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Increasing work zone safety:

Worker behavioral analysis with integration of wearable sensors and virtual reality

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Increasing work zone safety: Worker behavioral analysis with integration of wearable sensors and virtual reality

PI: Dr. Semiha Ergan
Email: semiha@nyu.edu
New York University
ORC-ID: 0000-0003-0496-7019

Co-PI: Dr. Kaan Ozbay
New York University
ORC-ID: 0000-0001-7909-6532

Suzana Duran Bernardes
New York University
ORC-ID: 0000-0002-3012-0631

Zhengbo Zou
New York University
ORC-ID: 0000-0002-7789-655X

Yubin Shen
New York University
ORC-ID: 0000-0002-5941-0579

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Executive Summary

Despite increased regulations, restrictive measures, and devices used for warning, work zone injuries and fatalities are still observed at highway construction projects with alarms/notifications being ignored. With a vision to reduce the number of injuries and fatalities, this project aims to understand the key parameters (e.g., work zone location characteristics, personal vigilance levels, notification frequencies) that play roles in achieving responsive worker behaviors towards alarms/notifications. Key questions this research answers are, what are the key factors of a work zone (e.g., construction work type, work zone work duration) that can lead to construction worker safety hazards? How can we effectively monitor construction workers' behaviors towards alarms when they are under hazardous conditions? What are the modalities, frequencies, and timings for pushing alarms to maximize workers' attention, to mitigate incidents/accidents?

Previous research studies in this domain show that mobile and short-term construction works are more susceptible to incidents/accidents due to their rapid and unstructured setting as compared to long-term construction works executed at well-delineated work zones. Given this point of departure, and through a rigorous literature review of state-of-the-art technologies work zone hazard mitigation and review of past work zone incidents/news stories, we identified three scenarios that are more likely to lead to a work zone incident, hence in need of investigation of how to maximize the workers' attention when safety alarms are sent. These three scenarios are:

(1) Scenario 1: Placement of traffic barriers to set construction perimeters at an urban intersection. For this, we used the intersection located at Myrtle Avenue and St Edwards Street in Brooklyn Downtown.

(2) Scenario 2: Surveying the road at an urban intersection located at the intersection of Willoughby Street and Jay Street in Brooklyn Downtown.

(3) Scenario 3: Installing sensors/equipment on the side of an urban highway located on the Brooklyn-Queens Highway, close to Commodore Barry Park.

These scenarios were generated using real intersections and highways around NYC. Based on these baseline scenarios that are more likely to result in work zone incidents, we proposed an integrated approach combining virtual reality (VR) and body area sensors to conduct user studies to monitor and analyze worker behaviors when they receive safety alarms regarding upcoming dangerous situations. We created three VR environments; each corresponding to one scenario identified to be prone to work zone incidents using the integrated approach, which includes four main steps as:

(1) Recreating real-world work zones in VR. This is done by using a laser scanner to collect point cloud data about the work zone and surroundings and then using the point cloud as an underlying dataset to realistically and accurately replicate the work zone in VR. Result of this step is a virtual reality model for each scenario.

(2) Enabling user interactions in VR for construction activities. For each scenario, the user interactions are designed corresponding to the construction work applicable to that scenario. For

example, in Scenario 1, the virtual user interactions include grabbing traffic barriers and putting the barriers in designated locations.
(3) Conducting a calibrated microscopic traffic simulation to obtain realistic traffic patterns around each work zone and embedding vehicle movements with potentially dangerous situations in the VR models.
(4) Developing a smartwatch application. This application is designed to send safety notifications and to monitor and record workers' responses as well as their physiological states (i.e., heart rate) using wearable sensors. It is then integrated to the VR environments.
The research team had finished the development of the three VR environments and demoed the full experiment set up at the 2020 TRB conference. Outreach activities also include an in-person demo with a New York State DOT administrator at the laboratory at NYU, and a technical seminar hosted online for the UTC members.
The research team secured an IRB approval from New York University to conduct user studies with the wearable sensor integrated VR environments. However, due to the coronavirus outbreak, all ongoing in-person research had to be suspended indefinitely, resulting in the inability of the team to conduct more user experiments and data analysis. The research team will continue with the user experiments as soon as the restrictions are lifted and analyze the data collected right after. The outcome of this research will help to calibrate when, at what frequency, and how (with what modalities) to share warnings with habitants of work zones for effective responses towards reduction of incidents.

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1. Introduction

According to Occupational Safety and Health Administration (OSHA), an average of three construction workers died every day in the U.S. during 2013-2018[1]. A recent study that comprehensively reviewed the current safety measures in roadway work zones shows that a significant amount of the fatalities and injuries occur at traffic work zones, when workers come into contact with construction equipment or passing by vehicles[2]. The Federal Highway Administration (FHWA) revealed that 50% of crashes occur within or adjacent to work zones during construction, putting workers in danger together with drivers[3]. The majority of literature on work zone safety focused on driver behavior[4,5,6], where speed, aggressive behavior towards workers, distraction, and substance use were identified as factors contributing to work zone incidents. However, work zone safety studies have yet to be coupled with the behavior analysis of construction workers.

Proactive warning approaches currently implemented at work zones include blinking lights with audible alarms, detection of vehicles crossing a predetermined perimeter, drone radars, and traffic cones with sound alerts[7,8]. One of the major impediments in wide real-world deployment of such technologies is the false and frequent alarms that cause workers to quickly disregard them. Another limitation is the lack of knowledge on the systematic assessment of different modalities of pushing alarms (e.g., vibration, audio, visual) along with the alarm frequency and duration to understand their effectiveness on workers' positive response towards such notifications. Hence, this study aims to improve the work zone safety in horizontal construction projects by examining the issues from the workers' perspective and assessing workers' behaviors towards alarms with the aim to calibrate the duration and frequency of alarms as well as determining an effective medium to push these alarms.

With the development of wearable technologies, an increasing number of research studies have been exploring the feasibility of using wearable sensors to send alarms to construction workers[9,10]. The advancement of VR enabled researchers to simulate potentially dangerous situations (e.g., speeding vehicles) in work zones without putting workers in harm. Therefore, the combination of VR and wearable sensors provides an opportunity for researchers to study the optimal configuration for sending notifications to workers.

This research first identified the key factors of a work zone that can influence the possibility of incidents as: work zone location, work duration and work type. Next, three work zone scenarios that are more likely to result in work zone incidents were identified based on a thorough literature review and screening of past news stories regarding worker injuries at work zones. Three scenarios based on real incidents were identified as more likely to lead to work zone incidents, including (1) setting up barriers to define a work zone perimeter that is close to an urban intersection[11]; (2) striping/marking a road on an urban highway[12]; and (3) installation of traffic sensors on the side of an urban highway[2].

Finally, we proposed an integrated approach utilizing VR and wearable sensors to determine when, how, and at what frequency to push alarms to workers at work zones based on the physiological states of workers collected from the wearable sensors and workers' behavior towards the alarms when they are in dangerous situations in VR. The approach is composed of four steps as: (1) recreating real-world work zones in VR, (2) enabling interactions in VR for construction activities, (3) conducting traffic simulation to obtain realistic traffic patterns near work zones and embedding vehicle movements in VR, and (4) developing a smartwatch application to send safety alarms and monitoring workers' responses as well as their physiological states using wearable sensors. The user studies will be conducted in VR, under the assumption that user behaviors in VR will carry over to real settings. The sensors used in this study include a smartwatch to receive safety alarms, and a photoplethysmogram (PPG) sensor to monitor workers' heart-rate variability when encountering a dangerous situation in VR and when alarms arrive. The proposed approach fills the gap of quantitative and systematic assessment of the characteristics of alarms (i.e., modality, frequency, and duration) with the goal to improve work zone safety.

2. Background

2.1. Key factors contributing to work zone related incidents

The standard work zone layout by the Manual on Uniform Traffic Control Devices (MUTCD) [69] is divided into four main areas: advance warning area, transition area, activity area, and termination area (Figure 1). The definition for each area is as follows:

- Advanced warning area is the area designated to warn the drivers approaching the work zone of ongoing work ahead. This area is crucial to guarantee the safety of road users and workers, as it brings awareness to the driver of changes in the road due to the work zone and the presence of construction/road workers, equipment and material. The traffic in this area are still subjected to the regular speed limit of the road. The high speed combined to other factors such as low lighting, fog, and driver distraction, and the presence of flaggers and/or other warning equipment not properly placed can lead to crashes.
- Transition area is designated to transition the incoming traffic from their original trajectories and speed to the work zone configuration. The control of the incoming traffic flow is performed by the use of tapers. Vehicles that were not properly warned in the advanced warning area can be caught by surprise by the tapering and lose control, hitting the barriers or going out of the road, hard break and get hit on the rear by a vehicle or hit the vehicle ahead that is breaking.
- Activity area is the longest area, and it is the section where the work occurs. Usually, the region where there is the presence of workers, equipment and material is separated from traffic by a buffer and barriers. The improper placement of the barriers and size of the buffer can increase the exposure of workers to the traffic and, therefore, increase their risk of getting hit by an intruding vehicle. The improper placement of equipment or the traveling behavior of the workers can also increase the risk of a crash.

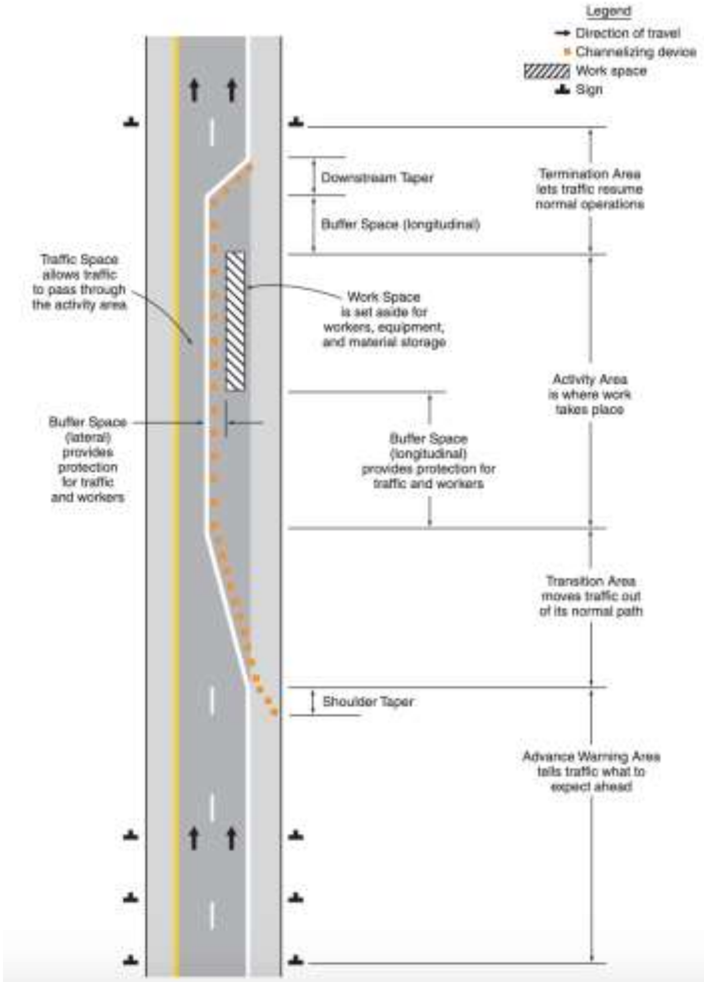


Figure 1 Temporary Traffic Control Zone as defined by the MUTCD(69)

The most recent federal statistic(55) on the number of fatal crashes in work zones is for the year of 2018, in which there was a total of 672 fatal crashes that resulted in 755 fatalities. Of these 755 fatalities, 124 were construction workers inside a work zone. Even though new technologies emerged, and more efforts have been made towards reducing the number of fatalities, over the past three years, the average number for worker fatality is still close to 130 per year. According to Daniel et al.(83), the activity area registered higher vehicle crash counts (77.6 percent), followed by the advanced warning area (14.8 percent). However, the length of each area varies widely, which might influence in the probability of a crash occurring in the longer areas such as the activity and advanced warning areas. Thus, they found the crash rates of each area for better addressing the risk priority. When considering crash rates, the activity area still ranks the highest (38.4 percent). Conversely, the advanced warning area ranks the lowest (11.4 percent) and the transition area the second highest (28.3 percent). The activity area was also identified as the one with highest risk by Garber and Zhao(14) and that rear-end crashes are more common.

Through a detailed literature review in transportation, construction, and construction safety domains, we identified key factors that contribute to having crashes around work zones and analyzed them under four categories as driver related factors, environmental factors, road related factors, and work zone related factors (as shown in Table 1). The majority of the studies found in the literature focus on analyzing factors that are mainly related to drivers and their behaviors when crashes occur in work zones. Driver related factors include the speed and speed variance, gender, age, vehicle type, distraction, being under the effect of alcohol or drugs, and aggressiveness. Another key contributor to work zone incidents are environmental factors, such as the lighting condition, weather condition, and the time of day when an incident occurs. Road condition is another important category contributing to work zone incidents, including the road type, pavement condition, number of lanes, and traffic volume. Work zone characteristics were also found to be influencing workers' safety onsite. Work zone conditions such as work zone duration, location, dimension, and construction work type have been correlated with the occurrence of incidents. Despite the apparent connection between work zone characteristics and the incident frequency/rate, there has been little research focusing on analyzing the worker behaviors onsite given specifics of the work zones.

Table 1 Key factors contributing to incidents at work zones.

