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Work Zone Safety: Behavioral Analysis with Integration of VR and Hardware in the Loop(HIL)

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Executive Summary

Although there have been efforts to achieve the zero deaths on horizontal construction projects, undesired crashes within work zones continue to happen, highlighting the need for continuous studies on work zone safety improvements. An advantageous tool to be used in such studies is the Virtual Reality (VR) technology, as it provides a safe and highly realistic environment for performing behavioral experiments without endangering the participants. However, researchers still face the challenge of integrating real-world traffic data and interactions in VR back to simulation environments. Hardware-in-the-loop (HIL) is a testing paradigm where physical sensors (e.g., work zone traffic/worker monitoring sensors, worker notification sensors) are connected to a virtual test system that simulates reality (e.g., virtual work zone with simulated dangerous situations). This paradigm is well-suited for conducting user studies for work zone safety because virtual test systems can be implemented using the virtual reality (VR), which allows for safe and realistic testing of a sensing system without putting workers in danger along with avoiding high upfront cost needed to generate research test beds in real world. Traffic simulations can be developed to replicate realistic traffic patterns based on physical characteristics of the road and vehicles, but a two-way link between traffic simulation and VR has yet to be established.

This study presents the development of an integrated platform that allows a two-way interface between traffic simulation and VR environments. The integrated platform enables both applications to spontaneously interact with each other to represent realistic traffic and work zone conditions in the VR environment. The main contribution of this study is the development of the integrated and immersive platform and its customized API tool, called Traffic Simulation-Virtual Reality Integration (TSVRI). The TSVRI API, which bidirectionally transfers information between simulation and VR in real-time, guarantees that the VR environment represents the dynamic characteristics of the work zone traffic and user interactions are fed back to the simulation model to continuously update the traffic information. The integrated platform was tested in alpha experiments and shown to be effective to reproduce realistic traffic scenarios, scalable to different work zone settings (long-, intermediate-, short-term, or mobile), and is ready to be used in experiments with a higher number of participants with different construction experience.

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1. Introduction

Most recent crash data reveal that around 670 crashes in the United States happened around work zones only in 2018, resulting in 124 worker fatalities [(1)]. The data in the last decade also indicate similar trends with an average number of worker fatalities around 126. Recent investigations revealed that 67% of 400 highway construction firms complained about crashes due to intruding vehicles, resulting in deaths, where 8% of these casualties are from workers [(2)]. Although there have been efforts to achieve the zero-deaths vision on horizontal construction projects, undesired crashes within and around work zones continue to happen, highlighting the need for continuous studies on work zone safety.

The most common safety measures adopted in previous years to improve work zone safety have targeted the drivers' behavior. Some of these safety measures aim to control the traffic speed by using fixed or variable message signs, police enforcement, speed display trailer, flagging and lane width reduction, channelizing devices [e.g., cones, drums, and barricades, flashing arrow panels, impact attenuator devices (TADs), and portable concrete safety shape barriers (PCBs)] [(3)]. These measures also include the design of work zone layouts and speed limits based on the Federal Highway Administration (FHWA) regulations [(4)] and the use of intrusion safety alarm systems such as SonoBlaster (i.e., impact-activated intrusion safety alarm system) [(5)], Intellicones (i.e., modular radio-based intrusion safety alarm system) [(6)], and Advanced Warning and Risk Evasion Systems (AWARE) (i.e., radar-based intrusion safety alarm system) [(7)]. The intrusion safety alarm systems, along with training and the use of high-visibility Personal Protective Equipment (PPE) are a few of the measures used to increase work zone safety from the perspective of workers.

Although various measures are being discussed and implemented at sites from the perspectives of workers and drivers, workers still find themselves exposed to traffic and at risk of being struck by a vehicle; especially, the workers of mobile and short-term work zones. Workers like flaggers and surveyors usually have no barriers between them and the traffic, which is one of the reasons why they are at the highest fatality risk [(8, 9)]. In addition to having few to none barriers, these road users need to direct their attention to the job they perform, which can limit their visual and auditory response to the events happening in the background. One of the ways to capture the attention of roadside workers is intrusion alarm systems. Intrusion alarm systems make use of audio and lightning features to safely alarm both drivers and road workers of an intruding vehicle. The primary challenge of these systems is that the auditory and visual cues might get mixed with those present in the work zone. Alternative to existing visual and auditory warning systems, tactile sensory warning systems are another common attention enhancement tool used in work zones. They have been shown to obtain accurate information transmission and response. These aforementioned solutions still need to be further investigated to validate their use and assess their performance in work zones [(10, 11)]. Hence, there is a need to understand how workers respond to different modalities of safety alarm systems at work zones.

One way of reducing work zone issues is the implementation of monitoring and alarm/notification systems (i.e., worker safety systems) at work zones. Real-world tests for evaluating worker safety systems (Figure 1a) require a sizeable experiment area, expensive equipment, and highly controlled safety protocols to prevent worker injuries, therefore such real-world testbeds eventually are far from what workers would experience in day-to-day work zones. Moreover, user-studies that involve evaluation of worker safety systems during real ongoing work can disrupt workers' work routine, which causes schedule delays or cost overruns and are not desirable at job sites. The lack of realistic representation is mainly because the experiment is highly controlled to guarantee the safety of participants, as it is unethical to expose people to real danger while performing experiments for the sake of research, and the number of vehicles is limited to one or two with pre-determined trajectories. On the other hand, Hardware-in-the-loop (HIL), as seen in Figure 1b, bridges the “virtual test systems” (i.e., work zone in VR with simulated traffic and dangerous situations) and the “worker safety systems” (i.e., worker monitoring and alarming hardware) by deploying physical hardware (e.g., ultrasonic sensors, smartwatches) to a simulation of reality (i.e., VR work zone).

