Although difficult to assert, the trend, depicted in Figure 3, suggests the possible presence of a relationship between the level of interest and adoption of safety technologies and the reduction of worker fatalities.

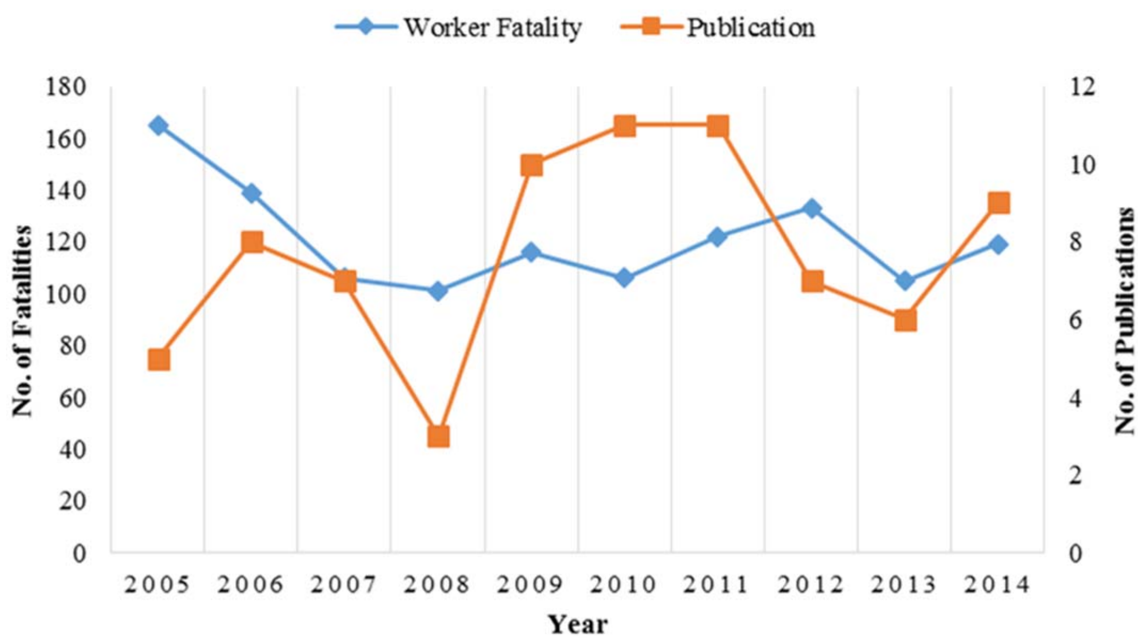


**Figure 3: Number of Work Zone Fatalities and WZST Evaluation Studies**

While the trend in evaluation studies is a better metric for measuring the level of interest in WZST (compared to the actual adoption of such technologies), an indication of interest is expected to translate to actual technology adoption (Davis et al. 1989).

The technologies evaluated in the articles reviewed primarily fell within three categories based on the objective of the WZST as follows:

I. Speed reduction systems (SRS): These technologies are used to reduce the traveling speed of motorists at advanced warning areas, transition areas, buffer areas, and work areas. The technologies could have direct or indirect physical impact on the traveling vehicle.

II. Intrusion prevention and warning systems (IPWS): Technologies set up to prevent errant drivers from intruding into a work zone and/or warn workers of imminent danger due to an intrusion into the work zone.

III. Worker detection systems (WDS): These are technologies implemented inside a work zone to alert workers and equipment operators of an imminent collision between a worker and equipment.

As seen in Figure 4, the WZSTS most frequently evaluated were changeable message systems (CMS), speed enforcement systems (SE), lane merge systems (LMS), and warning lights. These technologies fall within the speed reduction systems category.

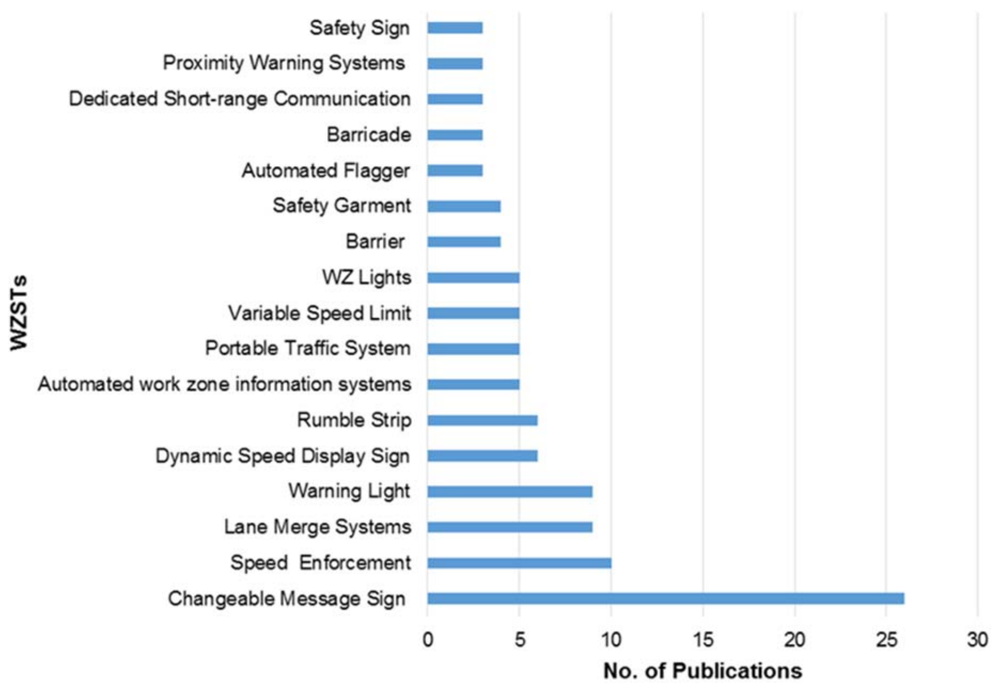


**Figure 4: Number of Evaluation Studies for each WZST**

Overall, the literature review indicates that there is a growing interest in the evaluation and use of WZSTs. Nevertheless, findings from the present study indicate varying evaluation approaches are executed for similar WZSTs. The lack of minimum evaluation requirements for WZSTs creates an avalanche of methodologies, which makes it inherently difficult to compare findings amongst similar studies.

Next, a retrospective analysis of work zone incidents was conducted to assess the usefulness of WZIAT. A comprehensive assessment of NIOSH Fatality Assessment and Control Evaluation (FACE) Program reports was conducted by the researchers to determine if WZIAT could have played a significant role in preventing the reported fatalities. In total, 25 highway work zone related fatality cases were reported and evaluated by NIOSH between 1984 and 2007. Although 80% of the documented fatalities were primarily caused by workers being struck by equipment, three fatalities were induced by intruding vehicles. Table 2 summarizes facts about each intrusion fatality. As seen in Table 2, using additional work zone safety devices such as work zone intrusion alert technologies could have improved the survival rate of the workers killed.

**Table 2: Summary of FACE Reports of Highway Work Zone Fatalities**

| **Cause of Fatality** | **FACE Recommendations** | **Possibly Prevented by WZIAT?** |
|---|---|---|
| Sleeping driver struck maintenance worker in work zone | Periodically monitor and evaluate employee conformance with safe operating procedures; adopt policies that require workers to work on the median side of the guardrail; educate the public regarding work zone safety issues | **YES**<br><br>Install WZIAT equipped with audio and vibratory alerts approximately 400 feet upstream of the worker |

| | | |
|---|---|---|
| Driver lost control of vehicle and veered into the work zone striking a DOT worker | Consider the use of supplemental traffic control devices; consider installing rumble strips along the roadway pavement edges to warn motorists | **YES**<br><br>Equip workers with personal alert systems. Install WZIAT across potential entry points around the work zone |
| Flagger struck by secondary contact from truck traveling at 55 miles per hour | Consider the use of additional warning signs and traffic control devices; provide and require use of hand-held or other portable radio communications equipment by flaggers at all times | **YES**<br><br>Implement WZIAT with speed detector and personal alert systems with at least 600 feet transmission distance |

## Task 2: Develop framework for WZST assessment, adoption, Intrusion Technology Acceptance Model (ITAM), and WZST evaluation protocol

### *Highway Work Zone Technology Assessment Process*

Given the important role safety technologies play in keeping workers safe in a work zone, it is essential to capture information that could help improve the adoption, implementation, and acceptance of useful technologies. DOTs play a central role in the adoption of WZST. In some states, DOTs include certain technologies into the traffic control plan thereby making the use of those technologies mandatory for contractors. A decision process map (shown in Figure 5) detailing a work zone safety technology acceptance process was developed based on the researchers' experience conducting evaluation studies on work zone safety technology. Interest in adopting a specific work zone safety technology is generally instigated by peer DOTs, researchers, or manufacturers.

Referring to Figure 5, to be considered for evaluation, the safety technology has to be captured in the DOT qualified product list (QPL). A QPL is a list of products and suppliers whose products are approved to use on projects without additional documentation and testing. If the technology is among the items in the QPL, the DOT evaluates internal interest in the product. If adequate interest is achieved, the Request for Proposal (RFP) scope is expanded to include a category that addresses the technology. Subsequently, researchers will be encouraged to submit proposals for evaluating the work zone safety technology. It is important to note that the process described above is strictly for a situation where a DOT is championing the evaluation of a specific work zone safety technology. If the idea emanates from a researcher, the researcher submits a Research Problem Statement (RPS) (assuming the released RFP accommodates the evaluation topic). If the RPS is successful, the researcher will be encouraged to submit a full proposal. If the proposal is accepted by the DOT, the technology is then tested to determine its effectiveness. The assessment usually includes a pilot test and live testing, and in certain cases, an extensive cost effectiveness analysis. If the proposal is rejected, the evaluation process is terminated. Subsequently, following testing of the technology, a report is developed to disseminate the findings from the study. If the work zone safety technology is considered effective, the DOT adopts the technology and may require contractors to use the technology in future projects. If the effectiveness of the technology is not conclusive, recommendations that could improve future adoption of the technology are made available.