Category/ Key Factors		**References for related research studies***
Driver	Vehicle speed	13,14,15,6, 16,17*
	Driver gender	16,18,19
	Driver age	17,18
	Driver aggression towards road workers	5
	Distracted driving	5,17,20
	Driving under influence	18,21,6,16,17
	Vehicle type	22,17
Environment	Lighting condition	16,18,19,22
	Weather conditions	23,5,24,19,16,17
	Time of day	25,26,27,15,24, 28,17

Road	Road type	22,29,19
	Number of lanes	21,15,28
	Pavement conditions	30,28
	Traffic volume	4,15
Work zone	Work zone activity type	29,27,28,24
	Work zone location	29
	Work zone duration	27,15
	Work zone dimension	4,14,15,19

**: numbers in this column refer to the reference number of a corresponding research study listed at the references section of this report.*

According to the literature presented in Table 1, the key factors can be better described according to which specific condition leads to higher frequency of crashes and severity. For the drivers perspective, the crash count and higher severity occurs when the vehicle is speeding, generally over the speed limit of the road, when the driver is female and/or between 25-64 years old, if the vehicle is of an SUV type and when the drivers are more aggressive towards the road workers. The driver being under influence of substances or distracted by their phones also have a high effect on the crash count. When considering the environmental conditions, more crashes occur in daylight, but they are more severe when they happen in low lighting. The presence of rain and fog also increases the crash frequency and severity. Roads that are poorly paved and/or have traffic level of service D are more prone to a high crash count. The literature also proves that work zones placed in curved segments of the road and with one or more lane closure present more risks to road workers. This might be explained by the need of drivers to change their trajectory due to the changes on the road geometry. Finally, the configuration of the work zone also plays a significant role in the number and severity of crashes that happen in them. Usually, mobile or short duration work zones that involve activities such as surveying or infrastructure maintenance, and that are located in urban highways register more crashes. The length of the work zone also significantly influences number of crashes registered; it is positively correlated with the number of crashes.

Most of the literature found on crashes related to work zones covers the factors related to the driver of the vehicles, the behavior of the worker can also contribute to the occurrence of crashes. The lack of worker conspicuity has been one of the factors shown to influence on the frequency of crashes in work zones[(5)]. Despite the apparent connection between work zone characteristics and the incident frequency/rate, there has been little research focusing on analyzing the worker behaviors onsite given specifics of the work zones. **Error! Reference source not found.** exemplifies where the literature focus when the topic is work zone safety. The figure is a word cloud of the most frequent words found on abstracts of 500 papers from engineering publications resulted from a search of the topic “work zone safety” on the Web of Science platform. We can notice that the number of the words found related to the traffic aspects of the work zone is higher than related to road workers. Studies about worker’s travel pattern inside the work zone, their positioning related to the traffic, their reaction time to possibly being hit by intruding vehicles, their response to warnings, and other aspects would help to fill the gap in the information available to improve work zone safety.

Figure 2 Word cloud of abstracts from papers resulted from a research on the topic “work zone safety”

In addition to the literature review, the research team also conducted a data analysis of the traffic incidents in the New York City area (five boroughs. The main goal of analyzing this data set is to identify the factors that are more impactful for causing accidents. While the NYPD crash data does not indicate whether the crashes are due to construction work, the generality of the data can still facilitate the development of VR environments, since we need to simulate the most commonly occurring scenarios for crashes.

The data included 1.5 million rows and 29 columns, with each row being a crash event. The columns of the data set include date, time, borough, zip code, latitude, longitude, location, on street name, cross street name, off street name, number of persons injured and killed, number of pedestrians injured and killed, number of cyclist injured and killed, number of motorist injured and killed, contributing factor vehicle 1-5, unique key, vehicle type 1-5. The research team used a widely adopted feature selection metric (i.e., Shapley values) derived from game theory to measure the importance of features (i.e., columns) in the crash data set. The results showed that the principal features related to the total number of injury and deaths are vehicle type, contributing factor vehicle, and time.

To further investigate each factor, we drew a distribution of each factor. For the scope of this analysis, we only looked into the accidents that led to injuries and fatalities (i.e., the number of people injured or killed is not zero), which includes about 300,000 accidents.

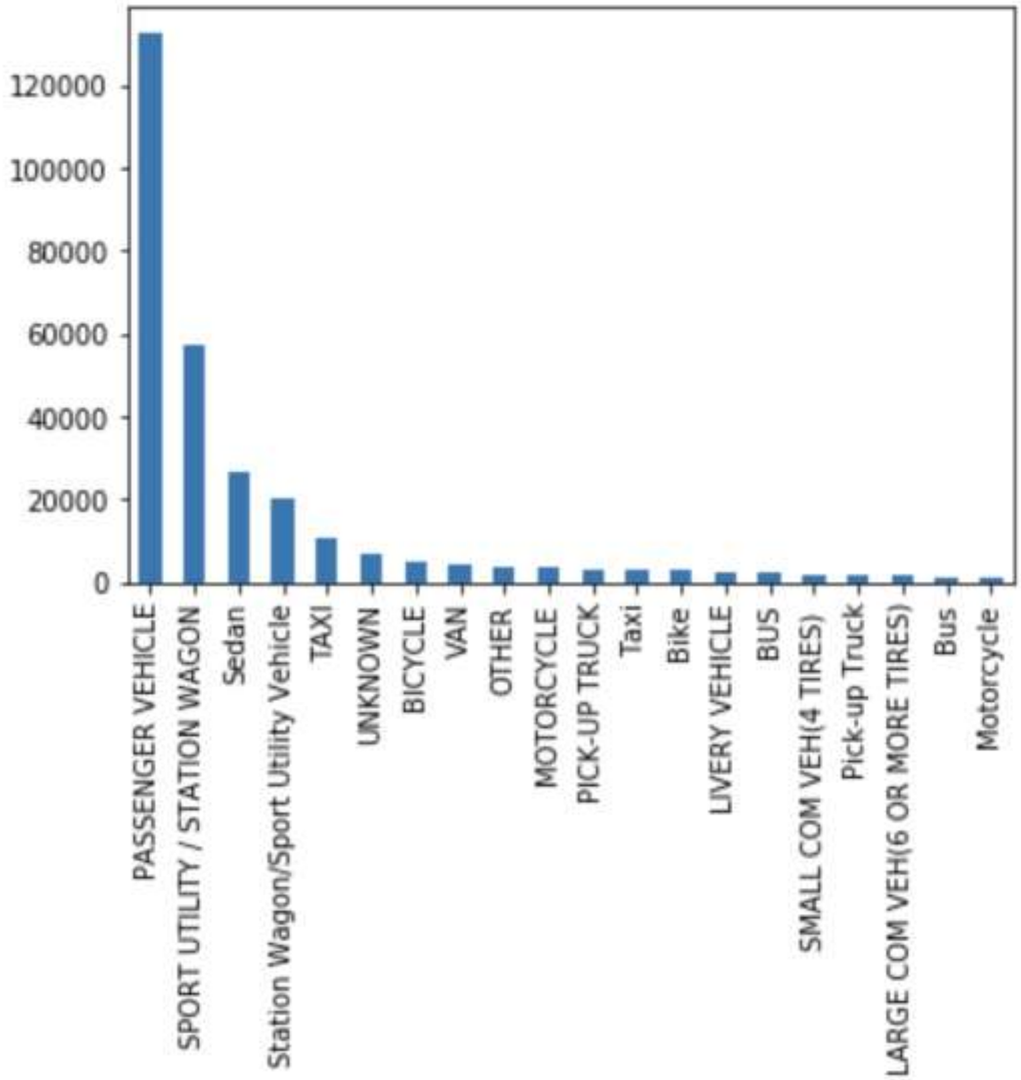


Figure 3 Distribution of the vehicle types that led to traffic incidents in NYC.

From Figure 2, it is apparent that the most prevalent vehicle types that are related to accidents are passenger vehicles, SUVs, sedans, and taxis, while other vehicle types are minimal in comparison.

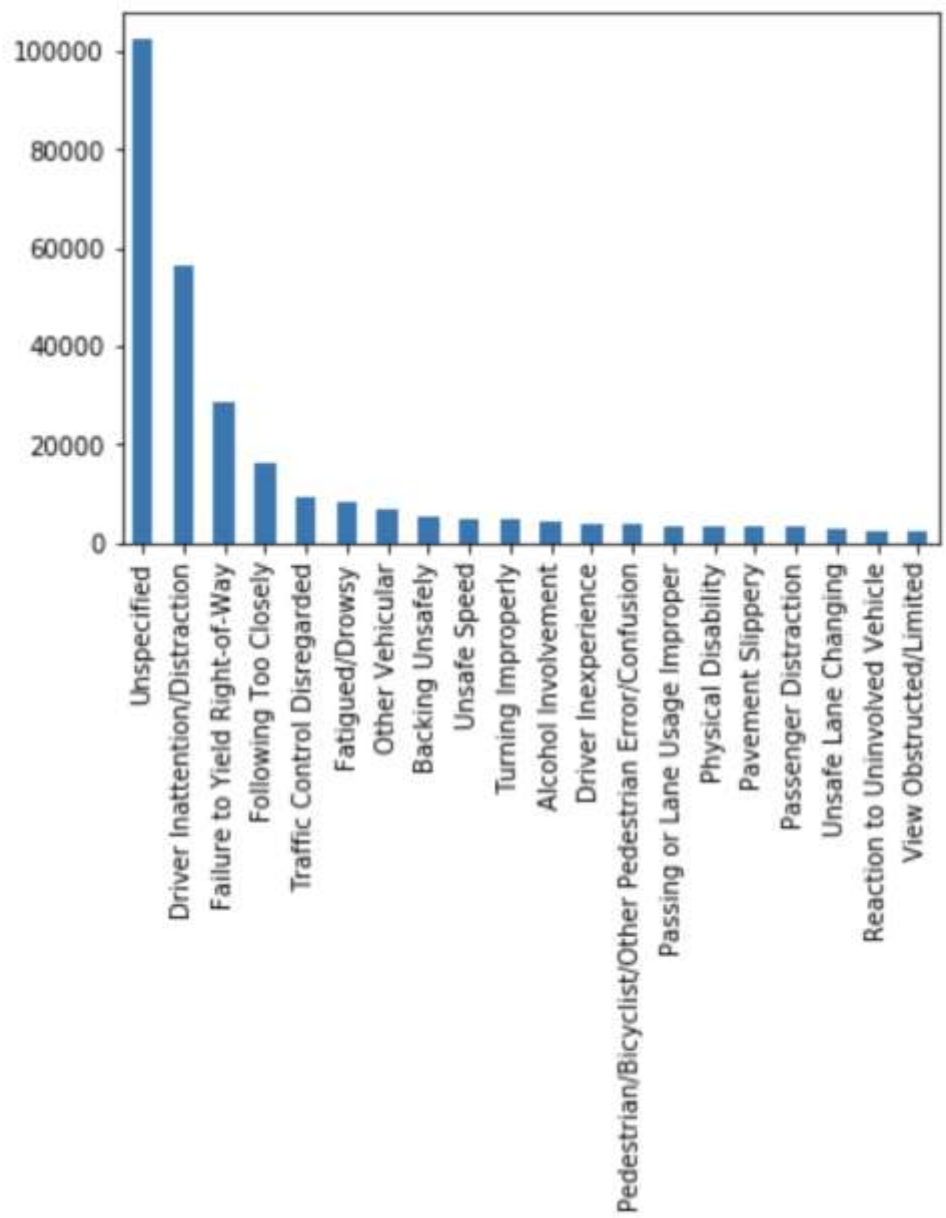


Figure 4 Distribution of contributing vehicle factor led to incidents.

From Figure 3, it is apparent that driver distraction, failure to yield, following too closely, disregarding traffic controls and fatigue are more relevant to accidents.

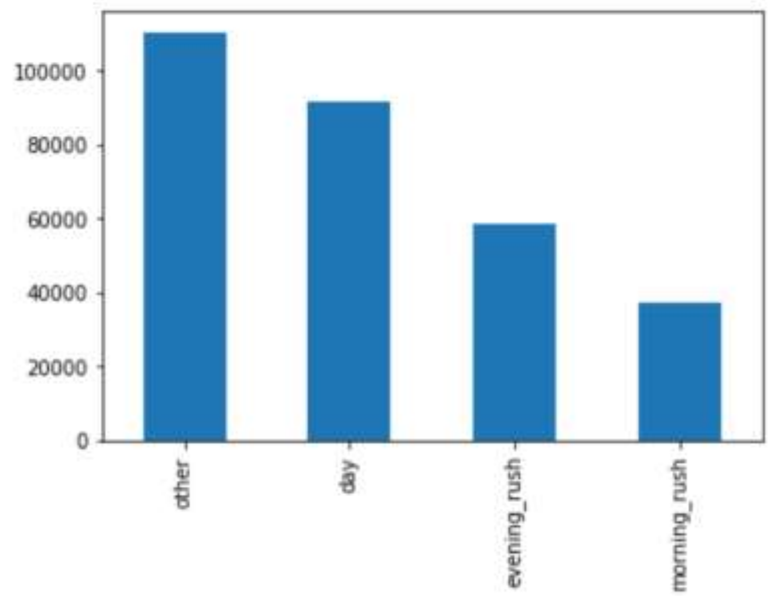


Figure 5 Distribution of time of day when the incidents occurred.

We defined morning rush hours as 7 am to 10 am, and evening rush hours to 4 pm to 7 pm, and time in between is defined as day. It is apparent from Figure 4 that accidents are more likely to happen during night times comparing to day times, and evening rush hours are more likely to lead to accidents.