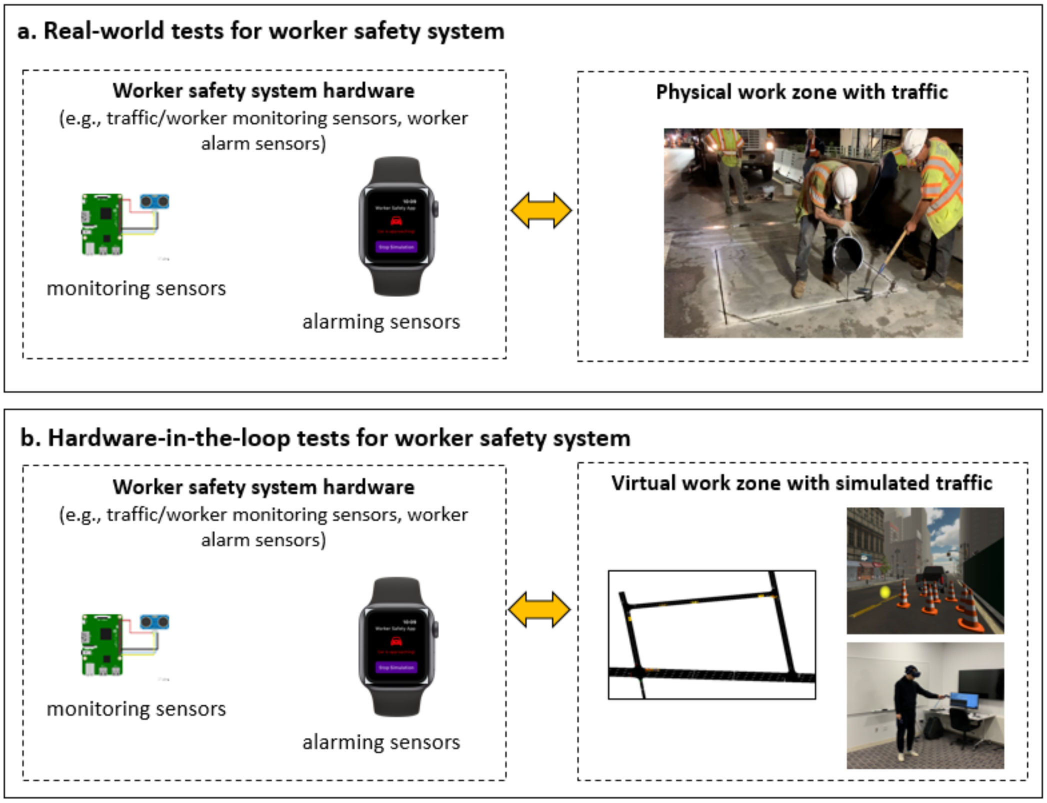

Figure 1: Overview of components involved in HIL-enabled vs. physical testing platforms for evaluating worker safety systems

To realistically simulate a physical work zone in such a setting, Virtual Reality (VR) technology provides opportunities. VR environments are virtual representations of real-world settings (e.g., a work zone), and have proven to be a suitable alternative for field experiments with real sense of presence as well as a good fit for performing human behavior studies [12,13]. However, in current VR studies, traffic patterns are often represented with pre-determined volume and vehicle trajectories [7] and feedback on user behaviors on the updated traffic patterns are ignored, both of which prevent the ability of VR in achieving an up-to-date representation of the real and continuously changing traffic behavior. Hence, one of the bottlenecks in using VR environments for studying worker behaviors towards worker safety systems is establishing a bi-directional flow between VR and simulation environments to automatically send realistic traffic patterns from traffic simulation environments to VR environments and modify these patterns in response to the actions taken by users in the VR environments.

Towards performing user studies in VR settings to test worker safety systems with real worker behavioral feedback, we developed an integrated HIL platform that enables an immersive experience for workers with realistic simulated traffic patterns and dangerous situations through bi-directional communication protocols. Workers' behavior in the virtual work zone is monitored while alarms can be sent to warn workers of potentially dangerous situations. This HIL platform includes two main components, as the virtual test system (i.e., virtual work zone) and the worker safety system (i.e., hardware being evaluated based on worker behaviors). The virtual work zone includes a traffic simulation platform and a game engine used to create VR environments. Major components of the virtual work zone include the state-of-the-art traffic behavior simulation platform-Simulation of Urban Mobility (SUMO) [14] and a gaming engine (i.e., Unity 3D) to generate and model virtual environments. SUMO's Traffic Control Interface (TraCI) API sends the outputs from SUMO to Unity3D. Then, a customized API tool, namely TSVRI, developed by the authors, enables the exchange of information regarding the modifications performed in Unity3D to SUMO. The updated modifications sent from Unity3D to SUMO generate a new simulation with these recent changes in the roads. The worker safety system implemented in this study include two main parts, a monitoring hardware and an alarming hardware. Monitoring hardware is geared towards monitoring worker's location with regard to the work zone perimeter, while alarming hardware is used to send alarms regarding potentially dangerous situation to the construction worker. The virtual test system and the worker safety system are connected using application servers that relay worker behavioral information (e.g., worker location) and safety alarms between the two components. This report provides the components of this integrated platform and the integration steps to guide the implementation of such platforms for related studies.

2. Motivation

One of the challenges of studying safety in work zones is the lack of comprehensive data and infrastructure for testing new technologies, especially when it comes to understanding the perspective of workers [15]. There is no available data set that provides information about road workers' behavior when exposed to dangerous interactions with vehicles and their reactions to existing safety warnings. In this study, a dangerous interaction is adopted as a hypothetical case study in which the lives of road workers, vehicle drivers, and passengers are put at risk due to the actions of drivers or workers. For instance, a road worker in the apparent trajectory of an intruding vehicle that is speeding is considered a dangerous interaction. To truly understand how road workers behave in a work zone environment while closely interacting with traffic and how they respond to safety alarms (auditory, visual or tactile), it is necessary to accurately reproduce the work zone environment, traffic conditions, and the various possible dangerous interactions.

Physically recreating different work zone scenarios in a controlled setting would require a substantial amount of financial, capital, and personnel resources. It would involve the cost of vehicles, construction materials such as fencing and construction equipment, hiring personnel to participate and control the experiments, and a location that would fit the infrastructure. Having participants go to real work zones is not ideal either, as it might generate conflicts with working hours. Moreover, both settings would increase the exposure of the participants to unsafe situations and other road users to a real danger. An alternative method to perform road workers' behavioral experiments is using VR technology, which has the advantage of providing a highly realistic environment without exposing the participants to real danger [16]. However, user experiments using VR technology still have to overcome the challenge of incorporating real-time field data in the VR environments [17].