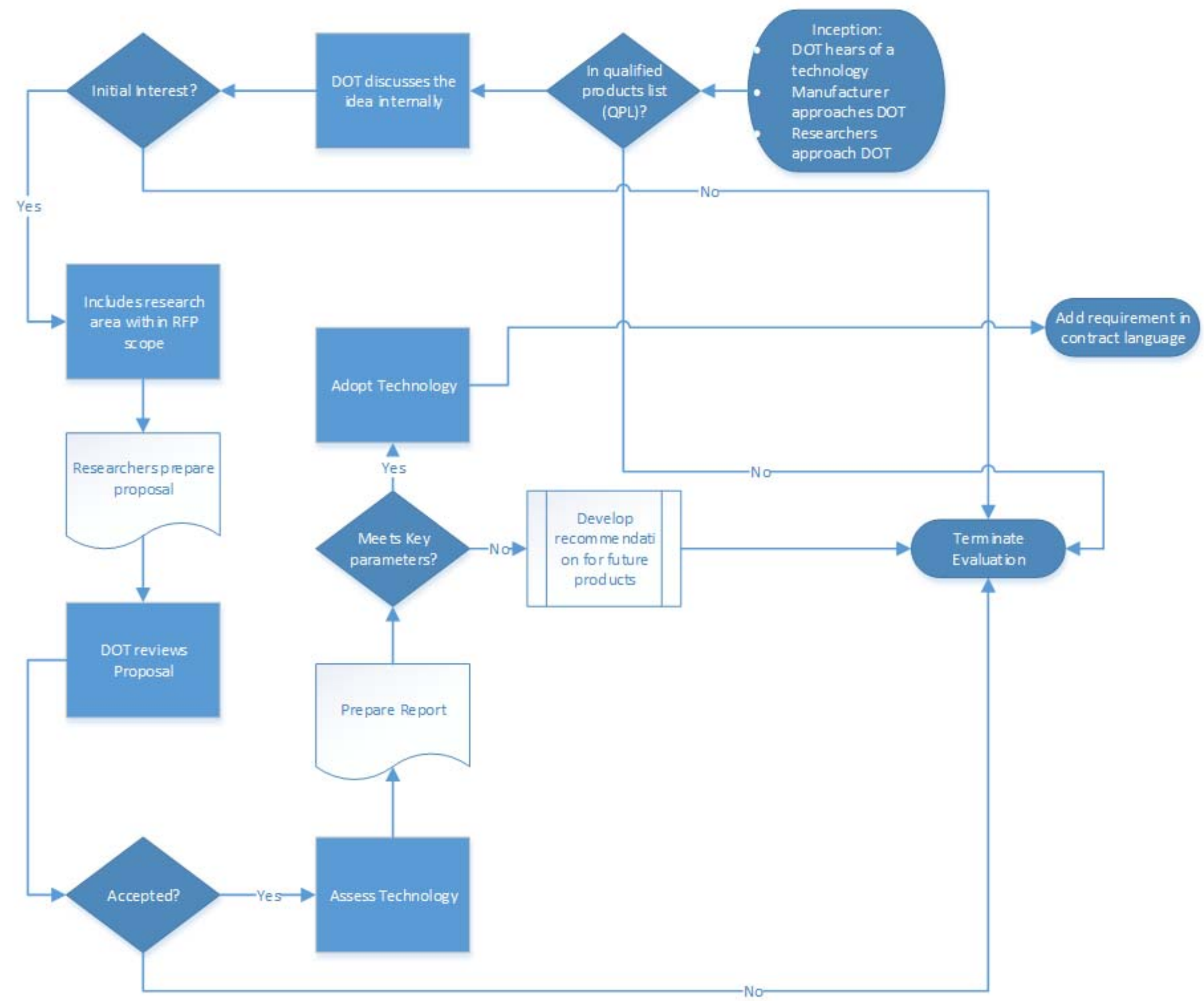


**Figure 5: DOT Decision Map for Work Zone Safety Technology Adoption**

It is important to note that although DOTs prescribe the use of certain safety technologies as part of a contract requirement, contractors could choose to utilize additional safety technologies in construction work zones. Currently, information on the process utilized by contractors to arrive at a congruent decision for adopting safety technology is nonexistent. Therefore, the researchers proposed and validated a framework that describes the process of adopting a safety technology. Also, this framework could be implemented within the "Assess Technology" stage of the DOT technology acceptance process.

### *Safety Technology Adoption Factors*

An integrative review of literature indicates that technology adoption can be predicted by assessing several factors distributed into four primary categories: individual, organizational, technological, and environmental. A theoretical framework describing the process leading to technology adoption can be found in Figure 6. Project managers from eight highway contracting organizations were interviewed to validate the accuracy of the proposed adoption process. These companies were primarily located in the Pacific Northwest with annual revenue ranging between $10 million and $2 billion.

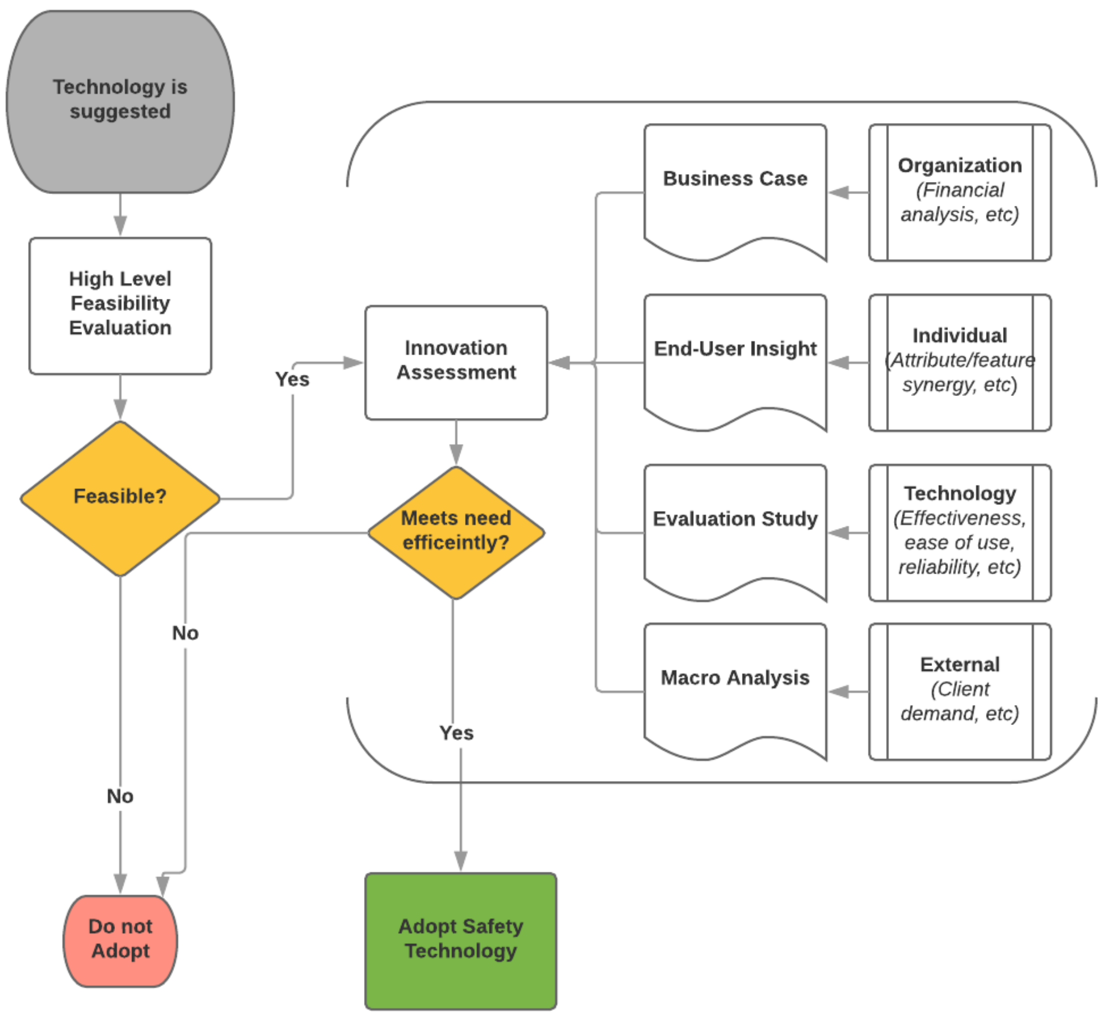


**Figure 6. Safety Technology Adoption Process**

One primary deficiency in extant literature associated with work zone safety is the lack of some consensus on the primary phases for conducting an evaluation study. An evaluation study is a key component in the technology category of the safety technology adoption process. In the next section, the researchers summarize the primary steps required to conduct an effective WZST evaluation study. The evaluation protocol was developed as part of a study conducted by Gambatese et al. (2017).

### *WZST Evaluation Protocol*

Developing a testing protocol, grounded in scientific rigor, plays a pivotal role in validating the findings of an evaluation-based study. According to Fyrie (2016), it is essential to develop a testing protocol for WZSTs to improve perception of usefulness which could impact user intention to adopt technology alongside encouraging the production of additional WZSTs. In order to develop a rigorous process, the researchers relied on Strategic Highway Research Program (SHRP) reports and past work zone technology evaluation reports (Agent and Hibbs 1996; Brown et al. 2015; Marks et al. 2017; Marks and Teizer 2013; Novosel 2014; Park et al. 2017; Teizer et al. 2010; Zhang and Gambatese 2017). To successfully evaluate a WZST, the steps depicted in Figure 7 are recommended and described in detail below.

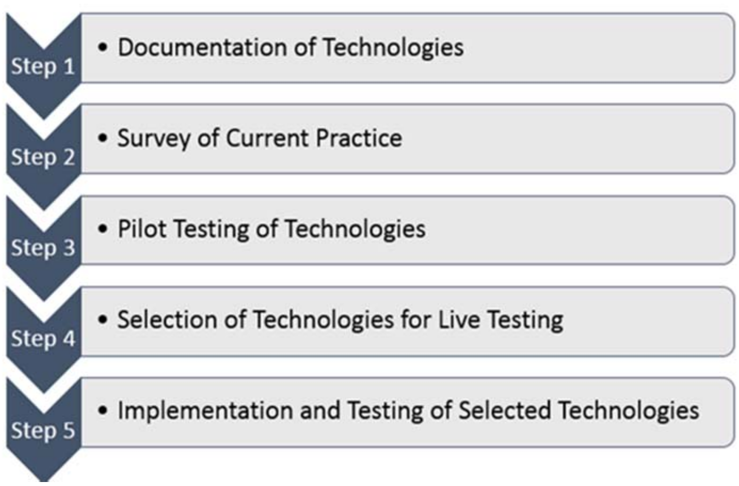


**Figure 7: WZST Evaluation Protocol**

Step 1: Documentation of Technologies

It is imperative to aggregate and review literature on currently available technologies that have high potential for preventing injuries in highway work zones. This step can be achieved through a comprehensive search of archival publications using Internet search engines. The output of this search and documentation should include technical specifications of the WZST, associated benefits of using the WZST, limitations to its use, and summaries of findings from prior research on the technology.

Step 2: Survey of Current Practice

Step 2 involves conducting a survey of highway construction and maintenance key stakeholders including state departments of transportation (DOTs), construction and traffic control contractors, equipment vendors, etc. The objective of the survey is to document current and recommended practices, barriers, enablers, and impacts associated with the WZST. Findings from Step 2 result in the identification of the status quo of the construction industry and its current best practice in terms of preventing accidents that could be prevented by implementing the WZST.

Step 3: Pilot Testing of Technologies

Based on the results of Steps 1 and 2, a sample of feasible technologies should be selected for pilot testing. Selection should consider technology availability, cost, ease of use, potential for improving safety, and potential for incorporating the technology in typical transportation control plans. Pilot testing of the selected technologies should be conducted under controlled, off-roadway conditions. Each selected technology should be assessed to capture its capabilities, and record how it is implemented. The results of the pilot testing provide vital information on feasibility of use, capabilities, and limitations related to each technology under investigation.

Step 4: Selection of Technologies for Live Testing

Following completion of the pilot testing and analysis of the results, Step 4 involves conducting focus group sessions with key stakeholders such as DOT personnel and construction contractors to identify and select specific technologies to implement and test in an active work zone. Feedback on each of the technologies should be solicited from each targeted group. Those technologies that are deemed promising by the focus group participants should be selected for further evaluation. In addition, potential construction and/or maintenance projects on which to conduct live testing of the technologies should be discussed with the participating DOT personnel and contractors and selected for Step 5.

Step 5: Implementation and Evaluation of Selected Technologies

Step 5 involves implementing the selected technologies on each selected case study project. Depending on the case study projects selected, each technology should be applied under different work zone conditions (e.g., short-term and long-term, daytime and nighttime, and stationary and mobile). Each selected technology should be implemented during actual work operations typically experienced on projects. The testing protocol should address a variety of criteria such as: ease of implementation and use, ability to detect potential hazard, ability to warn of impending hazard, sensitivity to false alarms, and impact on risk to worker safety, and implementation cost. Upon completion of testing, feedback on each technology should be collected directly from the construction and maintenance workers involved in each case study project.

Next, the researchers propose a basic theoretical framework – ITAM - for capturing information that influences the acceptance and utilization of a WZST (WZIAT as case study) by end users.

### *Intrusion Alert Technology Acceptance Model (ITAM) Structure*

Consumer marketing research has benefited greatly from applying predictive (forecasting) and assessment models that draw from understanding key factors that influence intention to accept a product. The present study combines the predictive strength of two well-founded technology acceptance and behavioral theories as a means to understand factors that influence the adoption of a WZST. Although designed mainly using constructs (parameters) associated with WZIAT, the proposed model can be applied to WZST and other technology adoption situations with similar characteristics. The two models to be combined are Technology Acceptance Model (TAM) and Theory of Planned Behavior (TPB) (Mathieson 1991; Venkatech and Davis 1996; Mathieson et al. 2001; Chuttur 2009). Figure

8 depicts the simplified intrusion alert technology acceptance model (ITAM) used in this study.