Based on the key factors described in Table 1 and the data analysis from Figure 1-4, we identified three scenarios that are more likely to lead to a work zone incident, hence in need of investigation of how to maximize the workers' attention when safety alarms are sent. The three scenarios are:

Scenario 1: putting traffic barriers to set construction perimeters at an urban intersection.

This scenario is based on an incident that occurred on 07/29/2019 in Kentucky. A 55-year-old traffic control worker was setting up traffic cones in the left lane of a major, four-lane interstate when he was struck from behind and killed by a motorist. The scenario was included because it matches the key contributing factors of unsafe driving practices, localization in a mobile work zone[67].

Figure 6 Example of a worker setting up cones.

Scenario 2: surveying the road at an urban intersection.

This scenario is based on an incident that occurred on 04/04/2018 at the Hutchinson River Parkway near exit 4N, a mile north of the I-95 exit. A 57-year-old male worker of the Department of Transportation was struck and killed by an SUV vehicle. The worker was performing regular maintenance of the highway infrastructure. The scenario was included because it matches the key contributing factors of lack of control devices, speeding and loss of control by the driver, presence of fog and short-term work zone[68].

Figure 7 Example of surveyor at an urban intersection.

Scenario 3: installing sensors on the side of an urban highway.

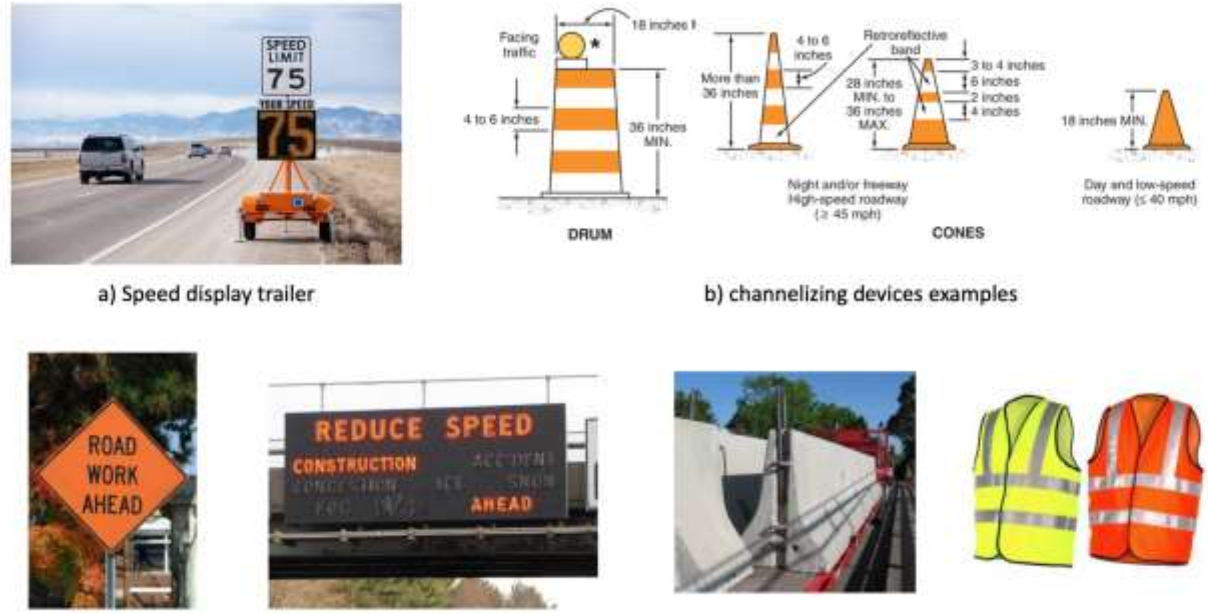
This scenario was chosen to complement the other two scenarios, as it includes an activity that has intermediate-term work zone characteristics. This activity is also common in several localizations. Other factor taken into consideration for this scenario is that it is somewhat easier to be reproduced, as the investigators were able to have access granted to scan a site during the sensor installation phase.

Figure 8 Example of workers finishing installing a weight sensor.

2.2. Current safety measures at work zones

Safety measures adopted at work zones vary according to the work zone complexity, which depends on the duration of the construction activity. Long-term (i.e., more than 3 consecutives days) and intermediate-term (i.e., more than a daylight period and no more than 3 consecutive days, or more than an hour during night-time) work zones are usually well planned and structured, while short-term (i.e., more than an hour but not more than a daylight period) and mobile (i.e., up to an hour and moves intermittently) work zones have fewer safety guidelines(27). Hence, short-term and mobile work zones are more prone to incidents, given that workers conducting tasks out of a secure perimeter are exposed to a higher risk of being struck by upcoming traffic(27).

Prevalent work zone safety measures aim to raise drivers' attention, such as fixed (Figure 9c) and variable message signs (Figure 9d), police enforcement, speed display trailer (Figure 9a), and (2) channelizing devices (Figure 9b), such as cones, drums, and barricades, flashing arrow panels, Portable Concrete Safety Shape Barrier (PCBs) (Figure 9e), and high-visibility worker's apparel(31) (Figure 9f). The Manual on Uniform Traffic Control Devices (MUTCD)(69) has a dedicated section, "Part 6", to temporary traffic control. It includes all the guidelines to guarantee the safety of all the road users and property while a work zone is in place. The manual details the current channeling, signalizing and marking methods, and Traffic Control Devices.



a) Speed display trailer b) channelizing devices examples

c) Fixed message signs d) Variable message signs e) Portable Concrete Safety Shape Barrier (PCBs) f) High-visibility worker's apparel

Figure 9 Examples of work zone safety measures[69,85-88]

In the worker safety sub-section, the MUTCD[(69)] highlights the following measures as essential to guarantee the workers safety:

- Training of workers
- Temporary traffic barriers between workers and traffic
- Speed reduction inside the work zone
- Plan the activity area to minimize the number of back-up maneuvers
- A dedicated work zone safety planning

The MUTCD also has dedicated sub-sections to address the flaggers safety and to provide guidelines for 46 typical applications of the safety measures at work zones. In the flaggers sub-section, it focuses on strategies that increase the flagger's visibility such as the use of high-visibility safety apparel and hand-signaling devices. Figure 9 shows the example of one of the typical applications provided by the MUTCD that can be closely applied to one of the studied scenarios (#2), which is a surveying activity. Figure 10 shows the legend of symbols used by the MUTCD for the typical applications, such as the one shown in Figure 9.

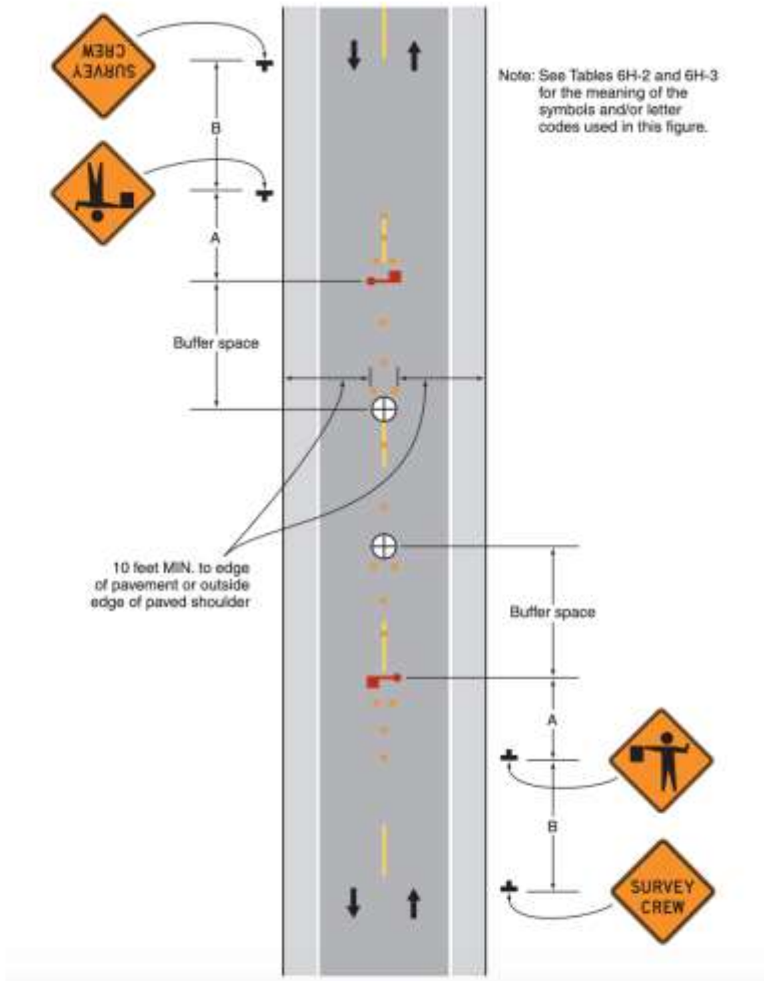


Figure 10 Surveying along the center line of a road with low traffic volumes (TA-16) [69]

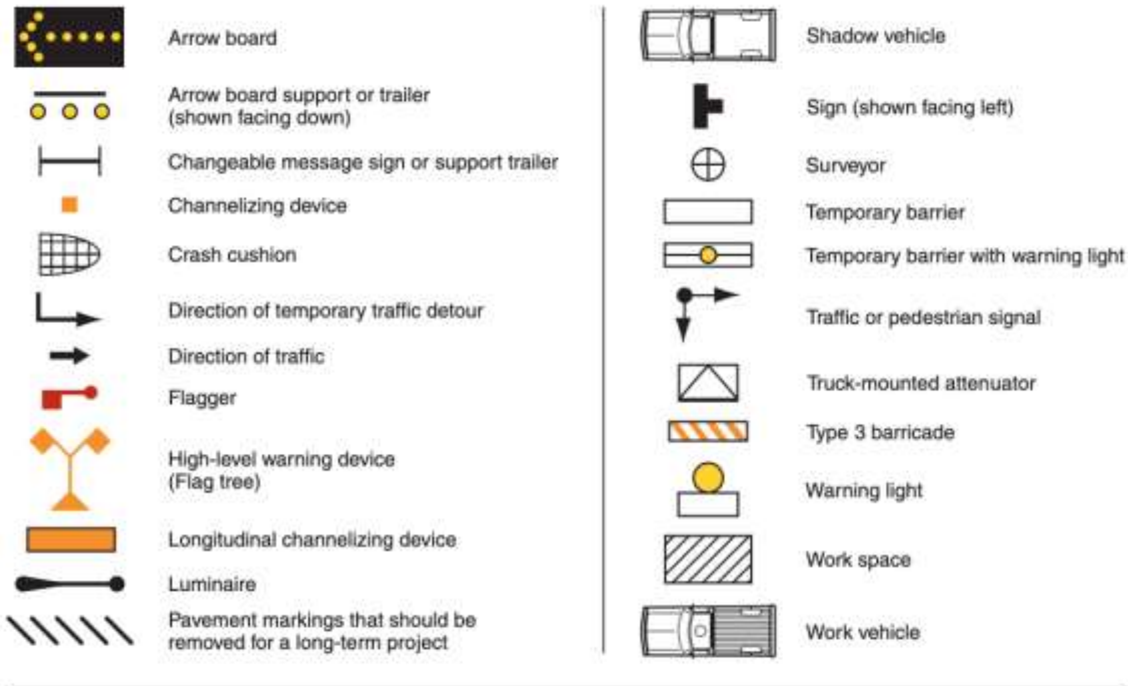


Figure 11 Legend of symbols used by the MUTCD[(69)]

In addition to the MUTCD, the Targeted Work Zone Engagement Framework Guidance Document by the FHWA[84] serve as an important guideline to guarantee the efficiency of work zones safety and mobility. It is part of the recent effort of state agencies and the FHWA to increase work zone safety. It addresses the current issues such as non-standardization of work zone crash reports, which leads to unreliable data for fully understanding the risk factors, how to correctly identify and mitigate safety problems in work zones and provide trustworthy resources for improving work zone safety and mobility. The main contribution of the document is the framework, shown in Figure 12, which target each goal set for improving safety and mobility (E.g., Work zone design, driver safety, and worker safety; Transportation management planning and congestion mitigation; Road user public outreach) and provide mitigation options and strategy for each goal.