Some studies have already used VR to study work zone environments from the perspective of the driver. For example, Bella [18] performed the 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 in speeding behavior inside the work zone under different scenarios continued to be a subject of interest in recent studies [19,20]. Another use of VR for work zone safety is for the analysis of key factors contributing to work zone crashes [21]. Even though VR technology has been consistently used in work zone safety studies, there is a gap in the literature regarding its use to understand the behavior in work zones of construction and road workers, and to calibrate emerging safety alarm systems using the reaction of workers to these systems.

The integrated HIL platform detailed in this report aims to provide a realistic experiment environment of work zones in the form of VR to understand construction workers' behavior towards "safety alarm systems" during dangerous scenarios. Part of the challenge of incorporating real-time data into VR environments, which prevents workers from achieving a true-to-life experience, is real-life traffic representations. In VR environments, the vehicles in traffic usually follow pre-determined pathways with minor changes in speed and direction, which can seem engineered instead of realistic when compared to real-world traffic. The second challenge, which is more specific to work zone VR environments, is that real-world construction workers can influence traffic by instituting traffic control measures (e.g., setting up traffic barriers), which needs to be reflected in the VR and simulation environments as well.

3. Background

This study builds on and extends the research studies at the intersection of (1) applications of VR in worker safety studies in the architectural, engineering, construction (AEC) industry, (2) current and emerging sensing technologies adopted at traffic work zones, and (3) previous research studies investigating sensors deployed onsite for construction worker safety.

3.1 Applications of Virtual Reality in Worker Safety Studies in the AEC domain

Virtual reality (VR) has been widely used in construction worker safety studies due to its ability of replicating realistic work zone environments. Furthermore, VR allows for an immersive experience of hazardous situations without actually putting workers in physical harm. Studies using VR in the domain of worker safety concentrates on three main aspects, as safety training and education, safety planning and safety inspection [22]. These application areas are not specific to horizontal work zones.

For safety training and education, traditional means (e.g., lectures, videos, and demonstrations) suffer from low engagement and learning from trainees. VR-based safety training aims to simulate realistic work zones where trainees can rehearse tasks safely while identifying potential risk factors for an operation [23]. The realistic and interactive VR environments increase workers' attention and enthusiasm to learn and to improve safety knowledge. Detailed information of the construction project, such as site layout, egress access, and material locations can be replicated in VR, which allows trainees to better understand the construction operations planned onsite. Studies comparing VR-based safety training with traditional methods concluded that VR is a more efficient and engaging platform for trainees to learn safety related knowledge [24]. On the other hand, VR-based training is found to be superior than training in the physical work zone environment due to its ability to simulate unsafe scenarios without putting trainees in danger. Furthermore, studies comparing VR-based training and training in physical settings concluded that VR requires fewer mental efforts from the trainees since demonstrations onsite can be overwhelming for trainees [25].

Safety planning refers to the identification of potentially unsafe scenarios and practices in a construction project prior to the actual construction. Traditional safety planning relies on 2D drawings, accident reports, and computer-aided design models (CAD files). This prevents construction crew, site safety managers, and owners from intuitively understanding the site layout, design requirements and previous incidents' circumstances. In this regard, VR-based safety planning offers superior level of immersion as compared to traditional mediums of planning documents [26]. As a result, construction crews can achieve higher ability of risk assessment and level of situation awareness, which are critical to site safety [27]. Evidence showed that in VR environments, construction workers are more likely to identify unsafe practices and scenarios as compared to photos and videos [27].

Safety inspections is the critical examination of the construction sites in terms of site safety and worker behavior. To effectively monitor worker behavior and site environment, site safety managers do visual inspections during walk-arounds or through the help of cameras installed at various locations onsite. However, these current practices have drawbacks, as physical walk-arounds take time and prevent the site safety manager to holistically understand the overall safety condition of the job site. On the other hand, video streams from static camera locations provide the flexibility of monitoring multiple locations simultaneously but limit the possibility of freely examine the site environments from different angles. VR-based safety inspection reconstructs the job site in a realistic 3D virtual environment, while locations of worker, material, and equipment can be tracked and represented in VR in real-time, which provide insights of travel speeds, paths, and locations of workers and equipment. Compared to traditional inspection methods such as camera recordings, the VR-based safety inspection enhances the ability of safety managers to identify job site hazards more promptly by enabling more flexible viewing angles and better context-awareness.

Despite the wide adoption of VR in construction worker safety applications, challenges remain for horizontal work zones, as the traffic pattern represented in these VR environments are often static and follow pre-determined trajectories. This prevents workers from experiencing a realistic work zone environment, and more importantly, limits the possibility of studying the impact of worker behavior on traffic patterns. This study builds on previous applications of VR in the worker safety domain, and adds a traffic simulation component to generate realistic traffic patterns in VR while enables the possibility of studying worker behavior's impact on traffic simulation.

3.2 Current and Emerging Sensing Technologies Adopted at Traffic Work Zones

Work zones are areas in which roadwork is done. They take place in the road and share the space with vehicle traffic most of the time. The layout of work zones can vary with the work to be performed, the location of them (i.e., urban vs. rural), and the type of road. According to the Manual on Uniform Traffic Control Devices (MUTCD) (28), work zones can be categorized as mobile, short duration, short-term stationary, intermediate-term stationary and long-term stationary, depending on the complexity of the work. Mobile work zones are for quick roadwork that takes up to an hour and needs to move intermittently (e.g., pothole filling, surveying, and tree trimming). Short-term work zones refer to the roadwork that happens during daytime for more than one hour but within a single day (e.g., traffic barrier repair, placement of overhead structures, and traffic hardware maintenance / installation) (29). Intermediate-term work zones are for roadwork that happens during daylight for more than a day but up to 3 days or lasts for more than hour during nighttime (e.g., pavement markings, barriers, and temporary roadways) (30). Finally, the long-term work zones are for roadwork that takes more than 3 days (e.g., installation of permanent barriers, marking in long segments of road). The long-term and intermediate work zones usually have detailed safety guidelines and are thoroughly planned, whereas short-term and mobile work zones have fewer specific safety guidelines and separation from traffic (31). Thus, workers in short-term and mobile work zones are more likely to be exposed to the risk of being struck by upcoming traffic (31).