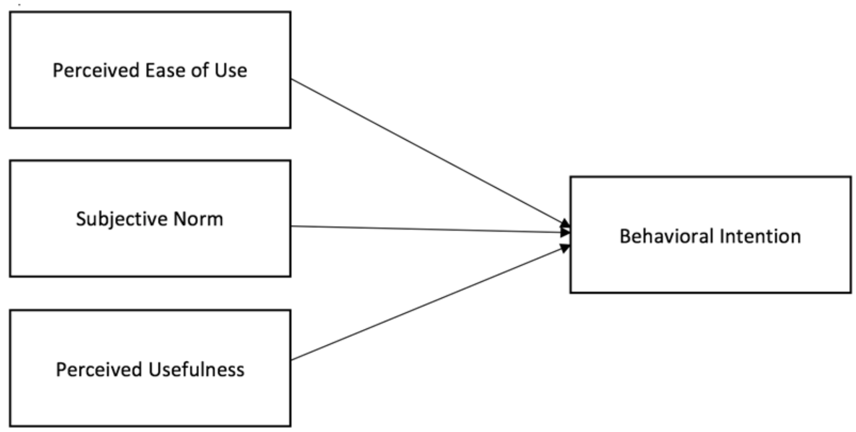


**Figure 8: Intrusion Alert Technology Acceptance Model**

The constructs above can be defined as:

- Perceived Ease of Use (PEU): belief that using a technology will require little effort
- Subjective Norm (SN): an individual's perception regarding a given action which is significantly influenced by the judgement of significant others
- Perceived Usefulness (PU): belief that using a technology would improve job performance
- Behavioral Intention (BI): an indication of a person's intention to perform a given task

BI was chosen instead of actual behavior (observable response such as accepting to use a technology) since the use of technologies such as WZIAT is not widespread. In addition, past research indicates that in most cases, behavioral intention, is a good predictor of actual use (Venkatesh et al. 2002).

The researchers kept the model simple given the exploratory nature of the present study. Future studies should consider including other TPB constructs such as attitude and perceived behavioral control.

### Task 3: Collect and analyze data from highway construction stakeholders

The researchers conducted an online survey in order to answer research questions V, VI, and VII. Following review of the survey instrument and protocol by the OSU Institutional Review Board (see copy of survey questionnaire in the Appendix), the researchers pre-tested the reliability and consistency of the survey questions using data received from civil and construction engineering students at OSU. Before collecting student feedback, a presentation which included videos and pictures of work zone intrusion accidents, work zone safety technologies, and results from a WZIAT evaluation study was facilitated and conducted by the researchers for the students. The presentation was conducted to ensure participating students had sufficient information to provide useful feedback on factors that could influence the adoption of WZIAT. A total of 145 responses were received from participating students in two different courses of which 135 responses were analyzed (10 responses were incomplete). Reliability tests including Kaiser-Myer-Olkin, Cronbach alpha, and Barlett test of sphericity were conducted to ensure that the research tools captured reliable information.

Following evaluation of the survey instrument, the survey questionnaire was distributed to the targeted highway construction stakeholders. Survey responses were collected from 181 individuals (316, including students) within the target population. Specifically, owner agencies, including DOTs and research institutions, accounted for 38% (69) of the received responses while general contractors, work zone safety consultants, and work zone technology manufacturers and vendors accounted for 38% (53), 11% (20), and 21.5% (39) of the responses, respectively. Furthermore, 64 respondents (35%) self-identified as project managers while 37 traffic engineers (20% of respondents) responded. Responses to the question “Are you familiar with work zone intrusion alert technology” indicate that most of the participants are familiar with WZIAT (80% of the 141 responses received to the question, approximately 62% of all respondents).

*WZIAT feature/attribute importance (combined and by work category)*

For some questions, the respondents were asked to provide their opinion about WZIAT using a Likert-type scale (e.g., 1 = not important, 5 = very important). When asked "How important are the following attributes to your decision to adopt WZIAT," participants indicated that worker comprehension of warning signal (mean response = 4.44) and adequate coverage distance (mean response = 4.25) are considered the most influential attributes that impact the decision to use a WZIAT. The results are summarized in Table 3. Ease of storage is considered the least important attribute (mean = 2.94). A comprehensive table of the results can be found in the Appendix.

**Table 3: WZIAT Feature/Attribute Importance to Adoption Decision**

| | **Mean Response regarding Importance of Feature/Attribute (1 = not important, 5 = very important)** | | | |
|---|---|---|---|---|
| **WZIAT Features/Attributes** | **Contractor (n=53)** | **DOT (n=69)** | **Manuf. & Vendors (n=39)** | **Total (n=316)** |
| Worker comprehension of warning signal | 4.6 | 4.67 | 4.3 | 4.44 |
| Adequate coverage distance | 4.51 | 4.36 | 4.22 | 4.25 |
| Driver adequately comprehends visual and audio warning | 4.25 | 4.39 | 3.62 | 4.21 |
| Impact of warning alert on driver | 4.17 | 4.41 | 3.78 | 4.18 |
| Few or no false alarms | 4.38 | 4.33 | 4.03 | 4.17 |
| Limits worker exposure | 4.51 | 4.48 | 4.08 | 4.15 |
| Multiple warning alert sources | 4.08 | 4.23 | 4.16 | 4.08 |
| Reusable | 4.19 | 3.79 | 4.10 | 4.04 |

Manuf. = technology manufacturer

### *Difference in mean rating between groups*

It is essential to conduct a statistical analysis to verify the presence of an alignment between the subgroups' - especially contractors and manufacturers – perceptions of important WZIAT attributes. This verification can be achieved by either a parametric or non-parametric independent sample mean test (t-test). First, the researchers assessed the data by work group to guide the application of parametric or non-parametric testing. A test for data normality was not conducted given that the sample size for each group was at least 30 (Ghasemi and Zahediasl 2012). Levene's Test of Equality of variance was conducted to determine if the assumption of homogeneity of variance was violated. The test returned a mixed result with six out of the 21 factors violating the equal variance assumption. Taking a conservative approach, the researcher elected to perform a non-parametric two-sample test – the Mann-Whitney U Test - to reduce the Type I error rate. Table 4 summarizes the results from the Mann-Whitney U Test between responses received from manufacturers and other work groups. As seen in Table 4, the level of importance assigned to each WZIAT attribute differed significantly for seven out of 21 attributes when comparing the manufacturers' responses to those received from the DOT employees. This result indicates the possibility of a misalignment between the end-users' and manufacturers' perceptions of the importance of each WZIAT attribute. This result suggests a need for heightened involvement of DOTs and contractors in the development phase of similar technologies. The development of standard tools that help bridge the knowledge gap between manufacturers and end-users should be encouraged.

**Table 4: Non-Parametric test for difference in mean between groups; Mann-Whitney U Test**

| **WZIAT Adoption factors** | **Contractor vs. Manufacturer** | | **DOT vs. Manufacturer** | | **Contractor vs. DOT** | |
|---|---|---|---|---|---|---|
| | U Statistic | p-value | U Statistic | p-value | U Statistic | p-value |
| Ease of deployment/retrieval | 973.5 | 0.602 | 1292.5 | 0.707 | 1652.5 | 0.317 |
| Easy to move the technology around | 728 | 0.032 | 1271 | 0.596 | 1588.5 | 0.176 |
| User friendliness | 849 | 0.105 | 1052.5 | 0.043 | 1700.5 | 0.45 |
| Little or no impact on traffic flow and control within work zone | 822 | 0.081 | 1332.5 | 0.929 | 1415 | 0.024 |
| Limits worker exposure | 778 | 0.026 | 1039.5 | 0.031 | 1797 | 0.852 |
| Easy to store | 857 | 0.139 | 1104 | 0.107 | 1771 | 0.755 |
| Resistance to environmental and physical impact | 871.5 | 0.467 | 923.5 | 0.023 | 1482.5 | 0.057 |
| Reusable | 978 | 0.629 | 1019.5 | 0.029 | 1328.5 | 0.008 |
| Easy to maintain | 900 | 0.352 | 1185 | 0.53 | 1712.5 | 0.722 |
| Extended battery life | 866.5 | 0.141 | 997.5 | 0.022 | 1586 | 0.221 |
| Cost of labor and equipment | 885.5 | 0.305 | 1167 | 0.385 | 1754 | 0.794 |
| Availability of equipment in the market | 734.5 | 0.047 | 1254 | 0.792 | 1527.5 | 0.123 |
| Cost of replacing parts/maintenance | 956.5 | 0.668 | 1264 | 0.846 | 1755 | 0.796 |
| Impact of warning alert on driver | 936 | 0.697 | 1102.5 | 0.207 | 1605.5 | 0.206 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Worker comprehension of warning signal | 824.5 | 0.142 | 1018 | 0.043 | 1750.5 | 0.621 |
| Multiple warning alert sources | 860 | 0.283 | 1268 | 0.951 | 1591.5 | 0.183 |
| Adequate coverage distance | 874.5 | 0.327 | 1260.5 | 0.907 | 1627 | 0.243 |
| Limited physical impact on vehicle | 729 | 0.033 | 1208.5 | 0.638 | 1604 | 0.222 |
| Driver adequately comprehends visual and audio warning | 725.5 | 0.027 | 869.5 | 0.004 | 1737 | 0.604 |
| Few or no false negative and positive alarms | 804 | 0.114 | 1063.5 | 0.122 | 1799 | 0.866 |
| Less dependence on existing infrastructure | 923.5 | 0.621 | 1218 | 0.683 | 1805 | 0.899 |

### *Potential impact of safety climate*

Given that past research indicates a possible correlation between safety climate and safety behavior (Schwatka and Rosecrance 2016), the researchers explored the potential relationship between safety climate and construction worker decisions to adopt a safety technology. To achieve this objective, the researchers utilized an adapted version of a safety climate maturity assessment tool developed by The Center for Construction Research and Training (CPWR) alongside the "behavioral intention" construct of the ITAM.

The safety climate measuring scale has eight leading indicators: Demonstrating Management Commitment; Aligning and Integrating Safety as a Value; Ensuring Accountability at All Levels; Improving Supervisory Leadership; Empowering and Involving Workers; Improving Communication; Training at All Levels; and Encouraging Owner/Client Involvement (CPWR 2015). To utilize the scale, workers are asked to answer questions (between 3 to 6 questions) within each leading indicator. The questions are designed to illicit responses regarding the company's commitment and attitude towards safety using a scale that ranges from inattentive to exemplary (see https://www.cpwr.com/whats-new/new-safety-climate-assessment-s-cat-website for more information on the safety climate measuring scale). Due to the length of the safety climate scale (36 questions requiring a decent amount of reading), the researchers reduced the number of questions for each leading indicator to two (16 in total). The reduction was achieved through evaluating the statistical analysis conducted by the developers of the safety climate scale – selecting the items in each category with the highest mean score and the least variance.

A total of 53 contractors completed the survey substantially. However, only a total of 45 of the responding contractors (85%) provided sufficient information for exploring the connection between safety climate and adoption decision.

To explore the potential link between safety climate and technology adoption, the researchers separated the respondents into two groups – "exemplary" and "below exemplary" – using the aggregate mean value of each leading indicator. That is, the responses received from each survey participant were summed and then divided by 16 (the total number of questions across the eight leading indicators). The researchers elected to set a cumulative mean threshold of 4.0 and above as "exemplary safety climate" in line with the design of the safety climate measuring tool. A mean value below 4.0 was considered not exemplary. Twenty-five of the 45 responding contractors (56%) self-reported a cumulative mean average greater than 4.0. Next, linear regression was chosen to investigate the level of impact safety climate could have on the "behavioral intention" construct. To conduct the analysis, the safety climate rating (SCR) mean value for the two groups (exemplary and not exemplary) were chosen as independent variables while the mean value of "behavioral intention" (BI) - which is part of the ITAM construct - was selected as the dependent variable. Prior to conducting the linear regression, the researchers checked to verify if any assumption was violated. Although the sample size requirement was met (at least 20 cases per independent variable), the researchers observed that the data was not linear and showed evidence of heteroscedasticity. Given the concerns identified within the data, the researchers elected to conduct a nonparametric analysis focusing on directionality. Spearman correlation was executed to investigate the directional relationship between SRC and BI. Although not statistically significant, the results, highlighted in Table 5, indicate that SCR for the exemplary group has a positive correlation with BI ($\gamma = 0.374$). Table 6 shows the relationship between SCR and BI for the "below exemplary" group was less than that of the exemplary group ($\gamma = 0.021$).