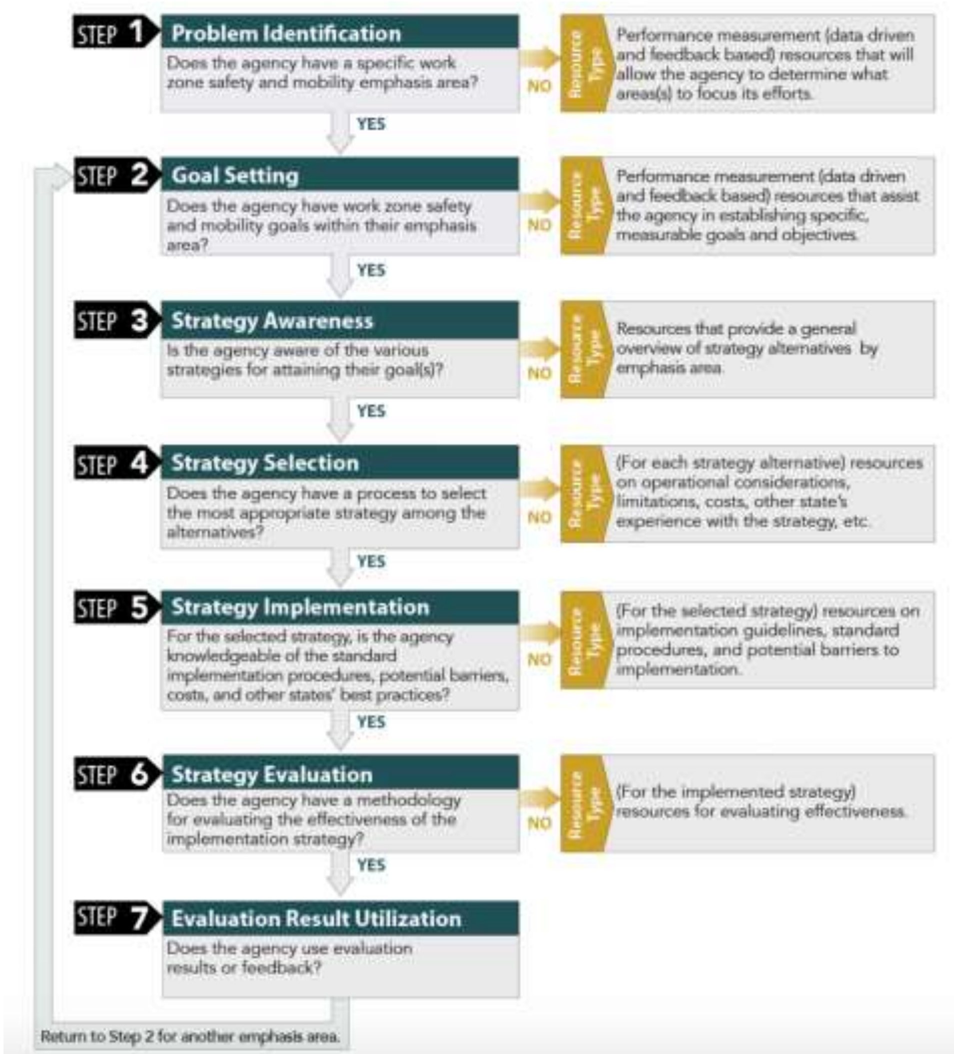


Figure 12 The Work Zone Targeted Engagement Framework by the FHWA[7]

The use of such framework is not only helpful to state agencies, but also to researchers focusing on work zone safety. They divide the goals for the work zone by emphasis areas:

- Emphasizes Area 2: Work zone design, driver safety, and worker safety.
- Emphasizes Area 3: Transportation management planning and congestion mitigation.
- Emphasizes Area 4: Road user public outreach.

For this project, the goals follow under the Emphasizes Area 2, based on the key factors found in the literature that consider the driver and worker safety overall, as shown in Table 2. With main focus on Intelligent transportation system (ITS) technology as a leverage to address the several mitigation strategies for the different goals.

Table 2 Emphasis Area #2 - Mitigation strategies for consideration by goal by FHWA[7]

Goal Setting	Mitigation Strategy (i.e., "Improved utilization of…")
Work zone design guidelines (e.g. Manual on Uniform Traffic Control Devices American Association of State Highway and Transportation Officials etc.)	Channelizing devices
	Temporary pavement markings
	Flaggers and uniformed traffic control officers
	Large Static signs/ marked detours
	Portable changeable message signs
	Arrow panels
	Shadow vehicle
	Enhanced flagger or automated flagger assistance devices
	Temporary traffic signals
	Work area lighting
	High-visibility apparel for workers
Better alert driver of travel path deviations	Temporary rumble strips
	Warning lights
	Intrusion alarms
	Intelligent transportation system (ITS) technology
Improve driver compliance to work zone devices, regulations	Law enforcement presence
	Automated enforcement
	Increased penalties for violations Decrease work zone encroachment incidents
	Temporary traffic barriers
	Moveable barrier systems
	Reduced speed limit Improve work zone access and egress safety and mobility
	ITS technology
	Large static signs Reduce conflict points within the work space
	Internal traffic control plan Enhance temporary traffic control effectiveness at rural, low-volume work zones
	Flagging on low-volume roadways
	Temporary traffic control on low volume roadways
Improve worker situational awareness	Backing alarms
	Worker training

In a comprehensive review[56] that assessed new and emerging ITS technologies for traffic control, the following Traffic Control Devices were examined: Turbo flare; Turbo flare with electronic movement detector (Turbo flare EMD); Traffic blanket; Portable plastic rumble strips (PPRS); Advance warning lights; Personal strobe light. The final selection of Traffic Control Device is shown in **Error! Reference source not found.**. Emerging technology evaluated includes: The SonoBlaster® Dual Alert™ Work Zone Intrusion Alarm; Safety Line SL-D12 work zone intrusion alarm; Wireless Warning Shield. This review showed that the Traffic Control Devices with the best results were the PPRS and Advance warning lights. Even though the new emerging technology presented by the report have the potential to guarantee the safety of workers such as surveyors, their cost-benefit analysis does not justify their use yet. A noteworthy emerging safety measure is the use of wireless warning systems using sound to either alert drivers to reduce speed due to the presence of a work zone or workers on-foot ahead and/or to alert workers of construction equipment[32] or vehicle intrusion[33].

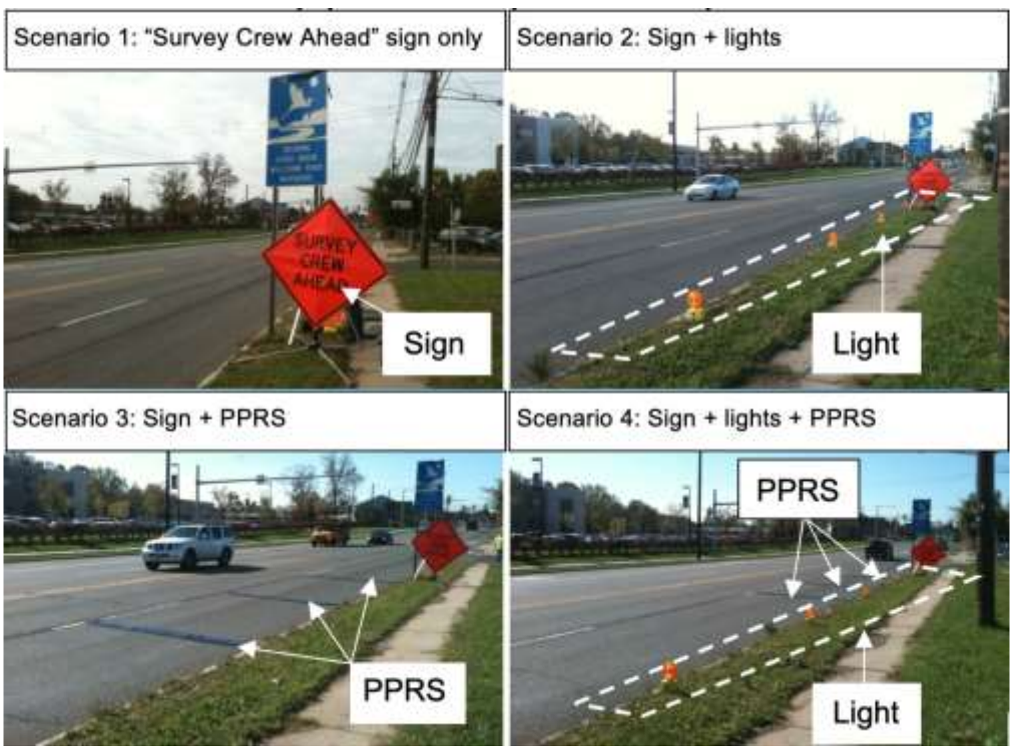


Figure 13 Different Traffic Control Devices used for surveyors' work (mobile work zone)

Tactile sensory warning system, using vibration, is one of the few alternatives found to the existent visual and auditory warnings. Tactile sensory warning has been shown to obtain accurate information transmission and response to the vibration signals. However, they still need to be further investigated for validation of their use in work zones[70, 71]. The current setup of the field experiments for testing new emerging warning systems, such as the previously mentioned, requires a large experimental area, expensive equipment, and it is not close enough to a real representation of what the participant would experience in real-life work zones. The loss of realistic representation is mainly because the experiment is highly controlled to guarantee the safety of the participants, and the number of vehicles is limited to one or two following a pre-determined trajectory.

In addition to the specific measures taken at traffic work zones, new technologies have been in development to address the common safety hazards (e.g., falling from height, slips and trips, struck by objects, electrocution) observed at vertical construction projects. Strides have been made in the areas of (1) proximity detection e.g., object detection, distance measurement using Bluetooth low energy tags(32) and laser scanners(34) and (2) location tracking e.g., worker location tracking and material tracking using Global Positioning Systems (GPS)(35) and Radio Frequency Identification (RFID)(36).

However, few of the technologies developed for vertical projects were adopted in horizontal construction projects. Furthermore, contradictory findings exist in the literature regarding the impact of traffic control devices on the frequency and severity of crashes in work zones, with studies supporting the use of traffic control devices to reduce the frequency of crashes(19) and studies that indicate the opposite(37). Such contradictory findings reveal the need for investigating the existing and emerging safety measures further.

2.3. Feasibility of monitoring human behaviors and bodily states using wearable sensors

With the advances in ubiquitous sensing and computing, it became easier to collect various types of physiological data on workers' bodily responses, health status, fatigue levels, and active/idle status. Wearable sensors such as smartwatches, wristbands, smart glasses are easy to deploy even in harsh construction environments(38). Various metrics have been proposed to understand the implications of human emotional and physiological states. Commonly used metrics include heart rate, muscle movement, and blood pressure to measure human experiences such as stress, pain, and anxiety(39). Wearable sensing devices enabled researchers to measure and monitor such metrics and to relate those metrics to the events and stimuli presented to the subjects.

A variety of body area sensors has been used in previous research to measure human experience. Human experience is assessed in two scales as valence and arousal. Valence is defined as the differentiation of an emotion (e.g., stress-relaxed, happiness-sadness) in the positive to negative scale, whereas arousal is defined as the intensity of that emotion (72).

EEG is an electrophysiological monitoring tool to record electrical activity of the brain by placing electrodes along the scalp(73). EEG helps in obtaining insights into how human brain works and reacts towards different spatial settings. The benefits of using EEG comes from the fact that it is non-invasive, easy to deploy (as compared to fMRI, PET, MEG), and can provide high quality and good time resolution of brain activity(74). It is also considered as one of the most intensive biometric research tools since it provides data for both emotional valence and arousal. It has been utilized in mental workload analysis of construction workers(75) as well as valence of construction workers under different work conditions[76] with accurate data captured from EEG headsets. However, analysis of EEG data is complicated due to unknowns of signal interpretations on different regions of the brain, and interpretation of it require supporting data on other biometric sensors to get conclusive results. This sensor can be easily combined with VEs for emotional experience detection and quantification; however, will not be solely enough to categorize the complex human emotions.

Galvanic skin response (GSR) is also a biometric tool, powerful to measure a widely referred metric called skin conductance. GSR provides data on the amount of sweat secretion from the skin, and is reported to have a positive correlation with the magnitude of emotional arousal[77]. As people are exposed to emotional events (e.g., stress, pleasure) in their daily life, emotional sweat levels increase; thus, increasing the skin conductance response (SCR) as sweat levels increase[78]. The data that is captured by a GSR sensor is a combination of a slowly varying SCR, which is known by the tonic activity, and a faster varying skin conductance response, which is known by the phasic activity. In order to be able to see the change in human SCR, the event related phasic activity must be separated from the tonic activity to be able to measure the change in human SCR peaks that occurred due to a stimulus.

A photoplethysmogram sensor (PPG) uses electrical signals derived from light reflected due to changes in blood flow during heart activity. Hear rate variability (HRV) is an indicator to the emotional response triggered by an environment. Emotional states could have a significant impact on HRV; when activity levels are controlled. Studies utilized HRV data to monitor operator physiology to minimize injuries[79]. With PPG sensors, HRV data can be reliably derived as R-Peak Intervals with millisecond accuracy, so that meaningful HRV data can be obtained with short-duration measurements. However, utilization of HRV metric alone will not be enough to capture human experience and should be paired up with other biometric sensors to get a holistic understanding of human experience.

Wrist worn PPG sensors were especially sought after in previous studies in the area of worker safety due to their ability to monitor elevated/reduced worker stress through heart-rate variability (HRV)[40]. HRV is an indicator of the bodily response triggered by a stimulus (e.g., an alarm received on the wrist), which can be used to capture construction workers' physiological states in dangerous situations[38,40]. Previous research showed wrist worn PPG sensors can achieve accurate measurements when worn correctly and when the subjects are not under heavy physical load, as compared to the gold standard of medical grade chest worn electrocardiography (ECG) sensor [41]. Previous research aiming to understand the latency of a wrist worn PPG sensor also concluded that the sensing latency for the sensor is in the millisecond range, hence neglectable in most user testing scenarios[42].

2.4. Virtual Reality in transportation studies

Due to the impracticality of creating job site hazards in real-world conditions, VR has been selected as a platform to evaluate worker safety on job sites. VR environments provide the flexibility to rapidly replicate and alter real-world conditions under controlled experiments. Previous studies confirmed that VR provides a high degree of realism for users[43] and can be used to study user behaviors as in real-world experiences[44]. The combination of VR and wearable sensors has also been validated from multiple previous studies focusing on design evaluation[45], worker stress evaluation[40], and worker cognitive load under stressful environments[46].