The most common safety measures adopted in previous years to improve work zone safety have targeted improving drivers' behaviors. Some of these safety measures aim to control the traffic speed by using fixed or variable message signs, speed display trailer, flagging and lane width reduction (3), and designing work zone layouts based on the Federal Highway Administration (FHWA) regulations (4). On the other hand, safety measures targeting construction workers focus on the use of intrusion safety alarm systems such as SonoBlaster (i.e., impact-activated intrusion safety alarm system) (5), Intellicones (i.e., modular radio-based intrusion safety alarm system) (6), and Advanced Warning and Risk Evasion Systems (AWARE) (i.e., radar-based intrusion safety alarm system) (7). These intrusion safety alarm systems, along with worker safety training and the use of high-visibility Personal Protective Equipment (PPE) are a few of the measures used to increase work zone safety from the perspective of workers.

Despite current safety measures, workers still find themselves exposed to traffic and at risk of being struck by a vehicle; especially, the workers of mobile and short-term work zones (i.e., work lasts less than one day). Workers like flaggers and surveyors usually have no barriers between them and the traffic, which is one of the reasons why they are at the highest fatality risk (8, 9). In addition to having few to no barriers, these road users need to direct their attention to the job they perform, which can limit their visual and auditory response to the events happening in the background. One way of capturing the attention of roadside workers is intrusion alarm systems. Intrusion alarm systems make use of audio and lighting features to safely alarm workers of an intruding vehicle. The primary challenge of these systems is that the auditory and visual cues might get mixed with those present in the work zone. Alternative to existing visual and auditory warning systems, tactile sensory warning systems are another common attention enhancement tool used in work zones, which have been shown to transmit accurate information regarding an intruding vehicle. However, these aforementioned solutions still need to be further investigated to validate their use and assess their performance in work zones (10, 11), to understand how workers respond to different modalities of safety alarm systems at work zones.

3.3 Previous Research Studies Investigating Sensors Deployed Onsite for Construction Worker Safety

Sensing technology has been implemented on construction sites for decades, covering a wide variety of application areas (e.g., worker safety monitoring, material route planning, progress monitoring, concrete curing). For construction worker safety, three main types of sensors are deployed onsite based on sensor operational principals (i.e., how sensors emit and receive signals), including time of flight sensors, energy field-based sensors and vision based sensors.

Time of flight (TOF) sensors, measure the distance between the sensor itself and surrounding objects (e.g., construction equipment, workers) by calculating the time of flight between the emission of a signal and the time when the signal is received. Based on the type of signals emitted, TOF sensors can be categorized as sonar (sound navigation and ranging), radar (radio detection and ranging), and LIDAR (light detection and ranging). Sonar (i.e., ultrasonic sensor) measures distance using high-frequency sound wave signal. While the ultrasonic sensor is cost effective and easy to deploy, drawbacks remain as high-frequency sound wave can be disturbed when transmitted in a long range (32, 33). Hence, ultrasonic sensors are well-suited for lab settings with minimal disturbances. Similarly, radar uses electromagnetic wave signal (often above 300 MHz) to measure the distance between the sensor and a physical object. Radar is superior than sonar in terms of sensing range, but it is more expensive, and the electromagnetic signal can be unevenly reflected by the target object's surface material resulting in frequently lost signal (34). Finally, LIDAR uses laser (a type of light signal) to measure distance and 3D shapes of the surroundings by rotating the laser emission sensor. The more laser beams a LIDAR transmits, the higher resolution the 3D surroundings are scanned. While LIDAR is the most accurate distance measuring sensor (35) among TOF sensors, it also is the most expensive. Furthermore, the dataset size collected through a LIDAR sensor makes it unfit for monitoring a dynamic work zone, but more suitable for scanning and reconstruction of a realistic but static representation of the work zone.

On the other hand, energy field (EF) based sensors (e.g., radio frequency identification, Bluetooth low energy) broadcast signals in all directions and detect proximity of other EF sensors via sensor signal communication. These sensors are more versatile since they do not require careful placement of the line of sight for the sensor. However, EF sensors are not as accurate as TOF sensors (36) in terms of sensing distance and location. Moreover, the use of EF sensors requires all targets to be equipped with one such sensor for others to detect, which prevents the use of these sensors at a large scale. EF sensors have been deployed onsite for worker location tracking (37). However, the low accuracy and fidelity of these sensors remain an issue to be solved before they can be reliably used for construction safety applications.

In recent years, vision-based sensors are increasingly considered and deployed for construction safety applications onsite. Vision based sensors uses imaging devices to capture photos or videos of construction sites on static (e.g., surveillance cameras) or mobile (e.g., drone-carried cameras) platforms. However, vision-based sensors do not have the ability to detect location or distance alone. Rather, they require accurate algorithms developed to process imagery or video data running from a remote server. With the development of computer vision techniques, these algorithms are becoming more available, hence making vision-based sensors suitable choices for worker safety applications.

Albeit the wide adoption of sensing technology in worker safety applications, challenges remain as there is a lack of realistic testing platform where the worker behavior towards these sensing solutions can be tested exhaustively and safely. The hardware-in-the-loop approach proposed in this study addresses this issue by creating realistic virtual work zones that can be used to conduct worker behavioral studies.

The integrated HIL platform proposed in this paper aims to provide a realistic experiment environment of work zones in the form of VR to understand construction workers' behavior towards "safety alarm systems" during dangerous simulated interactions. Part of the challenge of incorporating real-time data into VR environments, which prevents workers from achieving a true-to-life experience, is realistic traffic representations. The second challenge, which is more specific to work zone VR environments, is that construction workers in physical work zones can influence traffic by instituting traffic control measures (e.g., setting up traffic barriers), which needs to be reflected in the VR and simulation environments as well. These challenges are addressed in this integrated approach by implementing a bi-directional information path between the virtual work zone and the worker safety system that encompasses hardware monitoring and alarming the workers. Details of this approach is discussed in the next section.