**Table 5. Correlation between Behavioral Intention (BI) and Safety Climate Rating (SCR) of "Exemplary" Group**

| Spearman's rho | | SCR | BI |
|---|---|---|---|
| SCR | Correlation Coefficient | 1.000 | 0.374 |
| | Sig. (1-tailed) | . | 0.052 |
| | N | 25 | 25 |
| BI | Correlation Coefficient | 0.374 | 1.000 |
| | Sig. (1-tailed) | 0.052 | . |
| | N | 25 | 25 |

**Table 6. Correlation between Behavioral Intention and Safety Climate Rating (SCR) of "Below Exemplary" Group**

| Spearman's rho | | SCR | BI |
|---|---|---|---|
| SCR | Correlation Coefficient | 1.000 | 0.021 |
| | Sig. (1-tailed) | . | 0.461 |
| | N | 20 | 20 |
| BI | Correlation Coefficient | 0.021 | 1.000 |
| | Sig. (1-tailed) | 0.461 | . |
| | N | 20 | 20 |

**Task 4: Conduct financial analysis for WZIAT**

One possible reason for the relatively low number of commercially available intrusion alarm technologies is the lack of a cost-benefit analysis (Fayrie 2016). Furthermore, as intrusion alarm technologies require some investment, consumers (DOTs and contractors) need an empirical framework to determine the financial implication of the intervention. To develop a robust framework that provides parameters that can be used to judge if the investment in the intrusion alarm is worthwhile, the researchers relied on the frameworks described by AASHTO (2010), Theiss et al. (2014), Arico and Ravani (2008), and Sun et al. (2011). Given that the implementation of WZIAT requires a two-phase adoption process (adoption by state department of transportation and contractor), it is important that financial metrics specific to the end-users are considered. Hence, a framework for ROI (Contractor) and BCA (DOT) was developed. Three WZIATs – AWARE, Intellicone, and WAS – were evaluated as part of the financial analysis.

### *Cost of Implementing Work Zone Intrusion Alert Technologies*

According to Boardman et al. (2001), nine primary steps are required in other to conduct a basic financial analysis for government interventions, regulations, policies, programs, etc. The steps are:

I. Specify the set of alternative projects
II. Decide whose benefits and costs count
III. Catalogue the impacts and select measurement indicators, or units
IV. Predict the impacts quantitatively over the life period of the project
V. Monetize (add dollar values to) all impacts
VI. Discount benefits and costs to obtain present values
VII. Compute the net present value of each alternative
VIII. Perform sensitivity analysis
IX. Make recommendation based on findings

Given the scope of the current study, the researchers focused on the steps required to develop a financial implication analysis framework for each WZIAT (Steps III, IV, V, VI, and VII).

Steps III to V involve the identification, collection, and monetization of inputs and outputs (information) required to perform a financial analysis. Tables 7 and 8 capture essential information required to estimate the cost of implementing the technologies. The information presented in Tables 7 and 8 was acquired through interviews with contractors, reviewing literature on WZIATs and other work zone safety technologies, and assessing manufacturer's websites and manuals.

**Table 7. Cost Input Data**

| Cost Item | Work zone Intrusion Alert Technology | | |
|---|---|---|---|
| | AWARE | Intellicone | WAS |
| Capital cost ($/device) | 50,000 | 2,000 | $750 |
| Cost of required accessory/ies ($) | | 35 | |
| Battery cost ($/device) | 20 | 15 | |
| Battery life (weeks) | 32 | 32 | |
| Device Replacement rate (%/year) | 0.125 | 0.125 | 0.125 |
| Strobe Replacement rate (%/year) | | 0.10 | 0.13 |
| Maintenance worker wage rate ($/h ) | 26 | 26 | 26 |
| Maintenance time (hr/week/mile) | 2.1 | 4.2 | 4.2 |
| Wage rate multiplier | 1.5 | 1.5 | 1.5 |
| Disposal cost | 0 | 0 | 0 |
| Cost per day: | | | |
| Maintenance cost ($) | 20.48 | 40.95 | 40.95 |
| Device cost ($) | 78.12 | $3.13 | $1.17 |
| Sensor cost ($) | | $0.05 | |
| Battery cost ($) | 0.16 | 0.12 | |

**Table 8. Cost of using Work Zone Intrusion Alert Technologies in Work Zones**

| Cost Item | Work zone Intrusion Alert Technologies | | |
|---|---|---|---|
| | AWARE | Intellicone | WAS |
| Number of devices per mile | 1 | 1 | 8 |
| Used on one side of roadway | 2 | 2 | 16 |
| Used on both sides of roadway | 1 | 1 | 8 |
| Number of accessories per mile | | | |

| | | | |
|---|---|---|---|
| Used on one side of roadway | | 12 | 5 |
| Used on both sides of roadway | | 24 | 10 |
| Cost per device per day ($/day) | 78.13 | 3.13 | 1.17 |
| Cost per mile per day ($/mile/day) | | 0.17 | - |
| Labor cost per device per day ($/day) | 20.48 | 40.95 | 40.95 |
| Cost per mile per day ($/mile/day) | | | |
| Used on one side of roadway | 98.60 | 46.14 | 50.33 |
| Used on both sides of roadway | 197.20 | 92.28 | 100.65 |
| Cost per mile per year ($/mile/year) | | | |
| Used on one side of roadway | 7,888.00 | 3,691.00 | 4,026.00 |
| Used on both sides of roadway | 15,776.00 | 7,382.00 | 8,052.00 |

Information in Table 7 indicates that AWARE, Intellicone, and WAS cost (operation and capital cost) $98.60, $46.14, and $50.33 per day, respectively. With the exception of AWARE, operation cost is the primary cost driver, not the capital cost (Intellicone = 88.5% and WAS = 81.5% of total cost). These estimates does not include additional cost for personal safety devices; just the costs of buying and operating the basic technology are included. An eighty-day work year was assumed based on five work-months a year and four work-days a week. The work day was estimated based on the duration of a typical paving season in the Pacific Northwest. The number of annual work days will vary depending on the location. The cost per day calculation included a straight-line capital cost deprecation of each technology. A shelf life of eight years was assumed based on past research (Theiss et al. 2014). Table 8 summarizes the cost of implementing WZIAT on projects using cost per mile per year ($/mile/year). The analysis shown in Table 8 includes calculation for one and both sides of a roadway given that construction could happen simultaneously on both sides of the roadway (both directions of traffic). The total cost for applying the AWARE, Intellicone, and WAS in a work zone is $15, 776, $7,382, and $8,052 per mile per year, respectively. The factors used to arrive at the values in Table 8 are included in the Appendix.

### *Injury Cost Model*

The following steps were undertaken in order to estimate the cost associated with work zone accidents:

I. Estimate total number of work zone intrusion accidents
II. Estimate injury severity of work zone intrusion accidents (using MAIS)
III. Use comprehensive cost method to assign cost to injury severity
IV. Use Value of a Statistical Life (VSL) to estimate fraction for each injury category
V. Determine work zone intrusion-induced accident cost
VI. Use work zone required length and type of activity to separate out activities that cannot implement WZIAT
VII. Develop table that shows total cost and averted cost

The number of work zone intrusion accidents was estimated using information from the California Department of Transportation (Caltrans) and Oregon Department of Transportation (ODOT). The severity level of work zone accidents was estimated using the Maximum Abbreviated Injury Scale (MAIS) (AAAM 2015). The coefficient for each severity level was generated using the Value of a Statistical Life (VSL). The VSL is the additional cost that individuals are willing to bear for improving safety (risk reduction) (Moran 2016). Table 9 highlights the severity levels and cost associated which each level (Moran 2016).

**Table 9. Cost Associated with Different Levels of Accident Severity**

| MAIS Level | Severity | VSL (2016) Fraction | Cost (million $) |
|---|---|---|---|
| MAIS 1 | Minor | 0.003 | 0.029 |
| MAIS 2 | Moderate | 0.047 | 0.45 |
| MAIS 3 | Serious | 0.105 | 1.01 |
| MAIS 4 | Severe | 0.266 | 2.55 |
| MAIS 5 | Critical | 0.593 | 5.69 |
| MAIS 6 | Fatal | 1.000 | 9.6 |

Intrusion crash data from ODOT indicates that 165 intrusion-induced accidents occurred between 2011 and 2015, an average of 33 work zone intrusion accidents a year. According to Wong (2010), 308 work zone intrusion accidents were reported in California between 1998 and 2007, averaging 31 work zone accidents a year. In addition, Wong (2010) reported that accident distribution when classified by work zone duration varied; mobile operations accounted for 49% of the accidents, short duration operations accounted for 9%, and short-term stationary operations contributed 29% of work zone accidents. Although not current data, the researchers elected to use the data from Caltrans (Wong et al. 2010) due to the segmentation of the data into useful severity levels. Since the average crash rates are similar, the researchers assumed that the trend is applicable to 2017 as well.

The outcomes of a work zone intrusion led to a minor injury 91% of the time. A moderate and serious injury occurred 7% and 0.0034% of the time, respectively. On average, a fatality occurred approximately 2% of the time when an accident occurred.

In agreement with a previous study (Gambatese et al. 2017), some contractors were of the opinion that WZIAT should not be used on mobile projects given the inherent need to move frequently. However, some DOT personnel indicated the possibility of using WZIAT in mobile operations to improve worker safety. Therefore, the researchers decided to include mobile operation-related accidents in the cost analysis for the BCA but not for the ROI.

***Benefit Cost Analysis***

Table 10 lists the injury severity, injury cost, total costs, and the averted cost. The Injury Severity and Injury Cost are extracted from Table 9 while total cost is a multiple of the number of workers injured within each injury severity category and injury cost. For instance, the Total Cost of Injury Severity 1 is calculated by multiplying the injury cost (0.029) with the number of workers with a minor injury (91% of 308 or 281). The averted cost represents potential cost associated with avoiding an injury or fatality within the work durations using a countermeasure such as WZIAT.

**Table 10. Comparison of Work Zone Injury Cost (total) to Potential Averted Cost - BCA**

| Injury Severity (MAIS) | Injury Cost (million $) | Total Cost (million $) | Averted Costs (million $) |
|---|---|---|---|
| 1 | 0.029 | 8.128 | 8.128 |
| 2 | 0.45 | 9.702 | 9.702 |
| 3 | 1.01 | 1.041 | 1.041 |
| 4 | 2.55 | 0 | 0 |
| 5 | 5.69 | 0 | 0 |
| 6 | 9.6 | 59.14 | 59.14 |
| Total | | 78.01 | 78.01 |
| Expected Yearly Average | | 7.801 | 7.801 |

The estimated averted cost is optimistic since the underlying assumption is that implementation of WZIAT would prevent all injuries and fatalities. Due to insufficient data, it was impossible to estimate the actual fraction of preventable work zone intrusion-induced injuries and fatalities when WZIAT is applied. Therefore, applying a reduction factor would be prudent in order to not over-estimate the potential of the technologies. Table 11 highlights the averted cost when applying reduction factors ranging between 10% and 90%.