VR technology has also been adopted in the transportation domain[57] with the main interests in driving simulation, autonomous vehicles research, and visualization of unbuilt road/highway construction projects[58, 59]. Figure 12 shows a representation of mixed reality applied to transportation. While Augmented Reality (AR) can usually involve the superposition of relevant information on the drivers range of view to help in the decision-making process, the VR usually provides an immersive experience without the user having any contact with real-world roads. VR has been proven to be valuable in the research for Vulnerable Road Users (VRU), as it allows the researchers to study driver behavior without endangering the participants and road users. Three main types of studies aiming solutions for VRU include: (1) studies in which the traffic conditions with cars and pedestrians are simulated using microscopic traffic simulation models and realistically reproduced using VR technology for driving simulation experiments[60]; (2) studies in which the VR environment is built for observation of pedestrians' behavior while crossing a street[61]; and (3) studies in which the VR environment is built for observation of cyclists' behavior[62].

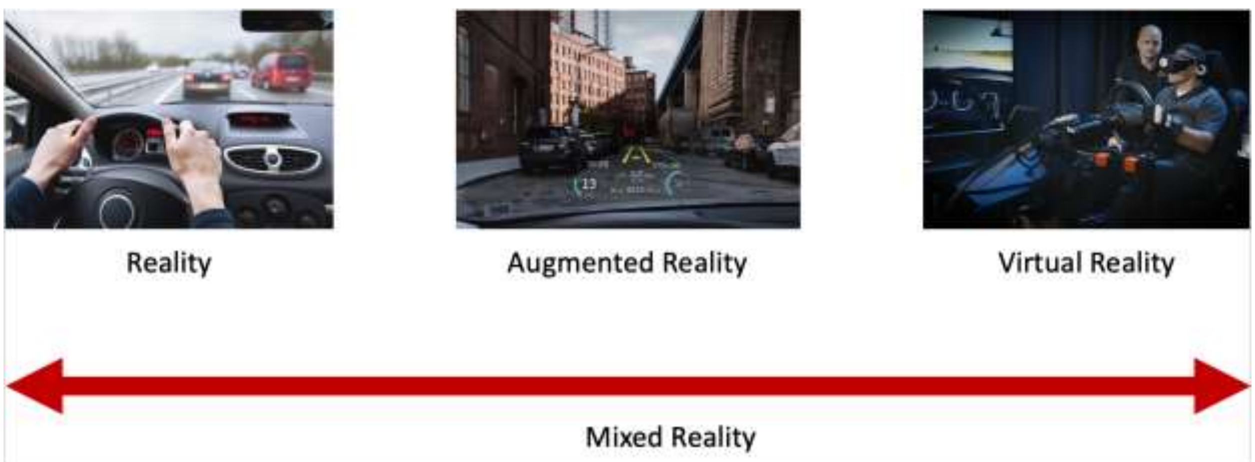


Figure 14 Spectrum of mixed reality

In addition, VR has also been used to study its use as training tool and the traffic behavior in work zones. Edara et al.[80] developed an immersive VR environment to test its efficacy in the training of road workers. The study showed positive results, indicating that the VR can successfully be used for training road workers before going to the real work zone environment. Bella[63] performed calibration and validation of a driving simulator to study the effects of temporary traffic signals on the traffic speeds in different areas of a work zone. The variation on speed behavior inside the work zone under different scenarios continued to be a subject of interest in recent studies[64, 65]. Another use of VR for work zone safety is for the analysis of key factors contributing to work zone crashes[66]. Even though the VR technology has been consistently used in work zone safety studies, a gap in the literature has been found regarding its use to understand the behavior of VRU in work zones such as the construction and maintenance workers, surveyors and flaggers. Also, some of the studies with VR analyzing the behavior of VRU did not consider the physiological effects of the use of the VR hardware on the participants. When performing behavioral studies that collect bio-data, it should be considered that the VR can disturb the heart rate frequency due to motion sickness[81].

2.5. Traffic simulation in work zone studies

The complexity of transportation systems and the difficulties in conducting real-world experiments make computer simulation an efficient tool for evaluating various traffic conditions. Microscopic traffic simulators are essential tools for describing traffic since they can model the interactions and dynamics between individual vehicles. These simulators have been commonly used for over 60 years now to analyze, evaluate, or test traffic management strategies, design changes or emerging smart transportation technologies representing traffic conditions in various locations from a couple of intersections to large city-wide networks. Microscopic traffic simulators describe the behavior of every “driver-vehicle” unit that compose the traffic flow. The inputs for these simulators are dynamic variables such as aggregated traffic volume, turning movement counts, and travel time. The simulation output such as vehicle trajectories (position and speeds), traffic data collected from modelled detectors, and travel time are used to analyze target scenarios quantitatively. In this project, the open-source traffic simulator Simulation of Urban Mobility (SUMO) was used to get the traffic pattern of the scanned roads for each scenario. The use SUMO as traffic simulation tool has been proven to produce realistic results when the scenarios and parameters are properly set, and the simulation is calibrated using real-data to feed SUMO’s built-in calibrator[82].

Microscopic traffic simulation models have been thoroughly used in work zone studies for traffic risk assessment[47], effects of speed control devices and speed limit reduction on the traffic in work zones[48], and impact of the work zone presence in the traffic conditions[49]. However, these studies have mainly focused on the effects of work zone on traffic but not on the interaction between traffic and workers. There is still a gap in the literature on the use of traffic simulation models to help understand the behavior of workers exposed to traffic in work zones.

This project identified the potential for improving work zone safety by integrating studies of construction worker behavior using VR technology and wearable sensors with traffic simulation models. From the microscopic traffic model built with SUMO, information such as vehicle, speeds and traffic volume were integrated to the VR application to be used in different scenarios. The integration of the microscopic traffic model with VR guarantees that the application is as close to reality as possible, since the simulation model is calibrated using real field data. Therefore, the reactions and behavior of the participants of the experiments would be closer to those when they are exposed to real-world traffic.

3. An Integrated Platform for Evaluating Workers' Behaviors and their Physiological States towards Safety Alarms

An integrated approach using VR and wearable sensors is proposed to study workers' behavior towards safety alarms they receive in variant modality, frequency and duration. The approach is composed of four steps as: (1) recreating real-world work zones in VR, (2) enabling interactions in VR for construction activities, (3) conducting a calibrated microscopic traffic simulation to obtain realistic traffic patterns near work zones and embedding vehicle movements with potential dangerous situations in VR, and (4) developing a smartwatch application to send safety alarms to monitor workers' responses as well as their physiological states using wearable sensors. In this study, dangerous situations are simulated to be caused by vehicles passing a virtual work zone. A dangerous situation can be caused by either a vehicle speeding or a vehicle invading the perimeter of a work zone, which corresponds to either speeding or collision alarms.

3.1. Reconstruct work zones in VR

This step includes using a laser scanner to capture 3D point clouds of real-world work zones and then recreate 3D models of the work zone in VR. The process of "scan to VR" has been an active research topic in the Architecture, Engineering and Construction (AEC) domain due to the increasing availability of high-resolution scanners and VR headsets. Furthermore, laser scanners provide a fast and accurate way of creating a digital representation of the real-world work zones, hence eliminating the need of a surveyor physically taking measurements of work zones repeatedly. However, there has not been a standard "best-practice" of "scan to VR" that is widely accepted. Two types of methods have been proposed, with the first being "scan-mesh-VR" and the second being "scan-measurements-VR"(50), as shown in Figure 13.

"Scan-mesh-VR" takes the scanned point cloud as an input to generate 3D mesh objects. Next, the mesh objects can be exported as common geometrical representation file formats such as .obj or .fbx files and later be imported to game engines where the objects can be modeled from the mesh or used as is. This method promises an automated approach, where no intervention from the modeler is needed. However, in practice, even with the state-of-the-art mesh generating algorithms, the process of scan to mesh cannot produce realistic results when the point cloud is not dense enough to form a consistent surface (51). On the other hand, "scan-measurements-VR" requires manual efforts. First, measurements of the object of interest (OOI) should be taken (e.g., the width of a street). Given enough measurements of the OOI, a modeler can use the measurements to recreate 3D objects in a modeling tool. This method suffers from long implementation time due to the extensive manual efforts from the modeler to take measurements, but it can be more accurate as compared to "scan-mesh-VR" because the measuring points are cherry-picked by the modeler. However, depending on the application domain and its needs, either method could be used.

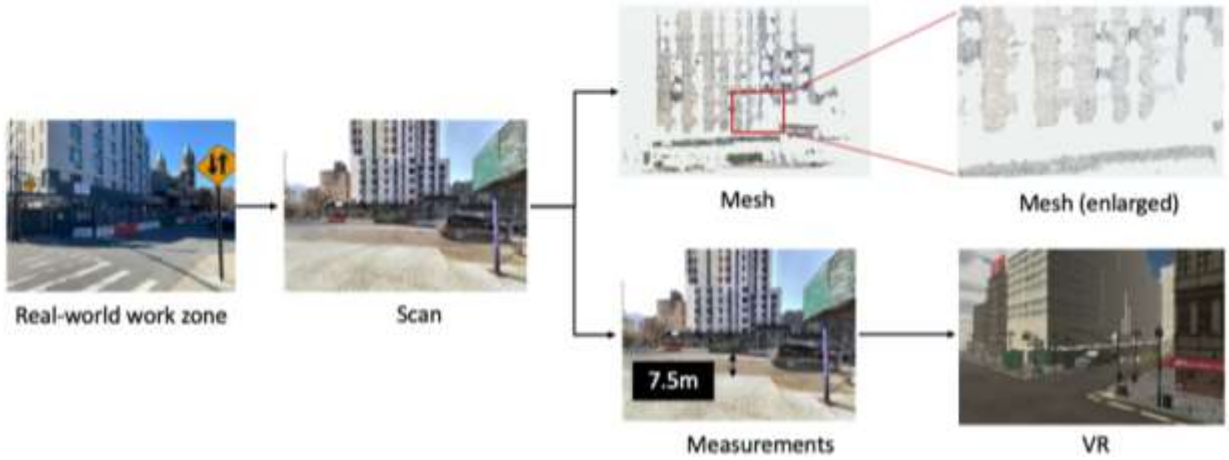


Figure 15 Scan-mesh-VR and scan-measurement-VR process.

In this study, both approaches were utilized. For scenario 1, we used “scan-measurements-VR “, and for scenario 2 and 3, “scan-mesh-VR” were used. Figure 14 shows the locations of the three testbeds, their scanned point cloud data, as well as the modelled VR environments. For all three scenarios, the Object Of Interest (OOI) is the road where the work zone is located. The width of the road and the length of the block were either measured (scenario 1) then used as references or created as mesh objects then imported into a game engine to recreate the work zone. Models of general objects such as buildings, fences, and traffic signals can be found online with open licenses, hence do not need to be remodeled. We also ignored the exact locations of the smaller objects in the scene such as garbage bin and trees and added them at sensible locations.

Figure 16 Three testbed scenarios captured in point cloud then converted to VR environments.

For the first scenario, the research team conducted six scans from two locations, with a total scan time of 40 minutes. The scans were later registered into a single point cloud, as seen in Figure 16.

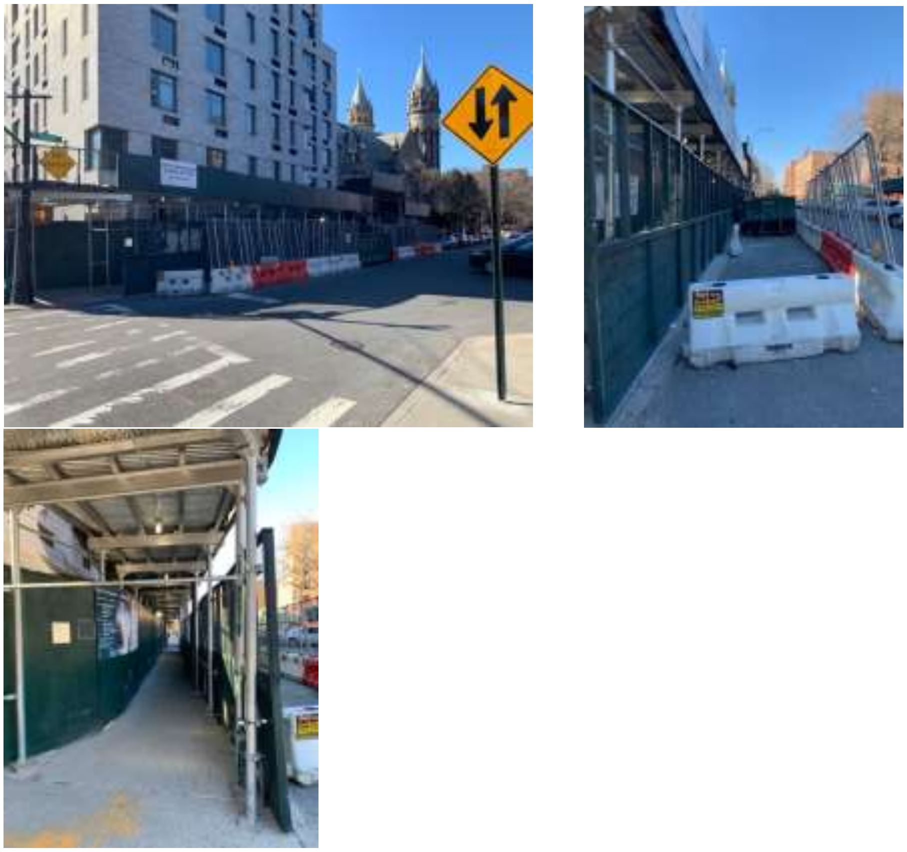


Figure 17 Work zone condition captured using a camera for scenario one.