4. Integration of VR, HIL, Biometric Sensors, and Traffic Simulations

4.1 Module 1: Integrated Platform for Enabling Real Interactive Traffic Simulations in VR

The integrated platform allows a two-way information flow between traffic simulation tools and VR environments, with the help of a cloud server to relay the information. As seen in , there are three components of the platform, 1) traffic simulation tools (e.g., SUMO), which are used to build realistic traffic patterns given a road network; 2) VR environments (e.g., Unity3D), which are used as experiment tools to provide a realistic visualization of a physical work zone environment for examining the human behaviors when traffic is present; and 3) cloud servers, which serve as mediums to relay the information between traffic simulation tools and VR environments, and interactions between these three components. The combination of these three components generates realistic traffic flow structured upon reliable and complex traffic models to be presented in the VR environments.

Essentially, the platform can be simplified as an implementation of the information flow pathways depicted in Figure 2, including a feedforward path and a feedback path. The feedforward path transmits the vehicular and traffic control information simulated in a traffic simulation tool to the VR environments. Reversely, the feedback path brings the traffic control changes that occurred in the VR environments back to the traffic simulation tool. To implement this platform, we chose SUMO as the traffic simulation tool and Unity3D as the game engine to implement the VR environments. SUMO was selected due to its open-source nature, which allows easy data access and transfer to other platforms. The TraCI protocol was implemented to initiate communication between SUMO and the cloud server, whereas the communication between VR environments and the cloud server was handled through a custom API, TSVRI, developed by the authors. In the following subsections, each component of the platform will be introduced in detail.

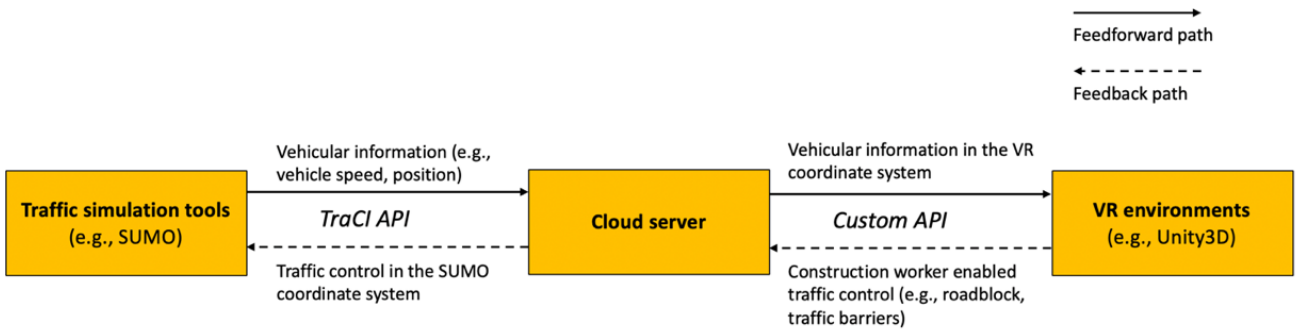

Figure 2: Feedforward and feedback path of Module 1

4.1.1. Traffic Simulation Component

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 defined, and moves individually through the road network [(14)]. Although there are commercial software packages with ready-to-use VR integration, such as PTV Vissim [(38)] and Paramics [(3939)], SUMO was chosen for this project due to its advantages when compared to them. The main advantages of SUMO can be listed as being 1) cost-effective; 2) highly flexible, programmable, and modifiable; and 3) supported with group/forums and documentation. These three characteristics of the software are crucial for simulation and representation of work zone events that occur during complex real-world conditions.

The input data of SUMO contains a road network consisting of nodes, edges, junctions, signals from OpenStreetMap [(40)] and traffic demand information, which can be obtained from observing the real-world traffic situations for the specific simulated area. The output of SUMO is vehicle-based information, such as vehicle speed and position, as well as traffic control information such as the traffic signal information. This information is then sent to the cloud server through the TraCI API. SUMO has been mainly used for the simulation of traffic behavior for studying the effects of roadway design, signalization, flow interruption, traffic control, extraordinary events, and policies on traffic conditions. These types of studies are usually performed by creating a scenario with initial conditions and then altering the parameters accordingly for the objective of the study. For example, SUMO has been used before to evaluate the use of variable speed limits control methods for reducing the congestion due to the presence of a work zone [(4141)]; the effects on traffic of dynamically changing traffic light status to green in the presence of an emergency vehicle [(42)]; and performance of Vehicular *ad hoc* Networks (VANETs) assisted by Road Side Units (RSU) in scenarios such as car crashes and spot weather [(43)].

TraCI and Scenario Development:

One of the most important features of SUMO is TraCI. It is the key component for embedding customized VR control modules into the simulation. TraCI 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 [(44)]. It 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. Moreover, it provides the opportunity of connecting SUMO with Unity 3D to implement VR environments [44].

While previous research studies [45,46] have used one-way communication between SUMO and Unity, this paper presents the development of a bi-directional communication integrated platform. Bi-directional communication is enabled when the traffic simulation output from SUMO is sent to Unity3D for reproducing real-life like traffic in VR, and then, when Unity3D sends information on changes in the environment, such as the placement of a new barrier or cone, back to SUMO. The information sent from Unity3D is processed by SUMO, which changes the environment of the on-going simulation with the new parameters. This new accessible and user-friendly integrated platform provides not only a more realistic environment but also a more interactive one, in which the participant's behavior affects the environment, by using ready-to-use software packages (e.g., SUMO and Unity3D). Recent products have shown to provide two-way communication between traffic simulation and VR environments; however, they are proprietary [47] and/or expensive commercial traffic simulation tools [48].

For the scenarios being tested in this work, the traffic simulations were calibrated by having traffic volume and turning movement counts during peak hours (6-10 a.m.) manually collected at the study intersection. The following sources were used to support the development of the simulation model: NYCDOT Traffic Information Management System (TIMS) [49], INRIX database [50], and video records from closed-circuit television (CCTV) cameras and drones. The calibration of this project includes conventional operational measures (traffic volume counts, travel time and turning movement counts (TMC)), and safety measures (severity distribution of surrogate safety measure (SSM)). Traffic conflicts quantified from surrogate safety measures were also extracted from CCTV and drone videos for calibrating safety measures.