**Table 11: Application of Conservative Factors (BCA)**

| Injury Severity (MAIS) | Averted Costs (million $) | Fraction of Preventable Injuries and Fatalities (million $) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% |
| 1 | 8.128 | 0.81 | 1.63 | 2.44 | 3.25 | 4.06 | 4.88 | 5.69 | 6.50 | 7.32 |
| 2 | 9.702 | 0.97 | 1.94 | 2.91 | 3.88 | 4.85 | 5.82 | 6.79 | 7.76 | 8.73 |
| 3 | 1.041 | 0.10 | 0.21 | 0.31 | 0.42 | 0.52 | 0.625 | 0.73 | 0.83 | 0.94 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 59.14 | 5.91 | 11.81 | 17.74 | 23.66 | 29.57 | 35.48 | 41.40 | 47.31 | 53.22 |
| Total | 78.01 | 7.80 | 15.60 | 23.40 | 31.20 | 39.01 | 46.81 | 54.60 | 62.41 | 70.20 |
| Expected Yearly Average | 7.801 | 0.78 | 1.560 | 2.34 | 3.12 | 3.90 | 4.68 | 5.46 | 6.24 | 7.02 |

Results from the data analysis indicate that WZIAT technology is worthwhile dependent on a technology's potential to prevent between 12.6% and 34% of intrusion-induced worker accidents (AWARE = 34%, Intellicone = 16.1%, and WAS = 17.6%). These percentages are the injury and fatality cost equivalent of the total cost of purchasing and operating WZIATs.

***Return on Investment***

The potential cost of injuries and fatalities associated with work zone intrusion and the monetary value of the injuries and fatalities that could be saved by implementing WZIAT are presented in Table 11. Unlike Averted Cost values in Table 10, Averted Cost in Table 12 suggest that it is not feasible to accrue all the potential benefits (cost savings) associated with implementing a safety countermeasure. Although the total cost associated with work zone accidents is $7.8 million yearly, WZIAT has the potential to impact only approximately 51% of the associated cost. This restricted extent of impact is because the contractors interviewed indicated that they are not willing to implement WZIAT in mobile operations – which account for approximately 49% of injuries and fatalities. The researchers multiplied the total number of accident (308) by 51% to determine the potential averted cost. It is important to note that by applying 49%, the researchers assumed a linear relationship between severity and frequency of injury – that is, injuries reduced across the severity levels equally - which is not always the case.

**Table 12. Comparison of all Work Zone Injury Costs (total) to Potential Averted Cost - ROI**

| Injury Severity (MAIS) | Injury Cost (million $) | Total Cost (million $) | Averted Costs (million $) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 1 | 0.029 | 8.128 | 4.145 |
| 2 | 0.45 | 9.702 | 4.948 |
| 3 | 1.01 | 1.041 | 0.531 |
| 4 | 2.55 | 0 | 0 |
| 5 | 5.69 | 0 | 0 |
| 6 | 9.6 | 59.14 | 30.159 |
| Total | | 78.01 | 39.784 |
| Expected Yearly Average | | 7.801 | 3.978 |

In addition, the researchers applied conservative factors similar to those applied in Table 11 to account for the injuries and fatalities within the 51% non-mobile activities. Table 13 shows that a minimum averted cost of $398,000 per year is obtainable if WZIAT prevents at least 10% of work zone intrusion injuries and fatalities.

**Table 13: Application of Conservative Factors (ROI)**

| Injury Severity (MAIS) | Averted Costs (million $) | Fraction of Preventable Injuries and Fatalities (million $) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% |
| 1 | 4.15 | 0.42 | 0.83 | 1.24 | 1.66 | 2.07 | 2.487 | 2.90 | 3.32 | 3.73 |
| 2 | 4.95 | 0.5 | 0.99 | 1.49 | 1.98 | 2.47 | 2.969 | 3.46 | 3.96 | 4.45 |
| 3 | 0.53 | 0.05 | 0.11 | 0.16 | 0.21 | 0.27 | 0.319 | 0.37 | 0.42 | 0.48 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 30.16 | 3.02 | 6.03 | 9.05 | 12.06 | 15.08 | 18.10 | 21.1 | 24.13 | 27.14 |
| Total | 39.79 | 3.98 | 7.96 | 11.9 | 15.91 | 19.89 | 23.87 | 27.85 | 31.83 | 35.81 |
| Expected Yearly Average | 3.978 | 0.40 | 0.8 | 1.19 | 1.59 | 1.99 | 2.39 | 2.78 | 3.18 | 3.58 |

Ideally, the injury cost model for calculating the ROI should be based on each company's safety record, that is, information on worker fatality, lost time injury, and injury without lost time. This information was not provided by the contractors interviewed as part of this study. Therefore, the researchers utilized the comprehensive Caltrans accident data. To maintain unit consistency, contractors interviewed were asked for the approximate amount of miles paved every year. The average response from three contractors was approximately 15 miles per year.  Based on the data analysis, WZIAT would be useful to contractors if the technologies prevent 2% -3% of injuries and fatalities caused by intruding vehicles.

Although the ROI could have a significant impact on the adoption of a WZIAT, if a technology is part of a state's stipulated traffic control plan, the contractor is required to use the technology regardless of ROI.

**Task 5: Evaluate proposed models and protocols**

To assess the factors that influence a worker's intention to adopt WZIAT, a range of 2 - 4 variables were used to measure each construct (perceived ease of use, social norm, etc.). The variables were selected from past literature and adapted to fit the research objective. Utilizing variables from previous studies ensured that face and internal validity were maintained. A path analysis – a subset of structural equation modeling (SEM) - using AMOS 25 Graphics (AMOS 25.0 2017) was conducted to analyze the correlations between each construct and a worker's intention to adopt WZIAT. To conduct SEM, a sample to construct variable ratio of at least 10:1 is required. That is, for every variable tested, at least 10 cases or respondents are required. In total, 142 respondents' (contractor = 53, DOT = 69, consultants = 20) provided feedback used for this analysis leading to a 14:1 ratio (10 variables). First, a reliability test was conducted to verify data consistency. Results from the Cronbach alpha test showed that the survey was generally reliable (minimum $\alpha = 0.65$). Next, four primary hypotheses were proposed based on past research and the researcher's experience:

- H1 = Perceived ease of use (PEU) of WZIAT will positively affect behavioral intention (BI) to adopt WZIAT
- H2 = Perceived usefulness (PU) of WZIAT will positively affect behavioral intention to adopt WZIAT adoption intention
- H3 = Social norm (SN) will positively affect behavioral intention to adopt WZIAT
- H4 = Perceived ease of use of WZIAT will positively affect perceived usefulness

As seen in Figure 9, all four primary hypotheses were supported. The path analysis results suggest that increased PU of WZIAT increases with an end-user's BI to accept WZIAT ($\gamma$ = 0.41). In this case, PU comprises factors such as the technology's ability to provide adequate safety coverage, adequate alerts, etc. PEU - which represents the level of ease associated with implementing the technology - also showed a positive relationship with BI to accept a technology ($\gamma$ = 0.23). This relationship implies that workers' BI to accept WZIAT is associated with increased perceived ease of use. Social norm also showed a positive correlation with behavioral intention to adopt WZIAT ($\gamma$=0.34). The PEU of WZIAT also correlated positively with PU, suggesting that PEU plays a significant role on how workers perceive the usefulness of WZIAT ($\gamma$=0.45). This result is consistent with the relatively high rating of factors associated with ease (e.g., easy to maintain, ease of deployment/retrieval, and easy to move around) seen in Appendix. Together, PEU, PU, and SN explain 54% of the variance in an individual's BI to accept WZIAT. PEU explains 21% of the variance in PU.

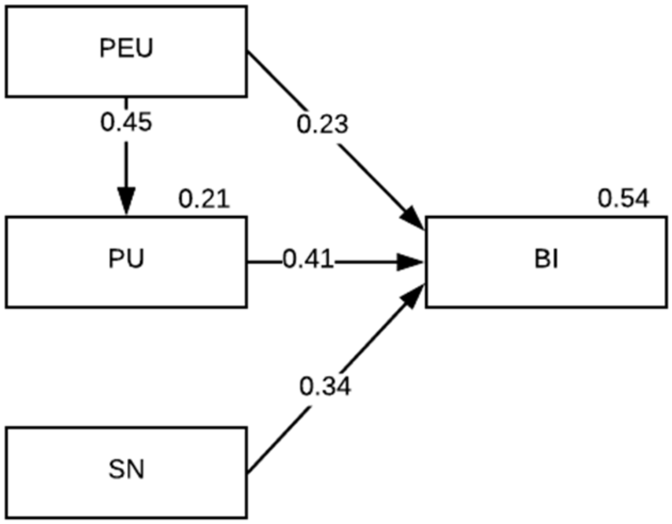


**Figure 9: Results of Hypothesis Testing**

The implications of the results are as follows:

- Workers must perceive that using WZIAT is not complicated and will not require extensive learning. WZIATs that are easy to install, retrieve, move, and maintain will likely be accepted before WZIATs that are more complex.
- Given that the primary cost driver of using WZIAT on projects is the labor cost associated with moving, retrieve, and maintaining WZIATs, technologies that are easier to use will significantly improve the PEU and increase the BCA thereby increasing the odds of adoption.
- Supervisors and managers play an important role in driving the acceptance of WZIAT (through SN).
- In order to achieve high behavioral intention to accept WZIAT, it is essential the PEU, PU, and SN are high.

***Develop and test ABM model***

Agent-Based Modeling (ABM) is a heterogeneous simulation method used to predict a group level output by aggregating individual agent reactions and interactions (Hamilton et al. 2009; Rand and Rust 2011). Given its bottom-up approach to predicting the outcome, it is considered a good theoretical tool for forecasting and understanding the impact of individual differences on group level outcomes in social science and marketing research.

One objective of the current study was to investigate the possibility of combining a diffusion simulation method - agent-based model in this case - and information obtained from a technology acceptance model. Responses received from the interviews and surveys were used to create constraints and boundaries for the simulations.

To develop the ABM, it is essential to define the phases in adoption. According to Innovation Diffusion theory, a population can be divided into three group when assessing technology adoption within a population: non-adopters, potential adopters, and adopters (Lee et al., 2011). Individuals who do not consider a new technology are termed non-adopters while potential adopters are individuals who consider the adoption of a new technology. The present study follows a similar premise. Technology adoption could occur at an organizational level and/or individual level. Technology adoption in the construction industry is considered most effective when it originates and exemplifies a top-down dynamic (top management initiates the adoption procedure) (Mitropoulos and Tatum 2000). In contrast, successful technology acceptance, that is, the actual use of the technology, is an emergent phenomenon – similar to a bottom-up approach.

For the present agent-based model, three primary constructs – SN, PU, and PEU – determine the intention of an end-user to move from a non-adopter to a potential adopter. This factors could be extended to include organizational demographic information such as company size (employees and revenue), company type (sub-contractor vs. general contractor), and individual demographic information such as age, experience, gender, etc.

A transition from non-adopter to potential adopter is achieved when the potential construct value of an agent is greater than or equal to a user-defined construct threshold. This threshold – the coefficient - indicates a measure of sensitivity. Consistent with findings in the present study, Affordability Theory, and previous studies (Gambatese et al. 2017; Rasoulkhani et al. 2017; Lynne et al. 1995), cost of implementing the technology is computed as the primary factor that influences an agent (and organization) to adopt a work zone safety technology (see Table 14). Affordability in the context of the present study is defined as the value of the technology relative to its cost (ROI and BCA). Figure 10 typifies this relationship between non-adopter, potential adopter, and adopter. The adopted modeling process is similar to those applied in past research (Rasoulkhani et al. 2017).

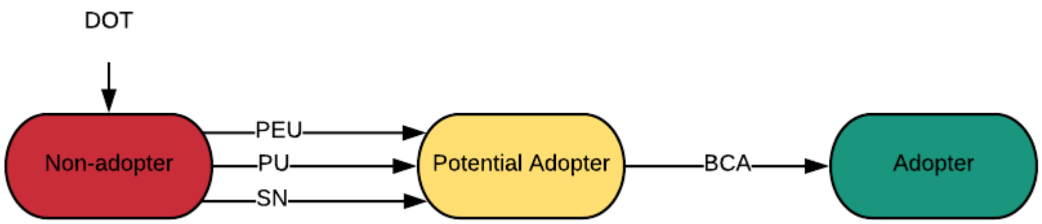


**Figure 10: Simulation theoretical framework**

Tables 14 and 15 list the factors required to develop and operationalize the agent-based model. The coefficients listed in Table 14 are extracted from the structural equation modeling conducted in the previous section while the cost information in Table 15 is extracted from findings from the financial analysis.