Point cloud registration is the process of is the process of finding a spatial transformation (e.g., scaling, rotation) that can align two point clouds that are scanning the same object of interest from different angels. The purpose of finding this transformation is to merge multiple point clouds into a globally consistent model within the same coordinate system, or to map a new point cloud to a known point cloud to identify features or to estimate its pose.

Figure 18 Two scans from two locations close to the work zone in scenario one.

For scenario two, the research team captured the 3D point cloud data of a work zone for three consecutive intersections close to the NYU Brooklyn campus. There were 18 scans collected from three intersections. The point cloud data after registration can be seen in Figure 17.

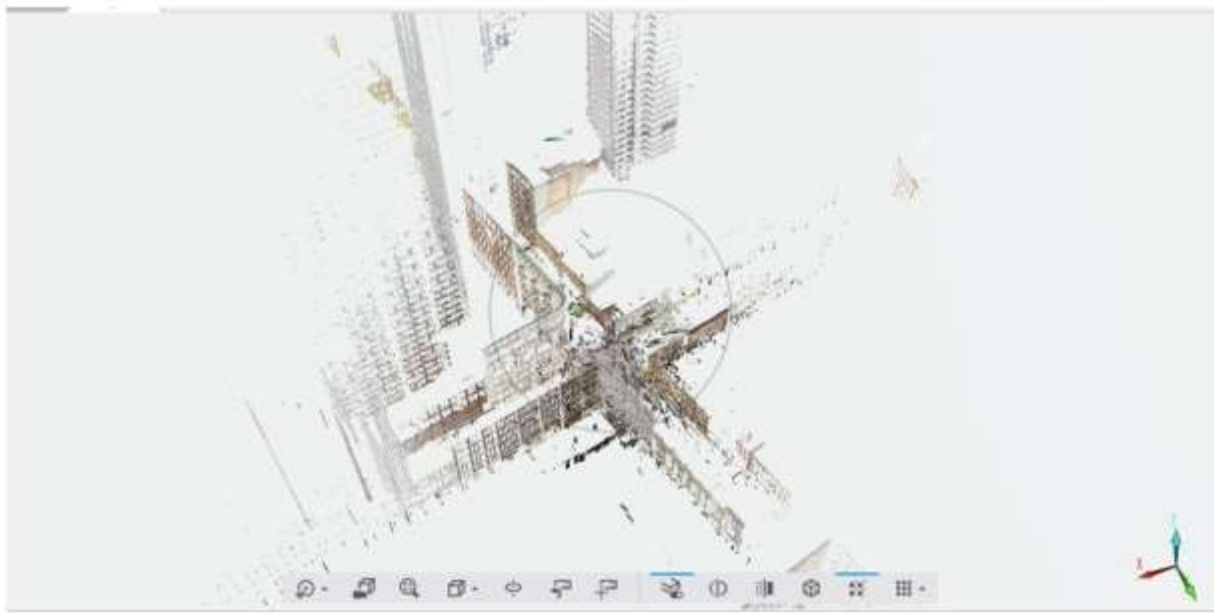


Figure 19 Point cloud of an intersection of work zone for scenario two.

For scenario three, the research team captured one urban freeway work zone on the Brooklyn-Queens Expressway (BQE). The work zone contains sensor installation on the side of a busy highway. The captured scans are shown below (Figure 18a). The work zone contains 7 scans (red circles in Figure 18b). The total scan time was one and a half hours.

Figure 20 Scanned BQE work zone during traffic sensor calibration.

3.2. Enable user interactions for construction tasks in VR

VR is widely adopted in the AEC domain for the purpose of design visualization[45], coordination[43], education[52], and safety training[46]. User interactions in these VR studies (i.e., how users control the avatar in VR and get feedbacks from the VR environment) vary based on the specific VR application. However, a consensus exists that natural and realistic VR interactions are more desired because higher level of realism of interaction has been associated with improved user experience and performance in VR[53]. The level of realism for interactions in VR can be measured by ***interaction fidelity***, which describes the degree of exactness with which real world actions are reproduced in VR[53]. Interaction fidelity (Figure 19) checks if the user interactions include accurate kinematic and kinetic representations relayed to the VR environments. Kinematic representation describes how well a body motion in the real-world is reproduced in VR. On the other hand, kinetic representation describes how well force implemented by the user in real-world is reproduced in VR.

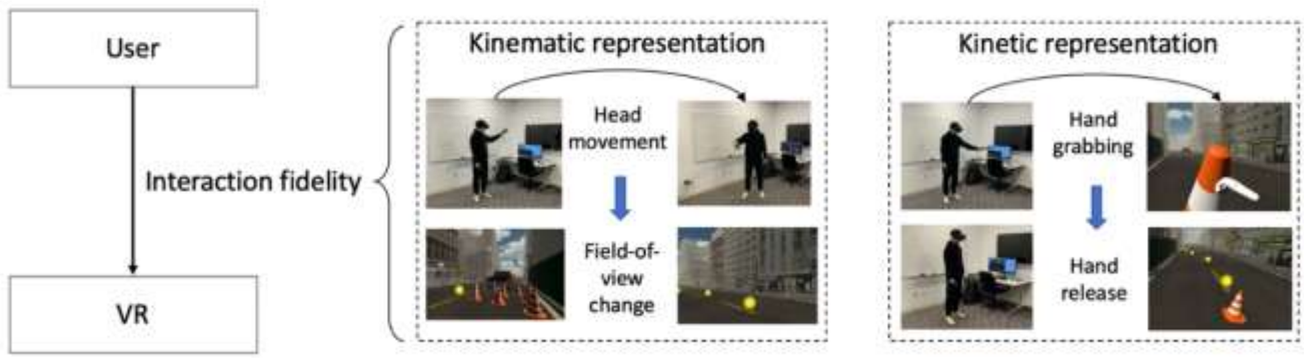


Figure 21 User interactions in VR measured by interaction fidelity.

In this study, worker head and hand movements are tracked and translated in the VR environment to enable worker position tracking and field-of-view change. Additionally, workers can grab the controller using either hand to trigger a grabbing motion in VR. The construction tasks in this study are determined by past news report of actual incidents happened onsite of work zones.

For scenario 1, the construction task is to set up a perimeter for a mobile work zone at an urban intersection. Workers are expected to put six orange traffic cones unloaded from a truck in pre-determined designated locations to finish setting up the perimeter of the work zone. In VR, designated locations of the traffic cones are marked using blinking yellow spheres. Once a worker finished putting one traffic cone, the corresponding location will have a steady green sphere to signal the worker that the cone is in place. When all traffic cones are put in place, the worker will be notified for the completion of the assigned task. For scenario 2, the construction task is to survey an urban intersection with a total station. The surveyor is supposed to first put targets at designated locations with a mechanism similar to the traffic cone placement in scenario 1. Next, the surveyor should operate the total station to aim at targets and wait for three seconds to make sure the target point was measured. For scenario 3, the construction task is to install sensors on the side of the road. The operator is supposed to first pick up the sensors then put the sensors to designated locations as shown in the VR environment as glowing circles on the ground. Next, the operator should check the accuracy of the sensors installed by interacting with a laptop in the VR, and check for each sensor's signal availability. The selection of these tasks eliminates the possibility of test subjects performing heavy physical workload to ensure the accuracy of the PPG sensor data. The tasks were also customized to ensure that users can finish within an hour according to the institutional review board (IRB) requirements.

Despite the realistic representations of the real-world work zone and the well-designed construction activities embedded in the VR environments, inexperienced users may still find navigating and interacting with the VR environments difficult. This difficulty stems from the disconnection between the physical world where the user resides and the virtual world where the user interaction is embedded. Most commercially available high-resolution VR headsets are constrained by a cord connected to a powerful PC, where the onboard graphics card handles all the graphics related calculation and the headset only displays the rendered results. This approach allows the inclusion of high-definition textures in the VR environments to improve realism. However, the limited range of movement prevents the users from roaming the VR environments freely, causing a disconnection of the physical world with VR.

3.3. Conduct traffic simulation to obtain realistic traffic patterns and embed vehicle movements in VR

Varying traffic patterns, such as increased demand during peak hours and vehicle trajectories containing vehicle positions and speeds in the vicinity of the real-world work zone, were simulated in the open-source micro simulator SUMO. SUMO is an open-source, microscopic, multi-modal traffic simulation software that addresses a large set of transportation problems, such as traffic management, evacuation, signal control, and safety analysis. Each vehicle is modeled explicitly, has its route, and moves individually through the network.

Compared to commonly used commercial micro-simulators, SUMO is advantageous because a) it is an open-source software which provides flexibility in building environment and programming application algorithms and can benefit from the constant improvements made by various developers; b) it can represent real-world traffic scenarios more realistically with its combination of embedded functions and flexible modules. This is crucial for simulating work-zone events and representing it when complicated real-world conditions and behaviors are applied, as is the case with this project. For these reasons, SUMO is selected as the preferred simulation software for this project.

The Traffic Control Interface (TraCI) is one of the most important features of SUMO and is the key to embedding customized VR control modules into the simulation. It is developed by an external institution and extends SUMO by providing a platform to interact with a running simulation online by connecting an external application to SUMO using sockets. TraCI allows users to retrieve attributes of vehicles, traffic lights, induction loops, road infrastructure, and other simulation objects to control or change the state of simulated objects, like the phase of signals and the route choice of vehicles. TraCI can be programmed using different coding languages such as Python, Java, C++, MATLAB, and .NET. It provides the opportunity of connecting SUMO with Unity to implement VR environments.

The input data of SUMO contains 1) a road network consisting of nodes, edges, junctions, signals, etc., which can be generated by the network editor; 2) traffic demand information; and 3) additional files such as signals, detectors, and variable speed signs. The output of SUMO includes vehicle-based information (disaggregated and aggregated), link-based information, detector-based information, and network-based information. In this study, traffic volume and turning movement counts during peak hours (6-10 a.m.) were manually collected at the study intersection and the simulation model was calibrated to represent these observed traffic parameters. The simulation network (an urban segment between two intersections) used in this study was calibrated to represent the observed volumes at the study location. The output of the traffic simulation includes vehicle ID, speed, acceleration, trajectory, and traffic volume.

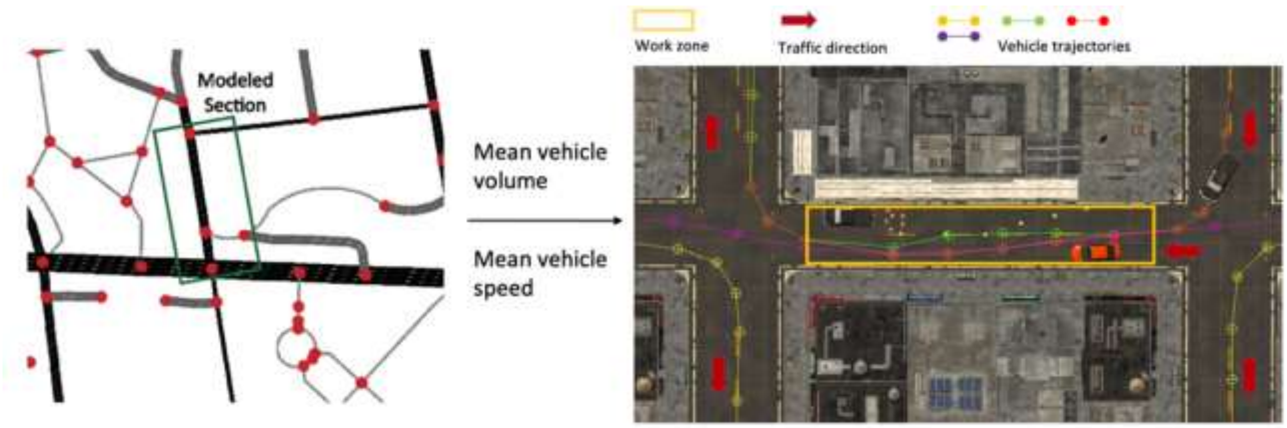


Figure 22 Traffic simulation outputs embedded in VR.

To realistically simulate traffic in the VR environment, the average vehicle speed and volume at the work zone location were calculated using the simulation outputs. The research team is working on an automated method to achieve real-time SUMO-Unity connection, so that the simulated traffic condition can be represented in VR, and the VR environment can serve as a feedback loop to the simulation to change some simulation parameters.

By default, the VR work zone is a safe environment, where cars travel at the average speed in an average volume (Figure 20). The simulated dangerous situations were added purposefully, which can be divided into two categories: speeding and invasion of work zone perimeter. Work zones have a strict speed limit usually lower than the regular speed limit of the same road to protect workers. Speeding while passing by a work zone is especially dangerous due to lane changes and narrowed lanes. In this study, when a vehicle is traveling 20% faster than the average speed, it is categorized as a dangerous speeding situation. On the other hand, invasion of work zone perimeter leads to crashes in work zones and causes damages to the work zone structure as well as workers on site. Vehicle trajectories were defined using sets of invisible nodes in VR. Vehicles travel from one node to the next to follow a trajectory. The locations of the nodes were hand-picked by the authors to reflect both safe and dangerous situations. When a vehicle travels on a trajectory that leads to invasion of the work zone perimeter, it is categorized as a dangerous situation.

Figure 23 Overview of the VR environment for scenario one.

When there is a dangerous situation simulated in the VR environment, a safe zone would appear in the VR environment. The safe zone is marked with shining green light in VR, as seen in Figure 22. When the worker is present within the boundaries of the safe zone, the simulated dangerous vehicle will not be able to come into contact with the construction worker.