The model parameters were then adjusted to replicate the behavior observed from the real traffic data from the intersection. The calibration considered operational measures, such as traffic counts and travel times, along with safety measures according to the objectives of the simulation project. For the operational part, the simulation model is calibrated to achieve lower overall discrepancies between observed (Y_n^{obs}) and simulated (Y_n^{sim}) measurements for multiple road segments and time intervals, and to avoid significant errors. Therefore, the Root Mean Square Percentage Error (RMSPE) is used as the goodness-of-fit measure. RMSPE is calculated using Equation 1.

$$RMSPE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{Y_n^{obs}-Y_n^{sim}}{Y_n^{obs}}\right)^2} \qquad (1)$$

Where, Y_n^{obs} and Y_n^{sim} are the observed and simulated performance measures respectively, and N is the number of links for volume or number of time intervals for travel time collection. When studying traffic safety, traffic conflicts are used as safety performance measures. Conflict distribution in terms of different levels of severity is used as the comparison target in this project since it can provide more details of the collected conflicts. The different levels of severity of traffic conflicts are categorized using the indicator time to collision (TTC). TTC, proposed by Hayward [51], is one of the most widely used longitudinal surrogate safety measures [52]. It is defined as the time required for two vehicles to collide if they continue on the same path at their present speeds. To measure the goodness-of-fit of the simulated conflict distribution compared to the ground truth distribution, the Kullback–Leibler divergence (a.k.a. relative entropy), which can quantify the "distance" between two distributions, is used. The Kullback–Leibler divergence from Q to P is defined according to Equation 2.

$$D_{\mathrm{KL}}(P \,||\, Q) = \sum_{x \in \mathcal{X}} P(x) \log\left(\frac{P(x)}{Q(x)}\right) \quad (2)$$

Where, P and Q are simulated and observed discrete conflict severity distributions respectively defined on the same probability space, $\mathcal{X}$. As the goal is to minimize the errors between simulation results and observed measures, the weighted sum of the RMSPE of operational measures and Kullback–Leibler divergence (D_{KL}) for safety measures is defined as the calibration objective function, which can be represented by Equation 3.

$$\text{Min} \quad L(\theta, I) = w_1 \cdot RMSPE_V + w_2 \cdot RMSPE_T + w_3 \cdot D_{KL} \quad (3)$$

where, $L(\theta, I)$ is the total simulation error, $RMSPE_V$ is the simulation error of link volumes, $RMSPE_T$ is the simulation error of travel time, D_{KL} is the simulation error of traffic conflict distributions, and w_1, w_2, w_3 are weights of the error terms. In this project, the three error terms are scaled to the same magnitude, then assigned equal weights for calibration.

4.1.2. VR Component and Development of VR Environments

Developing the VR environment includes two steps (Figure 3), namely, 1) importing the road network from a mapping service (e.g., OpenStreetMap) to the traffic simulation tool (e.g., SUMO) and the VR environments (e.g., Unity3D); and 2) adding detailed 3D mesh objects to the work zone, including buildings, street lights, scaffolds, signages, and other objects that were present at the work zone.

In the first step, after identifying the proposed work zone area for traffic simulation, the road network of that area can be downloaded from an open-source mapping service (i.e., OpenStreetMap), as seen in Figure 3a. The file downloaded from OpenStreetMap service, in .osm file format, then needs to be imported into SUMO and Unity3D. SUMO directly recognizes the .osm file format to generate the road network without the need for conversion. For Unity3D, the .osm file needs to be converted into a shapefile (i.e., a type of 3D representation that can be shown in Unity 3D) before it can be imported. Thereafter, SUMO and Unity3D will share the same road network exported from OpenStreetMap. In the second step, a laser scanner (i.e., a LiDAR sensor) can be used to accurately create a point cloud of the work zone, which can be used to generate 3D mesh objects that are present in the physical work zone (e.g., buildings, scaffolds) but are not included in the shapefile of the road network. The point cloud is essentially a six-channel data source, including the coordinates (i.e., x,y,z) and the color information (i.e., R/G/B) of the scanned points in the vicinity of the laser scanner. Mesh objects can be created from the point cloud data using a "scan to mesh" workflow, which links nearby points from the point cloud to form surfaces that resemble the real objects (Figure 3b). The details of the "scan to mesh" workflow can be found in [53].

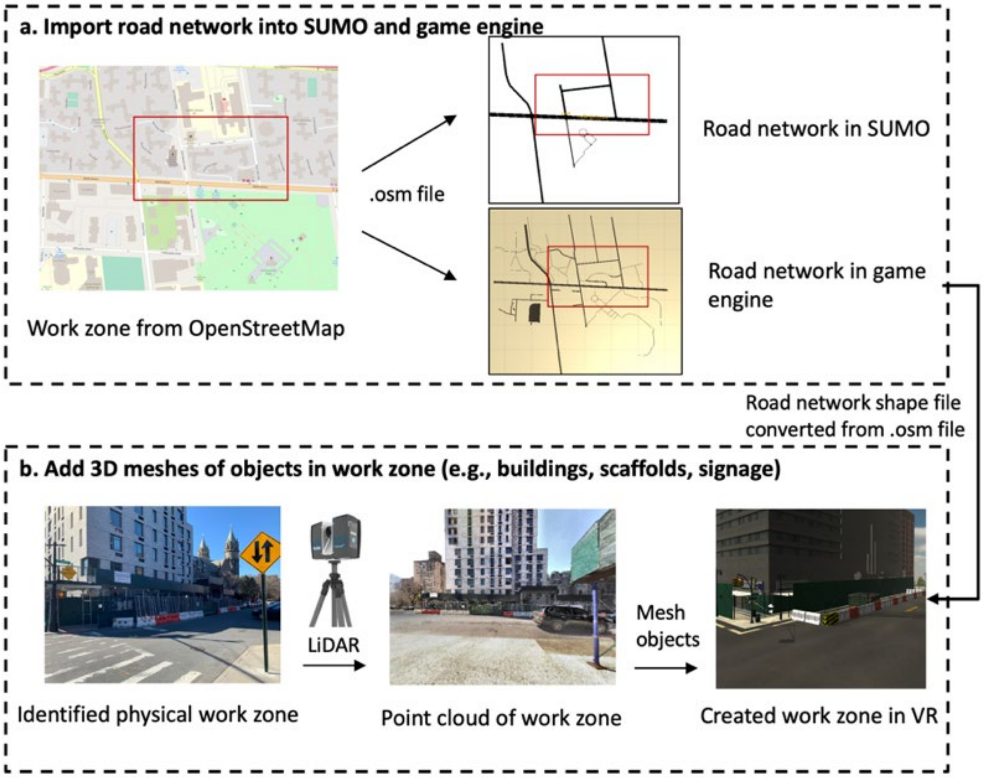

Figure 3: The VR development process with (a) import road network shapes into VR and SUMO, and (b) add detailed 3D objects of the work zone in VR