**Table 14: Coefficient and value of simulation constructs**

| Construct | Value | Coefficients |
|---|---|---|
| Perceived usefulness | If Yes=1, if No=0 | 0.41 |
| Perceived ease of use | If Yes=1, if No=0 | 0.23 |
| Subjective norm | If Yes=1, if No=0 | 0.34 |

**Table 15: WZIAT Cost Summary**

| Technology | Cost per mile | Benefit cost analysis* | Return on investment* |
|---|---|---|---|
| AWARE | $5,776.00 | 0.58 | 136% |
| Intellicone | $7,382.00 | 1.24 | 106% |
| WAS | $8,052.00 | 1.14 | 98% |

*assuming each technology can prevent 20% of injuries and fatalities

It is important to note that although Table 15 suggests that AWARE has a negative BCA, AWARE would likely prevent more than 20% of accidents and fatalities caused by work zone intrusion given its advanced technology and ease of implementation. Twenty percent was selected in the absence of empirical data and in order to create a range of values for the computational model.

AnyLogic 8.0 was utilized to develop a computational model for simulating the change in worker's behavior. In this model, only one class of agent – DOT level - is incorporated. This class of agent represents the first step in the adoption process (DOT -> construction company -> construction workers). Ideally, the model should reflect multiple classes of agents to mimic the complex nature of technology adoption on highway construction. However, the approach suffices given the exploratory nature of the present study. Future study should model the interactions between agents using more complex constraints and boundaries.

In total, 50 agents, representing each state DOT were utilized in the adoption model. A state DOT would likely adopt a WZIAT if the state DOT believes the WZIAT is useful, easy to use, or is used by other states. To determine the threshold that triggers a change of state (from non-adopter -> potential adopter -> adopter), the regression coefficients from the SEM were utilized. These constructs were parameterized using stochastic computation and used within the simulation as probabilistic factors for determining behavior. The formula below shows the mathematical expression of the model:

$$B_{r1} = w_1 (PU_r) + w_2 (PEU_r) + w_3 (SN_r)$$

$$B_{r2} = w_4 (BCA)$$

Where $B_{r1}$ and $B_{r2}$ refers to the potential adoption and adoption behavior respectively. $W_n$ represents the regression coefficient for each construct. The sum of the values in equation 1 could range from 0 to 1 with numbers below 0.5 considered low and numbers above 0.5 considered high. If the sum of the construct exceeds 0.5, the agent in question moves into the next state (from non-adopter to potential adopter). A probability threshold of 0.5 was selected similar to previous studies (Scalco et al, 2017). The same process applies to transitioning from potential adopter to adopter. BCA was selected as the preferred financial metric since the class of agent in question is the DOT. Given that investments with BCA results above 1 are considered positive investments, the researchers set a transition threshold of 1 and a range of 0.5 to 1.5.

The red area in Figure 11 represents non-adopter while yellow and green represents potential adopters and adopters. The simulation start date is May 2018 and it terminates in January 2025 – approximately 7 years in total. The simulation begins with all 50 state DOTs in a non-adopter state. The number of DOTs in the non-adopters state reduced by about 78% by the end of the simulation in 2025. Within a similar time frame, 19 state DOTs adopted WZIAT.

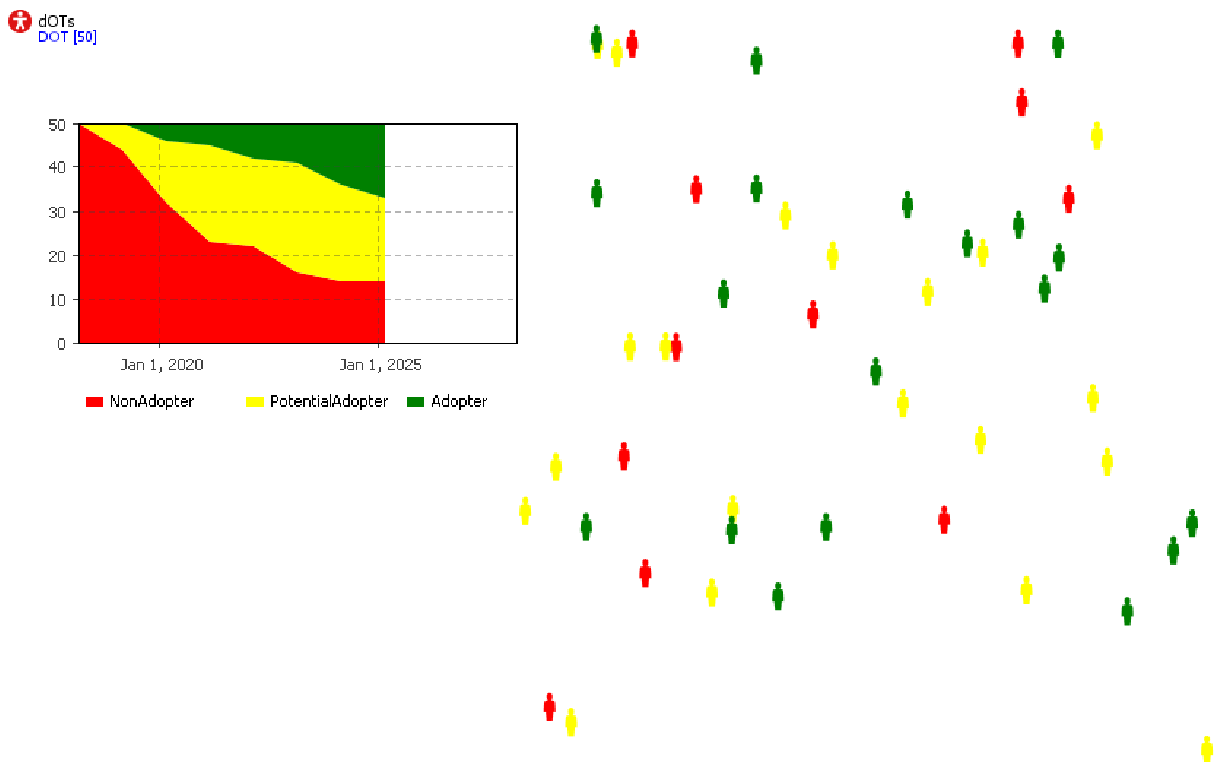


**Figure 11: WZIAT diffusion between 2018 - 2025within State DOTs**

Figure 12 depicts the rate of adoption when the regression coefficient of PU, PEU, and SN of the technologies is increased by 15% (cumulative coefficient). This increase resulted to a higher rate of adoption by year 2025 (approximately 75% of DOTs utilizing WZAIT). The results indicates that more state DOTs will adopt WZIAT if they believe that WZIAT is more useful in term of its effectiveness, durability; and is easier to implement, retrieve, and maintain. Also, results from the model indicates that social influences such could be a key factor for diffusion to occur. For instance, a state DOT would be influenced by the decision of another state DOT within close proximity to adopt WZIAT.

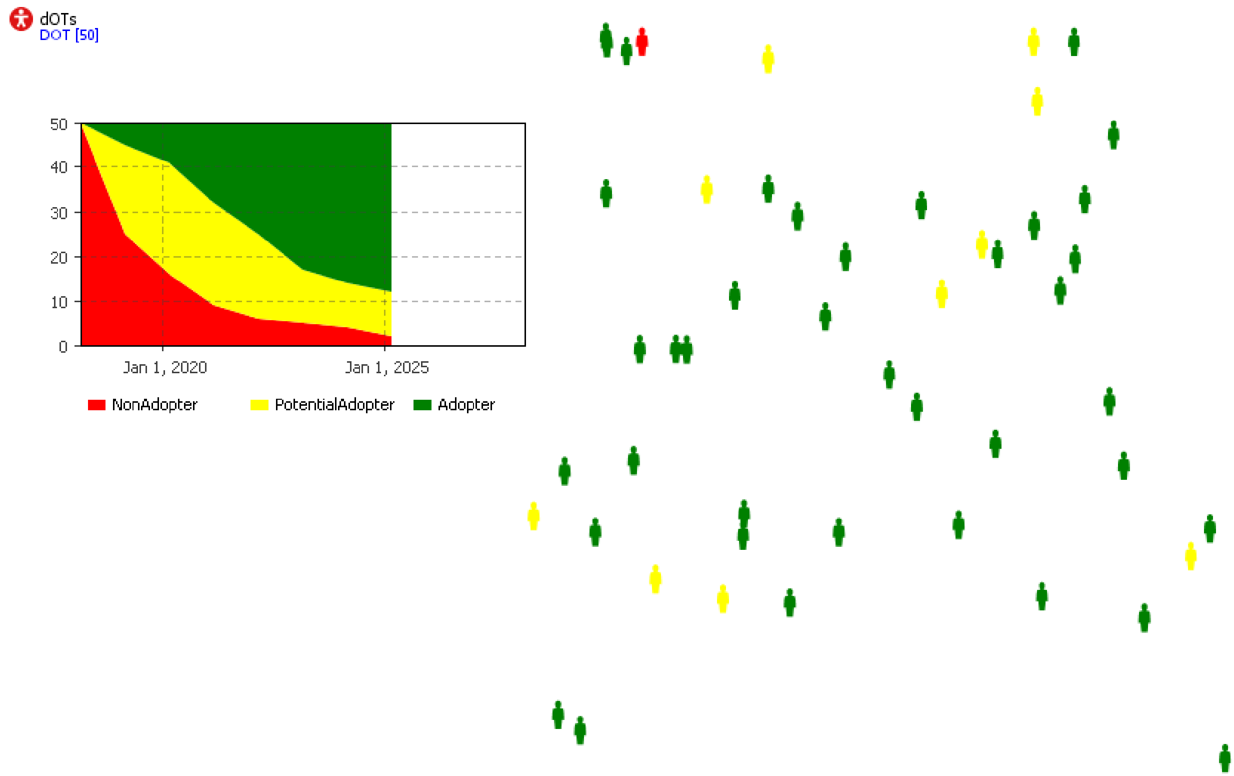


**Figure 12: Increased diffusion of WZIAT.**

# 7. Changes/problems that resulted in deviation from the methods

While executing the study, the researchers encountered difficulties generating responses from work zone safety technology manufacturers and highway construction contractors which impacts the generalizability of the study findings. Although theoretically sound, the development of an acceptance model using ABM requires additional parameters and boundaries to ensure that all potential factors are accounted for. It is important to note that although TPB and TAM were combined to develop an acceptance model for WZIAT, extending the theories to include models such as task-technology fit (TTF) and theory of reasoned action (TRA) could help identify more constructs that have an impact on the acceptance of work zone technologies such as WZIAT. Developing the financial analysis involved making some assumptions for information that were unobtainable. These assumptions were clearly stated and should be considered when generalizing the results of this study.

# 8. List of presentations/publications

Findings from this study will be published in academic journals and presented in conferences, workshops, and/or seminars.

1. Nnaji, C., Gambatese, J., and Eseonu, C. (2017). "Theoretical Framework for Improving Adoption of Safety Technology in Construction Industry." *2018 Construction Research Congress (CRC 2018)*, New Orleans, LA. [Accepted on October 17, 2017]
2. Nnaji, C., Lee, H., and Gambatese, J. (2017). "Can work zone intrusion-induced injuries and fatalities be reduced efficiently?" *Professional Safety*, ASSE [Acceptance, Jan. 20, 2018]
3. Nnaji, C., Gambatese, J., Lee, H.W., and Zhang, F. (2017). "Assessing the Impact of Work Zone Safety Technology: A Systematic Review." *Accident and Analysis and Prevention Journal*. [Submitted to the journal on September 19, 2017]

# 9. Dissemination plan

The researchers have submitted and published sections of this study in academic journals and conference proceedings. The researchers also plan to submit a comprehensive journal paper from the study to a top academic journal.

# 10. Conclusions

Workers within highway work zones are an at-risk population given the inherently risky nature of their jobs. The current study assessed the role technology plays in improving worker safety and provides information that should ease the process of adopting and implementing technology on highway projects.