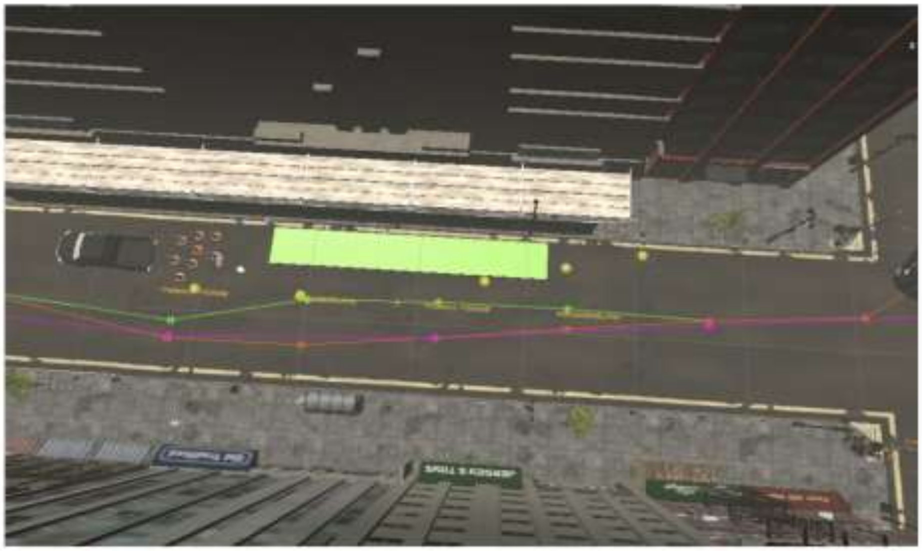


Figure 24 Safe zones highlighted in green when there is a simulated danger.

3.4. Monitor worker behavior towards safety alarms using wearable sensors

This part of the integrated platform has two major components, including a cloud server which handles alarms originated from the VR application, and wearable sensors to receive alarms from the server and monitor workers' physiological states. To elaborate, the occurrence of a dangerous situation in VR triggers an alarm sent to a cloud server through an HTTP request (Figure 31a). The request contains information about the alarm, including alarm ID, type (e.g., speeding, collision), alarm sent time, and the vehicle ID that triggered the alarm. For the wearable sensors, there are several brands of smart watches on the market which advertise themselves as wearable sensors with programable functionalities, such as Apple Watch and Samsung Galaxy Watch. Considering the development requirements, a well-designed Integrated Development Environment (IDE) and a robust Software Development Kit (SDK) is preferred to allow the researchers to develop the application as well as perform integration testing. As a result, an Apple Watch Series 4 was selected as the wearable sensors to deliver alarms to construction workers. An additional PPG was required to be worn during the test, although the Apple Watch supports heart rate monitor. The consideration is the Apple Watch built-in monitor accuracy could not be guaranteed during the period when any haptic feedback is triggered.

For the watchOS application development, the IDE was XCode 11 and the programming language was Swift 5. The operating system for the Apple Watch was watchOS 5. A general mobile application development process was followed for this application, which includes requirement analysis, UI/UX design, App development, Q\A testing. More details for these four stages are provided below:

Requirement analysis

The application was designed for supporting real time communication with the cloud server to receive safety alarms, deliver both haptic and auditory feedback and at the same time record the behaviors from the workers. As a result, the application must have the functionalities to get and post the messages through the network, perform multiple patterns of haptic and auditory feedback according to the alarm types and provide an user-friendly mechanism for users to record their reactions to the alarm.

UI/UX design

Considering the special use scenario in VR environments, where the tester's vision to the apple watch is blocked by the VR headset and controllers are held on both hands, a new interaction method was designed. To elaborate, the traditional user interface with button and text is not suitable for this scenario. As a result, a new interface was built with SwiftUI (an Apple Watch API), which adopted gesture recognizers as the prime way for interaction between the user and the device. Gesture recognizers simplify the event-handling process by tracking touch events and dispatch different reactions based on the different gestures predefined by the developers. Two gestures were included in the applications. Specifically, the alarms can be dismissed by a single tap gesture (known as the WKTapGestureRecognizer in the Apple watch API), whilst the long-press gesture (known as the WKLongPressGestureRecognizer) would stop the application from receiving future alarms. Figure 23 shows the screen map of the worker safety application.

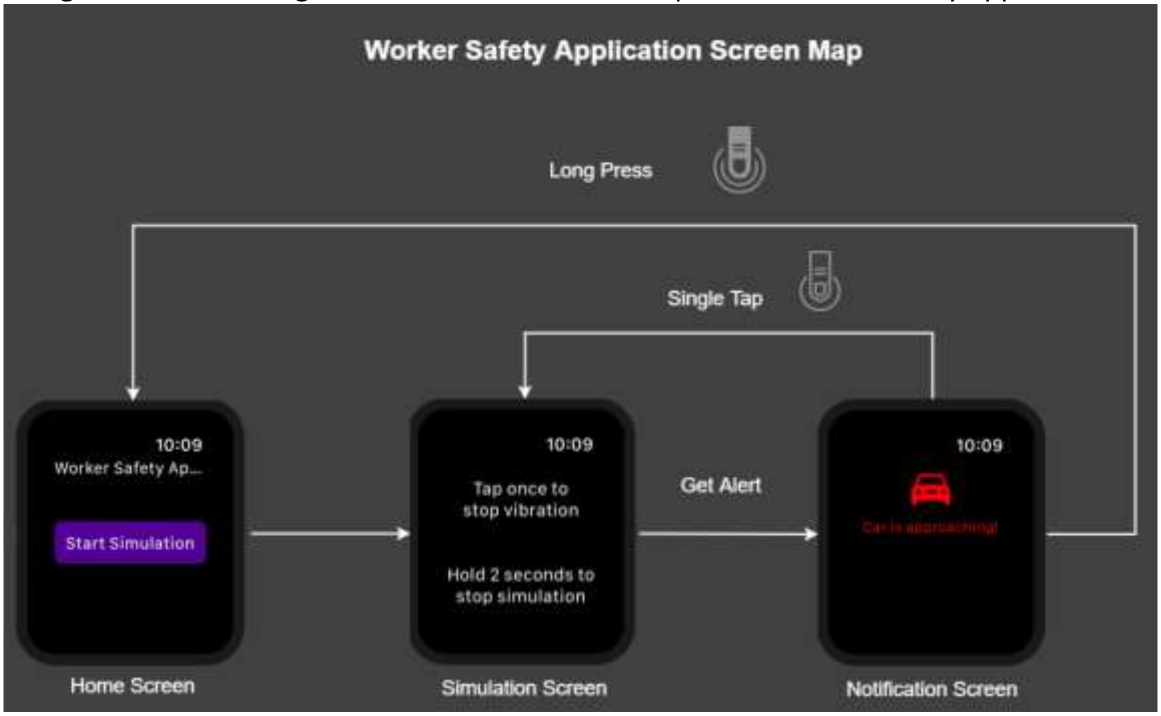


Figure 25 Worker Safety Apple Watch Application Screen Map

App development

There are three main modules in the application: the first one is the interface controller module, which handles screen transactions and user interactions such as touching a button and swiping the screen; the second one is the alarm module, which delivers different vibration and sound patterns to the user according to the alarm messages received; the last one is the network module, which gets messages from the server and posts the user behavior log back. Figure 24 illustrates the flowchart of the worker safety application.

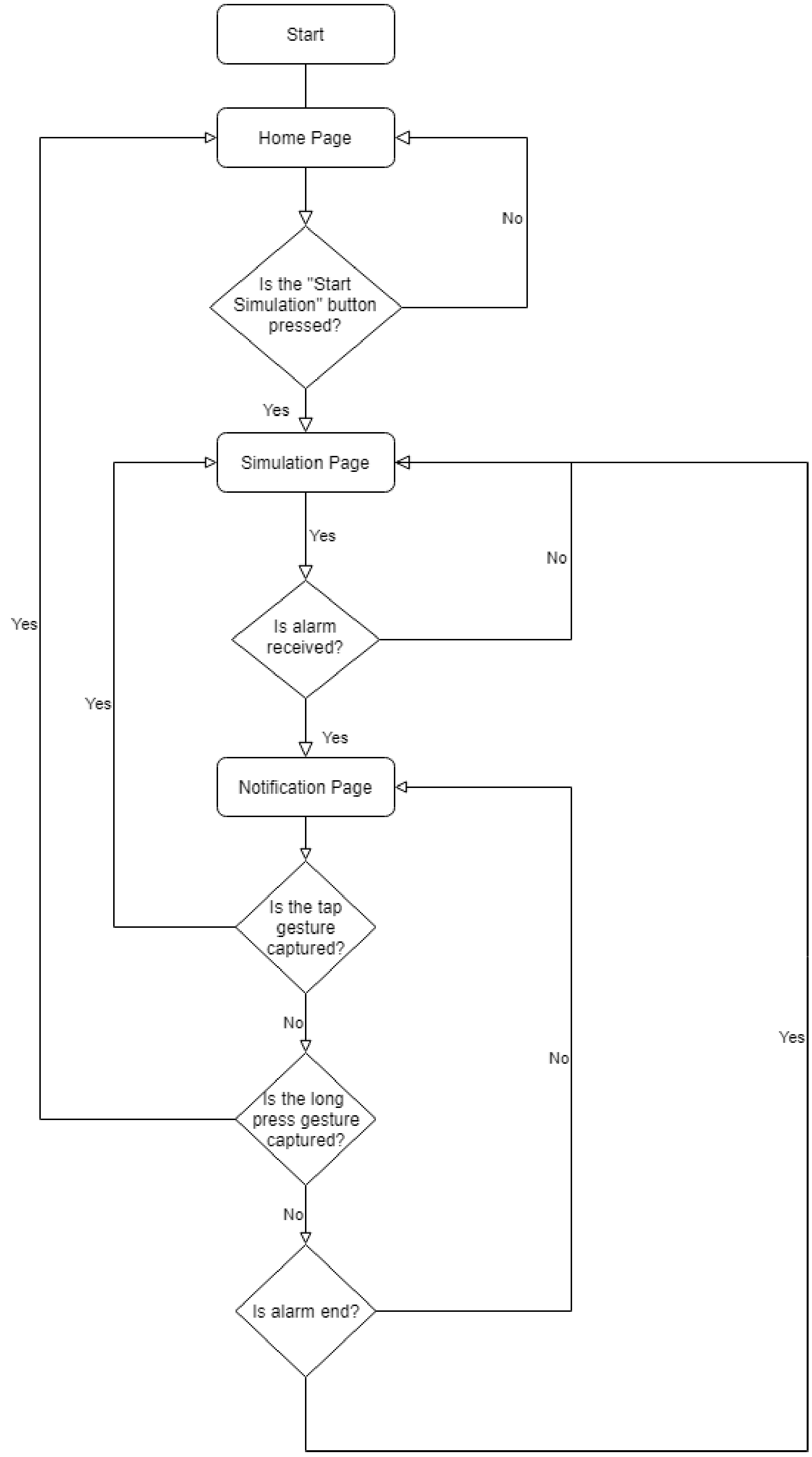


Figure 26 Worker Safety Apple Watch Application Flowchart

The interface controller module is the default module when an Apple Watch application is created in the Xcode. The WatchKit framework provides an elegant way to connect the Interface Objects in the storyboard to the outlets and action method in the code. In this way, the controller can respond to the user interactions it receives. For example, the "Start Simulation" button in the home screen (Figure 23) is connected to the action method "startBtn" which handles the screen transaction from home screen to simulation screen.

```
@IBAction func startBtn() {
    WKInterfaceController.reloadRootControllers(withNames: ["RunningPage"],
        contexts: nil)
}
```

Figure 27 Code snippet of action method for "Start Simulation" in the home screen

Another challenge for the apple watch application is the maximum screen wake time is 60 seconds. According to the WatchOS mechanism, the application will be suspended as soon as the screen turns off. As a result, the application needs the permission to be run in the background. A HKWorkoutSession is initialized in the interface controller module, which supports the functionalities even though the screen turns off. Please keep in mind that this design is specific to the special use scenario in VR environments. The Apple Push Notification service can be implemented if the user vision is not blocked. A code snippet is provided below showing how to set up the HKWorkoutSession.

```
private func start() {
    let configuration = HKWorkoutConfiguration()
    configuration.activityType = .other

    do {
        simulationSession = try HKWorkoutSession(configuration: configuration)
        simulationSession?.delegate = self
        healthStore.start(simulationSession!)
    } catch {
        print(error)
    }
}
```

Figure 28 Code snippet of setting up notification sending when screen is off.

Due to the restriction of the Apple Watch haptic design, there is no instinct method to control the haptic feedback by setting the duration and haptic type. A compromised way was implemented to set up a repeating timer which triggered the built-in haptic feedback in a pre-defined interval. There are twelve types of WKHapticType in the watchOS and WKHapticType.notification was selected considering the vibration strength and pattern. A code snippet is provided below showing how to trigger a custom haptic feedback.

```
a.timer = Timer.scheduledTimer(withTimeInterval: n, repeats: true) { timer in
  WKInterfaceDevice.current().play(.notification)
  a.vibrationCount += 1
  if (a.vibrationCount > n - 1) {
    a.vibrationCount = 0
    a.warningGroup.setHidden(true)
    timer.invalidate()
  }
}
RunLoop.main.add((a.timer)!, forMode: RunLoop.Mode.common)
```

Figure 29 Code snipped on selecting the watch vibration pattern.