4.1.3. Cloud Server Component and Information Flow Between VR and Traffic Simulation

After the VR environment is created and the traffic simulation is finalized, an information "bridge" needs to be built to allow the simulated traffic from SUMO to be reflected in real-time in VR and the traffic control measures taken in VR to be reflected in real-time in SUMO. The full client-server interaction through the network is shown in Figure 4. The networking protocol used for this platform is TCP/IP, because it is reliable (i.e., data from the sender is guaranteed to be transmitted through the network) and can preserve the order of the data delivered (i.e., data is received by the server in the order it was sent by the sender).

The information flow between VR environments and simulation tools includes a feedforward path, as indicated in solid arrows in Figure 4, and a feedback path, as indicated in dotted arrows. For the feedforward path, real-time simulated vehicle and traffic control information from the traffic simulation tool (Figure 4a) is packaged into a network packet (i.e., a unit of data sent through the network), and then sent to the cloud server. The packet sent from the simulation tool includes vehicle ID, speed, acceleration, trajectory, and traffic control. The cloud server (Figure 4b) receives the packet, then sends the packets to the VR environment after a transformation to the VR coordinate system. In the VR environment (Figure 4c), vehicles are moved based on the traffic patterns from the simulation. For example, for each vehicle, the position and head angle are determined by the SUMO simulation, and the information from the simulation was implemented as vehicle movements in VR in real-time.

On the other hand, construction workers' actions in VR environments can influence the traffic patterns in VR. For example, a worker could set up a temporary traffic barrier to curb the traffic flow. As a result, such influence should be reflected in the simulation software in real-time, which constitutes the feedback path. This feedback path starts with the traffic control information changes in the VR environments (e.g., a traffic cone is put in the middle of a lane). Next, the type of traffic control devices deployed, and the location of the device will be updated and sent to the cloud server before the server sends the corresponding information to the simulation software. Once the simulation software receives the type and location of the traffic control devices, it will adjust the vehicle movements in the simulation, which will then be sent to the VR environment through the server.

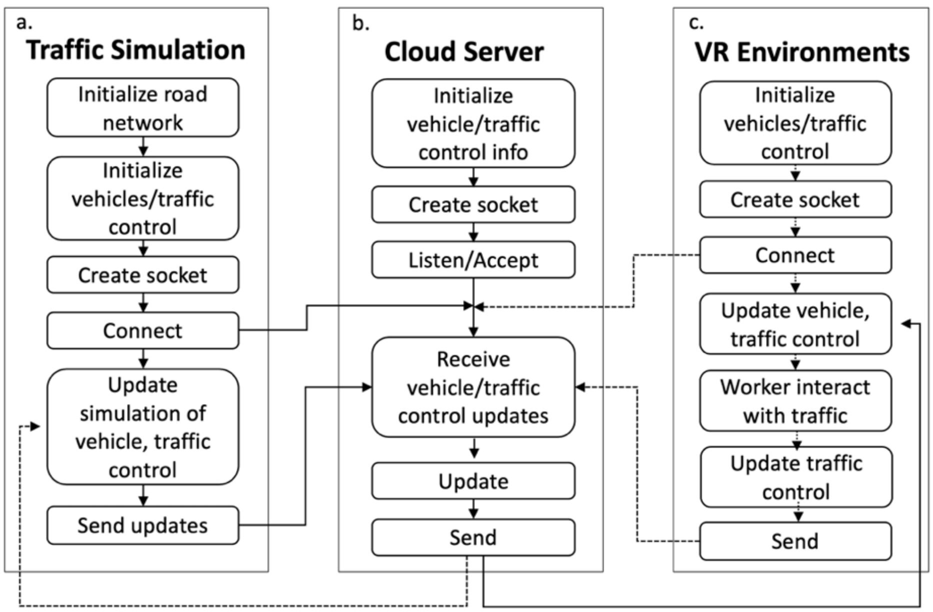

Figure 4: The client-server protocol for transmitting information between VR and traffic simulation software, solid arrows represent the network packets flow from simulation to VR (feedforward path in Figure 2), vice versa for dotted arrows (feedback path in Figure 2)

4.2 Module 2: Extending the Integrated Platform for HIL Integration

The hardware-in-the-loop integrated platform allows a two-way information flow between the virtual work zone and the worker safety system, with the help of an application servers to relay the information. As seen in Figure 5, there are two components of the platform, as (1) the virtual work zone, which includes a traffic simulation tool, a proxy server and a VR environment, where traffic patterns are realistically simulated in VR and worker behaviors in VR circle back to the simulation; and (2) the worker safety system, which includes monitoring hardware and alarming hardware, where the worker location with regard to the work zone perimeter was monitored by sensors and the worker receives alarms whenever a dangerous situation was detected in the VR environment. These two parts are connected through application servers (i.e., simulation application server, and VR application server) to relay information. The combination of these three components generates realistic traffic flow structured upon reliable and complex traffic models to be presented in the VR environments, and allows for a platform that can be used to test worker safety hardware by conducting user studies in VR. First component, virtual work zone, has been detailed in section 4.1.

Essentially, the platform can be simplified as an implementation of the information flow pathways depicted in Figure 5, including a feedforward path, a feedback path and a HIL path. The feedforward path transmits the vehicular and traffic control information simulated in a traffic simulation tool to the VR environments. Reversely, the feedback path brings the traffic control changes that occurred in the VR environments back to the traffic simulation tool. To implement this platform, we chose SUMO as the traffic simulation tool and Unity3D as the game engine to implement the VR environments. SUMO was selected due to its open-source nature, which allows easy data access and transfer to other platforms. The HIL path bridges sensor hardware deployed in the user studies to monitor worker location (i.e., ultrasonic sensors) and alarm workers of potentially dangerous situations (i.e., a smartwatch) and the virtual work zone, where simulated traffic pattern can cause hazardous situations, and traffic simulation can be impacted by worker behaviors (e.g., step out of work zone boundaries). In the following subsections, each component of the platform will be introduced in detail.