Current technologies used in work zone safety management play an essential role in improving worker safety through reducing motorist speed, alerting equipment drivers of potential collision with workers, and informing workers of an intruding vehicle. The findings from the present study provide essential information such as the key predictors of safety technology, financial analysis, and primary factors that affect a user's intention to accept a WZIAT to construction practitioners involved in technology adoption decision-making. For instance, the present study illustrates the severe impact that labor cost has on the overall daily cost of utilizing WZIAT. Reducing the time workers are involved in managing a WZIAT vastly reduces the cost associated with implementing WZIAT.

Utilizing this information, stakeholders can arrive at a congruent decision regarding WZIAT adoption that is supported by empirical data and which in turn improves the outcome – in this case, a reduction in injuries and fatalities in highway construction work zones.

# 11. Future Research Opportunities

Provided below are recommendations for future research based on findings from the current study:

- The development of adaptable standard tools that help bridge the knowledge gap between manufacturers and end-users should be encouraged
- There is a need for the development of a robust model for predicting potential adoption of technology
- Monte Carlo simulation should be applied to the financial analysis to help normalize some assumptions
- Work force development training is needed for workers to help improve integration of safety technology within construction operations

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# 13. Appendix

Appendix A: Survey

**Reducing Highway Construction Fatalities through Improved Adoption of Safety Technologies**

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Dear Participant,

We would like to thank you for taking the time to participate in this survey entitled "Reducing Highway Construction Fatalities through Improved Adoption of Safety Technologies."

The purpose of this study is to develop a tool that improves the adoption and diffusion of safety innovations in the construction industry. If you choose to take part in this survey, you will be asked to provide the following information:

- Perception on what factors influences the acceptance of work zone safety technologies·
- Perception on the impact of work zone safety technologies·
- Personal attributes such as title, type of company/organization, years of experience, etc.

The survey is expected to take approximately 15 minutes to complete. Your responses to this survey and personal information provided will be kept confidential, used only for academic purposes related to the study, and will not be distributed to the public. All identifying information connecting respondents to their responses will be removed as part of the data collection process. Publications generated from the research study will not include any information that can be used to identify respondents.

If you have any questions about the survey, please contact the researchers listed below. If you have questions about your rights or welfare as a survey participant, please contact the Oregon State University Institutional Review Board (IRB) Office at 541-737-8008, or by email at IRB@oregonstate.edu.

Research Team:

Dr. Chinweike Eseonu (Principal Investigator), Mechanical, Industrial and Manufacturing Engineering, Oregon State University, 204 Rogers Hall, Corvallis, OR 97331; Cell-phone: 541-737-0024;
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Chukwuma Nnaji, Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331; Cell-phone: (541) 908-0475; E-mail: nnajic@oregonstate.edu

Acknowledgement:

By continuing the survey, I have read the above description of the research. If I had questions or would like additional information, I contacted the researchers and had all of my questions answered to my satisfaction. I agree to voluntarily participate in this research. By answering the survey questions and responding to this survey, I affirm that I have read the above information, agree to participate in the research, and am at least 18 years of age or older.

Survey Questions

**Demographic Information**

Q1 Please select your role

- ❍ Owner Agency (e.g. Oregon DOT, etc.) (1)
- ❍ General Contractor (2)
- ❍ Sub-Contractor (3)
- ❍ Consultant (6)
- ❍ Equipment Manufacturer (7)
- ❍ Equipment Supplier (4)
- ❍ Student (8)
- ❍ Other (5) ____________________

Q2 What industry do you (or have you) worked in? Select all that apply.

- ❑ Heavy Civil (1)
- ❑ Marine Construction (2)
- ❑ Vertical Construction (Residential and Commercial) (3)
- ❑ Industrial Construction (4)
- ❑ Other (5) ____________________

Q3 Select the job title that best describes what you do.

- ❍ Project Manager (1)
- ❍ Project Engineer (2)
- ❍ Traffic Control Designer (3)
- ❍ Safety Officer (4)
- ❍ Safety Equipment Supplier (5)
- ❍ Road Maintenance Crew (6)
- ❍ Traffic Control Consultant (9)
- ❍ Traffic Control Crew (7)
- ❍ Other (8) ____________________

Q4. What is the approximate annual revenue of your company?

Q5. What is the size of your company? (Approximate number of employees)

Q6. Which sector would you best describe most of your company's projects? (Select all that apply)

- ❑ Residential (1)
- ❑ Commercial (2)
- ❑ Heavy Civil (3)
- ❑ Energy (4)
- ❑ Industrial (5)
- ❑ Marine (6)

Q7 How many years of experience do you have in the construction industry?

- ❍ Less than 1 year (1)
- ❍ 1 - 5 years (2)
- ❍ 5 - 10 years (3)
- ❍ 10 - 20 years (4)
- ❍ More than 20 years (5)

The questions in the next section focus on factors that could impact the use of a work zone intrusion alert technology. A work zone intrusion alert technology (WZIAT) is a type of safety system used in a roadway work zone to alert field workers and secure time for them to escape when errant vehicles intrude into the work zone. Please answer the following questions with the WZIAT in mind.

Q8 Are you familiar with work zone intrusion alert technology?

- ❍ Definitely yes (1)
- ❍ Probably yes (2)
- ❍ Probably not (3)
- ❍ Definitely not (4)

Q9 How important are the following attributes to your decision to adopt WZIAT?

| | Not Important (1) | Slightly Important (2) | Neutral (3) | Important (4) | Very Important (5) |
|---|---|---|---|---|---|
| Ease of Deployment/Retrieval (1) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Easy to move the technology around (2) | ❍ | ❍ | ❍ | ❍ | ❍ |
| User Friendliness (learning curve) (3) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Little or no Impact on Traffic Flow and Control within work zone (4) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Limits worker exposure (during deployment/retrieval of technology) (5) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Easy to store (6) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Resistance to environmental and physical impact (7) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Reusable (8) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Easy to Maintain (9) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Extended battery Life (reliability) (10) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Cost of labor and equipment (11) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Availability of equipment in the market (12) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Cost of replacing parts/ maintenance (13) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Impact of warning alert on driver or Driver comprehension of visual and audio warning (14) | ❍ | ❍ | ❍ | ❍ | ❍ |

| | | | | | |
|---|---|---|---|---|---|
| Worker comprehension of warning signal (conspicuity, quality of alarm) (15) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Multiple warning alert sources (audio, visual, haptic/vibratory) (16) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Adequate coverage distance (Sensor/light/sound/haptic) (17) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Limited physical impact on vehicle (collision with technology) (18) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Driver adequately comprehends visual and audio warning (19) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Few or no false negative and positive alarm (20) | ❍ | ❍ | ❍ | ❍ | ❍ |
| Less dependence on existing infrastructure (21) | ❍ | ❍ | ❍ | ❍ | ❍ |

Q10 How does WZIAT impact workers?

| | Strongly disagree/ unlikely (1) | Somewhat disagree/ unlikely (2) | Neither agree/like nor disagree/ unlikely (3) | Somewhat agree/ likely (4) | Strongly agree/ likely (5) |
|---|---|---|---|---|---|
| Implementing WZIAT enables workers to be more productive (1) | | | | | |
| Using WZIAT improves workers safety (2) | | | | | |
| Using WZIAT improves work quality (3) | | | | | |
| WZIAT is easy to use (4) | | | | | |
| WZIAT would have a steep learning curve (5) | | | | | |
| Workers will find WZIAT easy to use (6) | | | | | |
| People who are important to me would think I should use WZIAT (7) | | | | | |
| I will use WZIAT because people who influence my behavior (manager, etc.) would want me to use it (8) | | | | | |
| I will encourage the use of WZIAT (9) | | | | | |
| I will  likely incorporate WZIAT into your work operations (if it was my decision to make) (10) | | | | | |
| I will recommend the use of WZIAT to my boss (11) | | | | | |

The questions in the next section focus on safety climate and culture. “Safety climate” is defined as “the values, attitudes, motivations, and knowledge that affect the extent to which safety is emphasized over competing goals in decisions and behaviors.” (Barnes 2009)  Please kindly indicate how you perceive your organization's attitude towards worker safety management.

Q11 In my company, management…

- ❍ Does not participate in safety audits. (1)
- ❍ Only participate in safety audits in response to a worker injury or adverse safety event. (2)
- ❍ Participate in safety audits only when required. (3)
- ❍ Initiate and actively participate in internal safety audits. (4)
- ❍ Actively participate in internal safety audits and use the information for management performance evaluation. (5)

Q12 In my company,…

- ❍ There is no formal safety management system; safety trends are not analyzed. (1)
- ❍ The safety management system is reviewed and safety trends are only analyzed in response to worker injury or an adverse safety event. (2)
- ❍ The safety management system is reviewed and safety trends are analyzed from time to time. (3)
- ❍ The safety management system is reviewed and safety trends are analyzed annually to ensure effectiveness and relevance. (4)
- ❍ The safety management system is reviewed and safety trends are analyzed bi-annually to ensure effectiveness and relevance. (5)

Q13 In my company,…

- ❍ The primary focus is on increasing productivity and reducing costs. Employees are rewarded for taking shortcuts to meet production goals. (1)
- ❍ When a project falls behind schedule, production becomes valued more than safety. (2)
- ❍ As long as minimum safety requirements are being met, production and cost reduction are the main priorities of a project. (3)
- ❍ For the most part, safety is not compromised for the sake of productivity. Projects are completed as safely as possible. (4)
- ❍ Safety is never compromised for productivity, schedule, or cost. Safety truly comes first. (5)

Q14 In my company, management…

- ❍ Does not invest in safety program development or provide adequate resources to conduct work safely. (1)
- ❍ Only invests in safety program development and devotes minimal resources to safety activities after an accident or an adverse event has occurred. (2)
- ❍ Participates in safety program development and allocates resources to the extent that it is required by regulatory authorities or the owner. (3)
- ❍ Provides adequate resources to ensure a safe working environment. Develops a safety program that is shared with all employees. (4)
- ❍ Provides on-going financial support for ongoing development of safety policies, programs, and processes. Invests in systems and processes to continually improve the jobsite safety climate. (5)

Q15 In my company,…

- There are no safety related metrics included in manager or supervisors' performance evaluations. (1)
- The only safety metric used in managers and supervisors' evaluations is the number of worker injuries, and often that is ignored. (2)
- Managers and supervisors are held accountable for meeting the minimum required safety standards; but, poor project safety performance carries few real consequences. (3)
- Managers and supervisors are primarily held accountable for lagging safety indicators (e.g., Recordable Injury Rate), but some leading indicators (e.g., safety climate metrics) have been included. (4)
- Managers and supervisors are held accountable for leading (e.g., safety climate metrics) and lagging safety indicators. Proactive safety leadership is a critical component of their evaluation and promotion. (5)

Q16 In my company, safety expectations, roles, and responsibilities…

- Are not identified or articulated to individuals working in the work place. (1)
- Are only clarified after an adverse safety event. (2)
- Are only set to meet OSHA requirements. (3)
- Are frequently, clearly, and consistently communicated to employees. (4)
- Are discussed with employees across the entire company, with sub-contractors, and owners; they are reinforced on a daily basis. (5)

Q17 In my company,...