The communication between the Apple Watch and the cloud server was also customized according to the new interaction method. A "pull mode" was implemented which allowed the devices to request data from cloud server periodically and deliver it to the users. The HTTP long polling technique was implemented for the HTTP requests. Comparing with the regular polling strategy at a fixed interval, the long polling provides a timeout for the server to respond. The server holds the request open until new data is available. The client will send out new requests only if the timeout is expired or the response is received, which largely reduced the latency as well as the traffic to the server. Alamofire was adopted as the HTTP networking library which was written in Swift and provided fully functional support on top of Apple's Foundation networking stack. The long polling request initialization code snippet is provided below:

```
var req = URLRequest(url: URL(string: END_POINT_URL)!)
req.httpMethod = "GET"
req.setValue("application/json", forHTTPHeaderField: "Content-Type")
req.cachePolicy = NSURLRequest.CachePolicy.reloadIgnoringCacheData
req.timeoutInterval = 5  // the long polling timeout is set to 5 seconds
```

Figure 30 Code snippet of the cloud server pushing the notification to the watch app.

The following code snippet presents the main function used for the HTTP request. If there is no response from the server during the long polling interval (the timeout is set to 5 seconds), the application will catch the timeout error and initialize a new request.

```
func getAPI(a: RunningPageController) {
        Alamofire.request(self.req).validate().responseJSON { [weak self] response in
            switch (response.result) {
            case .success:
                if let json = response.result.value {
                    let responseData = json as! NSDictionary
                    let isCarApproaching = responseData.object(forKey: "result") as! Int
                    // validate the message and make response
                    if (isCarApproaching) {
                        // show the warning icon
                        self?.warningGroup.setHidden(false)
                        // trigger vibration based on the type of alarm
                        self?.vibrate(responseData.object(forKey: “type”))
                    }
                    self?.getAPI(a: self)
            case .failure(let error):    // handling timeout error and other exceptions
                self?.getAPI(a: self)
            }
        }
    }
}
```

Figure 31 Code snippet showing the watch app retrieving alarm information from the cloud server.

Q\A testing

Manual testing was performed both in the emulator and the physical device. Xcode provides a built-in simulator for developers to test their applications under different IOS versions and devices. After the simulator is started, developers can use the mouse to simulate any input from the user. A unit testing was performed to check if each module worked as designed individually. After the unit testing, an integration testing was performed to evaluate the application in order to expose any defects during normal usage. Finally, the application was deployed (build and run) in the Apple Watch. According to the Apple Watch design documentation, an iPhone is mandatory to be paired with the Apple Watch in order to install any application in the Apple Watch. A field testing was performed to inspect the functionality and usability of the application.

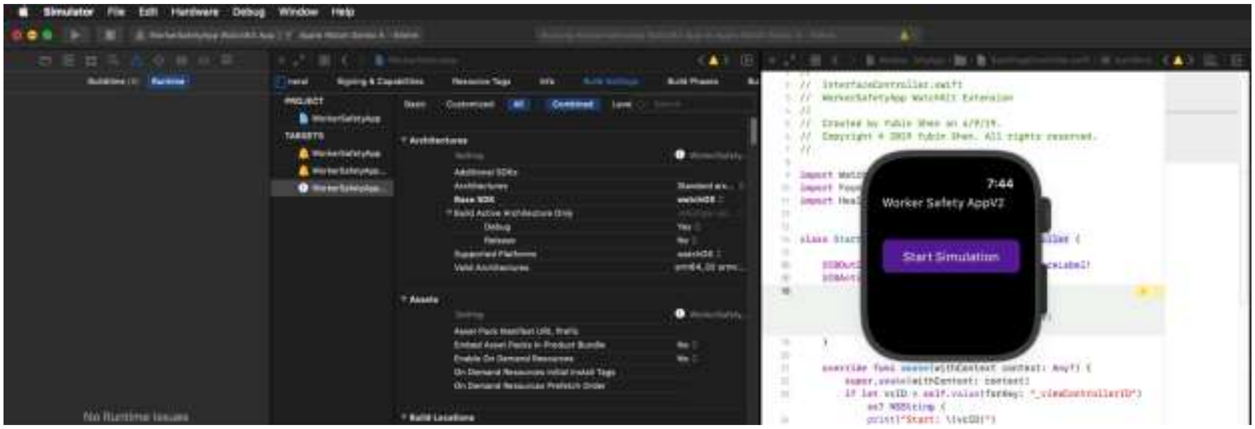


Figure 32 Integration testing with Simulator in Xcode

Although the application was fully functional and worked as designed, there are still some aspects that require improvement. The first issue is the application is power-consuming. The average usage time for Apple Watch is 4 hours which could not last for a normal workload for a worker. Another issue is the application is tight coupled with the VR environment. The core assumption for the design is the user's vision is blocked by the VR headset. The application requires new mechanism to improve the user experience if the user do not use VR headset, such as notification service.

For the cloud server (Figure 31b), a Python web framework called "Tornado" was implemented as the web server application. By using non-blocking network I/O, Tornado can scale to tens of thousands of open connections, making it ideal for long polling and other applications that require a long-lived connection to each user. A queue of safety alarms is maintained containing the alarm information from the VR application. The newly arrived alarm will be added to the alarm queue while the oldest alarm currently in the queue being checked for time-out (i.e., exceeds the maximum time to respond to an alarm). If the alarm is not timed-out, the cloud server then sends the alarm to the smart watch equipped on the worker. The smart watch (Figure 31c) then uniformly draws from a pre-defined set of modalities (e.g., vibration, sound), frequencies (e.g., 3/20 seconds, 6/20 seconds), and durations (e.g., 3 seconds, 5 seconds). Next, the alarm will be delivered to the worker on the smart watch, and the worker can decide to read or dismiss the alarm by tapping the smart watch display or simply ignoring the alarm. In the meantime, the workers' response (i.e., dismiss or read) towards the alarms are being monitored. Currently, the test subjects can acknowledge receipt of the alarm by touching the screen of the smartwatch once and dismiss the alarm by touching the screen twice. For future research, the smartwatch will also be modeled in the VR environment, and alarms will be replicated in VR as the subjects receive them. Additionally, while the workers are performing the assigned tasks in VR, their HRVs are constantly monitored by a PPG sensor. HRV is used to infer the level of vigilance and stress of workers when they receive safety alarms of potentially dangerous situations.

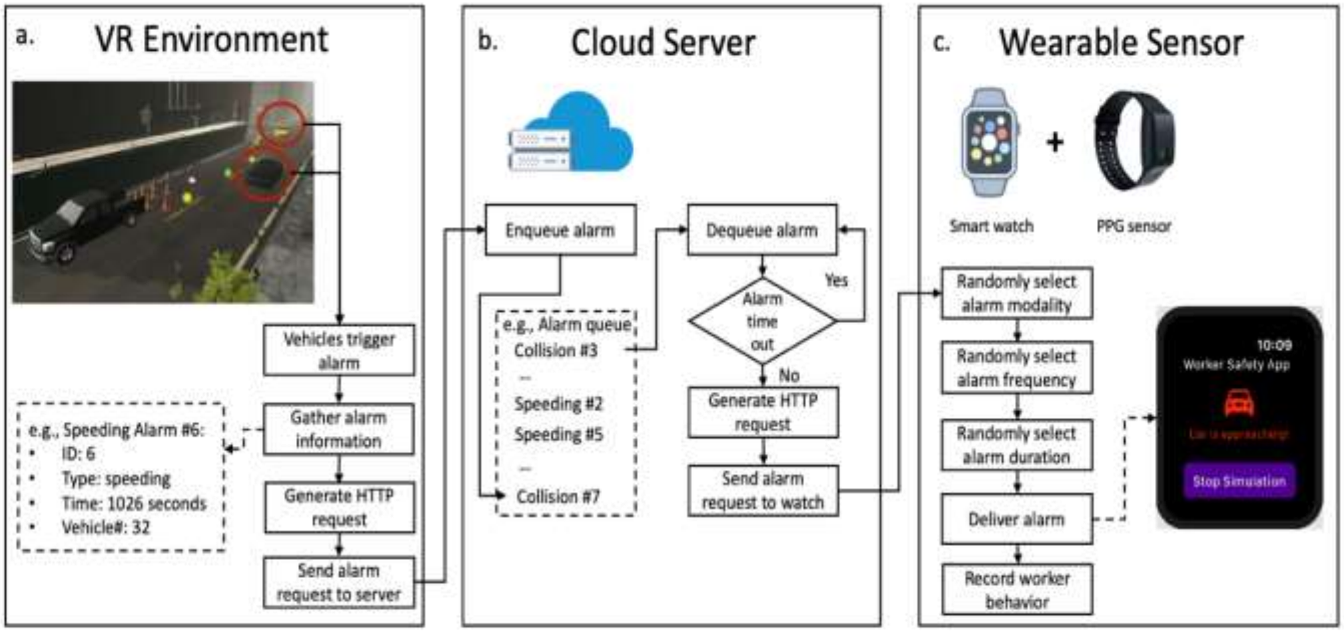


Figure 33 Alarm delivery mechanism from VR to wearable sensors on workers.

In addition to the alarm the workers received on their wrists, they also receive visual alarms in the VR environments in the form of an opaque display panel popped up on their upper right corner of their field of view (as seen in the figure below). The research team is planning on implementing a virtual smart watch in the VR environment, so that the construction workers can visualize the alarm in the VR environment. The advantage of a smart watch replica in the VR environment is that the participants will have a more natural interaction as to raise their wrist when they feel a vibration, and see the alarm being replicated on their virtual wrist, to increase the feel of realism.

Figure 34 A speeding alarm panel in the view of the worker in VR environments.

The research team plan to conduct user studies to test the effectiveness of alarms sent in various modalities, frequencies and durations. The results of this study will (1) prove if there is a statistical difference of worker behaviors towards alarms sent in various modalities, durations and frequencies; (2) explore if workers experienced any physiological changes when receiving alarms and when facing "dangerous" situations in VR; and (3) create a reinforcement learning based approach using the collected user interaction data with the alarms to build an alarm system capable of sending alarms that are most likely to be noticed by the workers to avoid work zone incidents.

4. Conclusion and future work

This study proposed an integrated approach to create a VR plus wearable sensor platform to study when and how to push safety alarms to construction workers at work zones based on their behaviors towards previous alarms. The data collected from the wearable sensors will be used to calibrate an alarm system to optimally deliver safety alarms for maximum worker attention. Towards this goal, within the context of this report, we introduced the technical details of the system components and how they were integrated over a specific scenario implemented in VR. The content of this report will extend the current line of research by providing the technical guidance on integrating biometric sensors, traffic simulations, and interaction gadgets (e.g., smart watch) in VR platforms for interactive user studies.

The research team had secured an approval from the institution's IRB with the application number IRB-FY2020-3946 and had started initial alpha tests within the research group with four participants before the coronavirus outbreak that caused all in-person research to shut down. The participants' response towards the alarms delivered in various modalities, frequencies and duration were monitored and analyzed. During initial testing, the alarms were delivered in two modalities, as vibration and visual alarm. Alarm frequency was set as either 3/20 seconds or 6/20 seconds, and the alarm duration was set as either 1 second or 3 seconds. The hypothesis of the initial testing is that the behaviors of the workers (i.e., read or dismiss) will be statistically significantly different when the alarms are sent in different modalities, frequencies, and durations with a significance level of 0.05. The hypothesis was tested using a paired t-test. From the t-test results, it is apparent that the participants were sensitive to (i.e., the participants' behavior towards the alarm being statistically significant) the alarm modality and frequency but not the duration. Further user tests will be conducted to validate the initial results with a larger subject pool once the suspension of in-person research is lifted.

The outcome of this study will (a) inform us whether data from wearables are meaningful to correlate with human responses to alarms and (b) provide a guidance to effectively integrate wearables to work practices at job sites and define a sequence of steps to follow to analyze the collected data. In the long run, as shown in [54], it is also possible to use other rich sources of real-world data in addition to the simulated data that is being collected in this study to further analyze safety impacts of different traffic work zones at the network level. The research team is also working on an automated method to achieve real-time SUMO-Unity connection, so that the simulated traffic condition can be represented in VR, and the VR environment can serve as a feedback loop to the simulation to change some simulation parameters.

Once the in-person research ban is lifted by the IRB, the research team will start to conduct user studies to test the effectiveness of alarms sent in various modalities, frequencies and durations. The team expects to recruit more than 90 test subjects and use the collected data to conduct data analysis to (1) prove the statistical difference of worker behaviors towards alarms sent in various modalities, durations and frequencies; (2) find if workers experienced any physiological changes when receiving alarms and when facing "dangerous" situations in VR; and (3) create a reinforcement learning based approach using the collected user interaction data with the alarms to build a recommendation system capable of sending alarms that are most likely to be noticed by the workers to avoid work zone incidents.

5. Outreach activities

5.1. Demo at the 2020 TRB conference as a UTC project

The research team participated in the 2020 TRB conference at Washington D.C. The team presented the VR model for the first scenario as a UTC project. More than 20 people experienced the VR environment to finish the construction task in VR. Photos of participants trying the VR environments are shown in Figure 31. A video of the team demonstrating the technology can be found on YouTube: https://www.youtube.com/watch?v=9kwFahVFnX0.

Figure 35 Photos of participants trying the VR environment at TRB 2020.

5.2. Research seminar

The research team held a technical seminar on May 26th, 2020 to the members of the C2SMART institutions. The seminar is entitled "Increasing work zone safety: Worker behavioral analysis with integration of wearable sensors and virtual reality". During the seminar, the research team presented the integrated approach proposed to quantify worker behavior towards safety alarms. Furthermore, the research team demonstrated the workflow of integrating SUMO traffic simulation with a game engine, so that traffic conditions can be simulated in real-time in the VR environments.

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