- Supervisors have no supervisory training and have little understanding or knowledge of regulatory requirements. (1)
- After an incident occurs or regulatory action is taken, there is a discussion among higher level management about the importance of supervisory leadership. (2)
- Supervisors take OSHA 30-hour training and thus are familiar with OSHA regulations but they have little or no leadership training. (3)
- Supervisors are trained on regulatory guidelines and leadership. (4)
- Supervisors are provided with and required to take leadership training that includes topics such as: how to communicate with, and motivate team members; how to conduct pre-planning meetings; and how to inspire crew members to also be proactive safety leaders. (5)

Q18 In my company, supervisors…

- Manage and punish using intimidation and focus only on individual behavior without taking what may have been a faulty process into account. (1)
- Start caring for their crew and acting as safety leaders only after an incident occurs or regulatory action is taken. The behavior displayed is short-lived. (2)
- "Talk the safety talk", but often do not follow their own advice and expectations. (3)
- Initiate and actively participate in safety program activities that are focused on continuous improvement. (4)
- Instill a sense of safety ownership at all levels, serve as effective safety communicators, excellent role models for safety, and are able to coach and teach. Safety is infused into every meeting. (5)

Q19 In my company, employees…

- Feel no sense of responsibility for their co-employees' or their own safety. (1)
- Aren't engaged in promoting safety until after an accident occurs. (2)
- Are engaged in promoting safety to the extent that is required. (3)
- Participate in all aspects of ensuring safe working conditions, beginning at the planning and design stages. (4)
- Are empowered and rewarded for going above and beyond to ensure safe working conditions where they always feel responsible for their and their co-employees safety. (5)

Q20 In my company,…

- Worker feedback regarding safety conditions and hazard reduction is not sought. They just want employees to “get the job done.” (1)
- Employees are asked for safety advice and feedback after an injury or adverse safety event has occurred. (2)
- Worker feedback regarding safety is sought only when initiated by employees or during mandatory safety meetings. (3)
- Management actively involves employees in identifying hazards and solving safety problems by including them in daily pre-job safety and crew task/hazard analysis. (4)
- Management actively seeks worker input on safety. Safety and even non-safety meetings and walk-arounds focus on solving specific problems identified by employees and others. (5)

Q21 In my company, Injury and illness data…

- Are not collected, unless there’s a fatality that must be reported to OSHA or other entities. (1)
- Are collected, but they are only reviewed after an adverse safety event has occurred. Issues are not formally tracked nor are resolutions communicated across the organization. (2)
- Are collected for the purpose of being compliant with OSHA requirements. Supervisors pass safety information on to their crew only when required by management. (3)
- Are regularly and formally collected and shared with managers and supervisors; supervisors are encouraged but not required to share information with their employees. (4)
- Are gathered through formal systems for regularly sharing and follow-up improvement actions with managers, supervisor, and employees. (5)

Q22 In my company,…

- There is no adequate safety-related communication effort. (1)
- Safety-related communication efforts occur only in response to an adverse safety event. (2)
- Safety-related communication effort meets OSHA requirements. (3)
- Safety-related communication effort is made when there’s a new standard or policy that needs to be followed. (4)
- Safety related communication effort is formalized both vertically and horizontally throughout the company and in the work place. (5)

Q23 In my company…

- There is no training verification process. (1)
- Training cards or certificates are only investigated after an incident has occurred. (2)
- Training is verified only to the extent required by OSHA regulations. (3)
- Training for all employees, including sub-contractors, is verified regularly. (4)
- Training for all employees, including all sub-contractors is verified before work is conducted on every project. Knowledge and skill competence are regularly assessed. (5)

Q24 In my company,…

- Trainers have no formal qualifications. (1)
- Because of job-site experience alone, senior level employees (e.g., foreman) are asked to conduct safety training. (2)
- A formal safety curriculum is developed and administered by trainers who meet minimal OSHA qualifications. (3)
- Safety curriculum is developed by highly qualified trainers. (4)
- Safety curriculum is developed and administered by highly qualified and experienced content experts with knowledge of adult learning principles. (5)

Q25 At my jobsite, the owner/client…

- Does not require safety pre-qualifications from general contractors or sub-contractors; selections are based on the lowest bid. (1)
- Only considers contractor safety and health comes when an adverse safety event occurs. (2)
- Relies on federal, state, and local safety laws for pre-qualification criteria. Bids include a budget for OSHA fines. (3)
- Selects contractors based on prior safety and health performance – as well as bid. (4)
- Selects general and sub-contractors based on safety program, practices and climate rather than low bid. Contractors with poor safety records are excluded from bidding. (5)

Q26 At my jobsite, the owner/client…

- ❍ Cares most and sometimes only about low-cost bids and on-time project completion. (1)
- ❍ Acknowledges that safety matters, but only if it does not interfere with production. (2)
- ❍ Agrees that safety matters and supports it to the degree that matches OSHA regulations. (3)
- ❍ Believes safety is equivalent to productivity and communicates that to all contractors, sub-contractors, supervisors, and employees. (4)
- ❍ Views themselves as ultimately responsible for safety. Often uses an Owner Controlled Insurance Program because it requires supporting stringent safety and loss control procedures. (5)

Q27 The injury rate in my organization is...

- ❍ Below industry average (1)
- ❍ On-par with industry averages (2)
- ❍ Above industry average (3)

End of Survey

Appendix B

| | Contractor (n=53) | | | DOT (n=69) | | | Manufacturer&Vendor (n=39) | | | Consultants (n=20) | | | Students (n=135) | | | Total (n=316) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | S. D | Skew | Mean | S. D | Skew | Mean | S. D | Skew | Mean | S. D | Skew | Mean | S. D | Skew | Mean | S. D |
| Ease of Deployment/Retrieval | 4.21 | 0.84 | -1.43 | 4.07 | 0.86 | -1.42 | 4.08 | 0.98 | -1.73 | 4.2 | 0.62 | -0.12 | 3.69 | 0.958 | -0.734 | 3.94 | 0.926 |
| Easy to move around | 4.26 | 0.86 | -1.50 | 4.09 | 0.87 | -1.41 | 3.95 | 1.03 | -1.75 | 4.3 | 0.57 | -0.038 | 3.85 | 0.927 | -1.014 | 4.01 | 0.908 |
| User Friendliness | 3.92 | 0.73 | -1.42 | 3.81 | 0.86 | -1.04 | 4.05 | 1.12 | -1.52 | 4 | 0.46 | 0 | 3.9 | 0.992 | -0.783 | 3.91 | 0.915 |
| Little or no Impact on traffic Control | 3.68 | 1.07 | -0.59 | 4.07 | 0.99 | -1.27 | 4.03 | 1.09 | -1.22 | 4.1 | 0.64 | -0.08 | 3.79 | 1.008 | -0.547 | 3.88 | 1.012 |
| Limits worker exposure | 4.51 | 0.70 | -1.04 | 4.48 | 0.70 | -0.99 | 4.08 | 1.01 | -1.45 | 4.2 | 0.52 | 0.294 | 3.86 | 0.955 | -0.547 | 4.15 | 0.889 |
| Easy to store | 2.81 | 0.98 | 0.40 | 2.74 | 1.04 | 0.14 | 3.03 | 0.99 | -0.57 | 2.5 | 0.69 | 0 | 3.04 | 0.969 | 0.21 | 2.9 | 0.982 |
| Resistance to environmental impact | 3.72 | 0.89 | -0.44 | 3.42 | 0.85 | -0.19 | 3.83 | 1.03 | -0.65 | 3.25 | 0.55 | 0.132 | 3.9 | 0.916 | -0.795 | 3.71 | 0.913 |
| Reusable | 4.19 | 0.94 | -1.40 | 3.79 | 0.92 | -0.63 | 4.1 | 1.02 | -2.09 | 3.85 | 0.75 | -0.591 | 4.12 | 0.97 | -1.137 | 4.04 | 0.955 |
| Easy to Maintain | 4.04 | 0.8 | -0.53 | 3.97 | 0.8 | -0.51 | 3.82 | 0.9 | -1.23 | 3.6 | 0.6 | 0.712 | 3.92 | 0.93 | -0.824 | 3.92 | 0.89 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | | 7 | | | 8 | | | 8 | | | 9 | | | 5 |
| Extended battery Life | 3.91 | 0.74 | -0.44 | 3.71 | 0.88 | -0.32 | 4 | 1.08 | -1.74 | 3.8 | 0.77 | -0.403 | 4.02 | 0.91 | -0.829 | 3.92 | 0.896 |
| Cost of labor and equipment | 3.57 | 1.08 | -0.46 | 3.62 | 1.05 | -0.52 | 3.74 | 1.12 | -1.12 | 3.5 | 0.89 | -0.25 | 3.67 | 0.968 | -0.504 | 3.64 | 1.021 |
| Availability of equipment in the market | 3.85 | 0.84 | -1.11 | 3.59 | 1.00 | -0.39 | 3.53 | 1.03 | -0.77 | 3.35 | 0.81 | 0.541 | 3.56 | 0.903 | -0.23 | 3.6 | 0.928 |
| Cost of replacing parts maintenance | 3.6 | 1.01 | -0.53 | 3.59 | 0.93 | -0.21 | 3.5 | 1.08 | -0.74 | 3.3 | 0.80 | 0.055 | 3.67 | 0.889 | -0.388 | 3.6 | 0.938 |
| Impact of warning alert on driver | 4.17 | 0.89 | -1.19 | 4.41 | 0.63 | -0.56 | 3.78 | 1.53 | -1.04 | 4.8 | 0.41 | -1.624 | 4.07 | 0.967 | -0.854 | 4.18 | 0.978 |
| Worker comprehension of warning signal | 4.6 | 0.60 | -1.25 | 4.67 | 0.53 | -1.31 | 4.3 | 1.00 | -2.07 | 4.8 | 0.41 | -1.624 | 4.24 | 0.859 | -1.069 | 4.44 | 0.778 |
| Multiple warning alert sources | 4.08 | 0.76 | -0.41 | 4.23 | 0.79 | -1.00 | 4.16 | 0.99 | -1.81 | 4.2 | 0.62 | -0.12 | 3.96 | 1.05 | -1.01 | 4.08 | 0.922 |
| Adequate coverage distance | 4.51 | 0.67 | -1.44 | 4.36 | 0.73 | -0.92 | 4.22 | 1.09 | -1.57 | 4.2 | 0.41 | 1.624 | 4.12 | 0.873 | -0.985 | 4.25 | 0.826 |
| Limited physical impact on vehicle | 3.23 | 1.01 | -0.02 | 3.65 | 0.95 | -0.19 | 3.68 | 1.18 | -0.72 | 3.8 | 0.83 | -0.194 | 3.45 | 1.144 | -0.381 | 3.51 | 1.076 |
| Driver adequately comprehends visual and audio warning | 4.25 | 0.92 | -1.29 | 4.39 | 0.69 | -0.65 | 3.62 | 1.37 | -0.94 | 4.8 | 0.41 | -1.624 | 4.19 | 0.83 | -0.677 | 4.21 | 0.909 |
| Few or no false | 4.38 | 0.7 | -1.04 | 4.33 | 0.8 | -1.33 | 4.03 | 1.0 | -1.52 | 4.15 | 0.4 | 0.442 | 4.05 | 1.03 | -0.767 | 4.17 | 0.93 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| negative and positive alarm | | 7 | | | 3 | | | 7 | | | 9 | | | 2 | | | 3 | |
| Less dependence on existing infrastructure | 3.43 | 1.03 | -0.31 | 3.41 | 1.02 | -0.30 | 3.35 | 0.92 | -0.33 | 3.15 | 0.59 | -0.004 | 3.56 | 0.967 | 0.092 | 3.45 | 0.966 | |

APPENDIX C

| Component | Description | Estimation | Source |
|---|---|---|---|
| Shelf life | | 8 years for each device | Theiss et al. 2014, assumption |
| Work week/years | | 20 | |
| Boli wage | | 26 | http://www.oregon.gov/boli/WHD/PWR/Pages/PWR-Rate-Publications---2018.aspx |
| # of work day/week | | 4 | |
| Strobe cost | | $ 35 | https://www.mad4tools.com/dorman-conelite-led-traffic-lamp-light-with-cone-bracket#tab_description_tabbed |
| Battery cost | 2 AA Duracell | $15 | https://www.bhphotovideo.com/c/product/567719-REG/Duracell_MN2400B2_AAA_1_5v_Alkaline_Coppertop.html |
| WAS PSD | | $100 | https://www.tapconet.com/store/product-detail/JYab/worker-alert-system-personal-safety-device-vibration-unit?sku=TG-WAS-PSD |
| Maintenance time/day | | 0.5 – 1.05 hrs | Theiss et al. 2014, interview data |
| Wage rate multiplier | | 1.5 | Theiss et al. 2014 |
| # of workers in a work zone | | 10 | Interview data |

| | | |
|---|---|---|
| # of miles paved annually (state) | 170 | ODOT 2016 review statistics |
| # of miles paved annually (contractor) | 15 | Interview data |
| # of devices and accessories per mile | | Gambatese et al. 2017 |