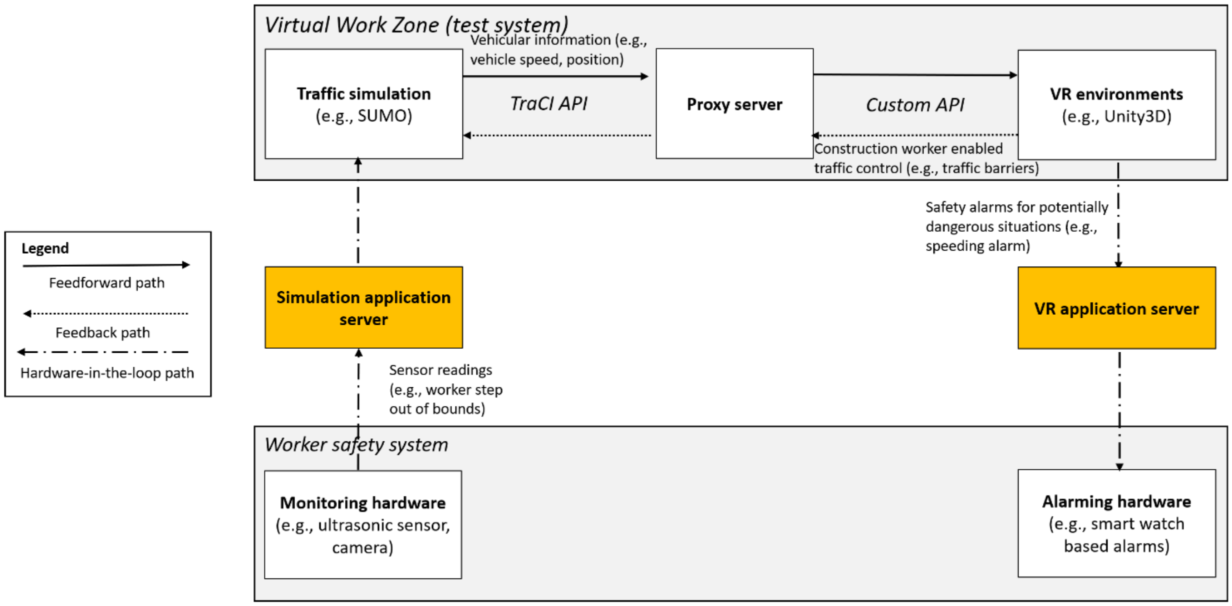

Figure 5: Hardware in the loop integration of VR, traffic simulation, worker alarm system, and work zone monitoring system

**(Virtual Work Zone system has been detailed in the previous subsection 4.1)*

4.2.1 Worker Safety System Component

The worker safety system component in this study includes two parts, as monitoring hardware and alarming hardware, which are physical sensors implemented in this study for studying worker behavior towards safety alarms sent to them during dangerous situations. In this study, the monitoring hardware is focused on worker locations monitoring, with an implementation of ultrasonic sensors to enforce a construction work zone perimeter. However, the larger scope of monitoring hardware can include other aspects of the work zone safety, such as vehicle trajectory monitoring or worker location tracking. This can be done through vision-based sensors installed at physical work zones.

In this study, the monitoring hardware is focused on worker locations monitoring, with an implementation of sensors to enforce a construction work zone perimeter. For this part of the project, the team reviewed the literature of hardware in the loop (HIL) studies for traffic safety and developed a list of sensors for potential use in the experiments. Discussions focused on the challenges of each sensor hardware and associated requirements to integrate with the current experiment setup to communicate warnings to the VR participant on their physical location in the designated lab space. Table 1 presents the comparison made of different sensors considered for enforcing the physical boundaries of a work zone.

Sensor	Type of Signal	Cost	Distance Range	Indoor Use	Size	Ease to Implement
LiDAR	Light Pulses	Medium-High	0.1-40 m	Yes	Small-Large	Medium
RADAR	Radio Waves	Medium-High	Up to 140 m	Yes	Small-Large	Medium
Sonar	Sound Waves	Low-High	Up to 0.4 m	Yes	Small-Medium	High

Table 1: Comparison of sensors for use as physical hardware to integrate with the worker safety simulation setup

Given the table, the team decided on using the ultrasonic sensors for their cost-benefit when considering the scope of the study and ease of integration with the VR environment. We have taken into consideration its low cost and sufficient distance reading range. The hardware setup for this platform consists of the VR hardware, which includes a system of headsets, controllers, and laser trackers, and the ultrasonic sensors installed on Raspberry PIs that can be used to measure distance between physical objects and the sensor. In the lab, four ultrasonic sensors were installed on four corners of the work zone spaces, where the subjects can freely move without triggering the perimeter alarm (Figure 6).

On the other hand, the alarming hardware can include many types of sensors categorized by the sensory medium, as audio, visual and vibration-based sensors. Previous studies showed that audio and visual based alarms can be easily subdued at work zones due to the constant noise and flashing signages present onsite. Hence, vibration-based alarms might be more effective in terms of raising workers' attention towards alarms of potentially dangerous situations. In this study, a smartwatch-based alarm sensor was used to send safety alarms, and three types of sensory inputs were implemented as audio, visual and vibrating alarms. Using this worker safety system coupled with the virtual work zone, three types of alarms exist, as speeding alarm (i.e., when a vehicle is speeding in the vicinity of a work zone in VR), collision alarm (i.e., when a vehicle is headed towards the work zone direction with a possibility of intruding the work zone in VR) and perimeter alarm (i.e., when the worker is stepping out of bounds of the physical space marked as work zone in the lab setting). These alarms are to be sent to the subjects in varying modalities, frequencies, and durations with the goal to understand how workers behave with regard to these characteristics of alarms to maximize worker attention for future alarms.

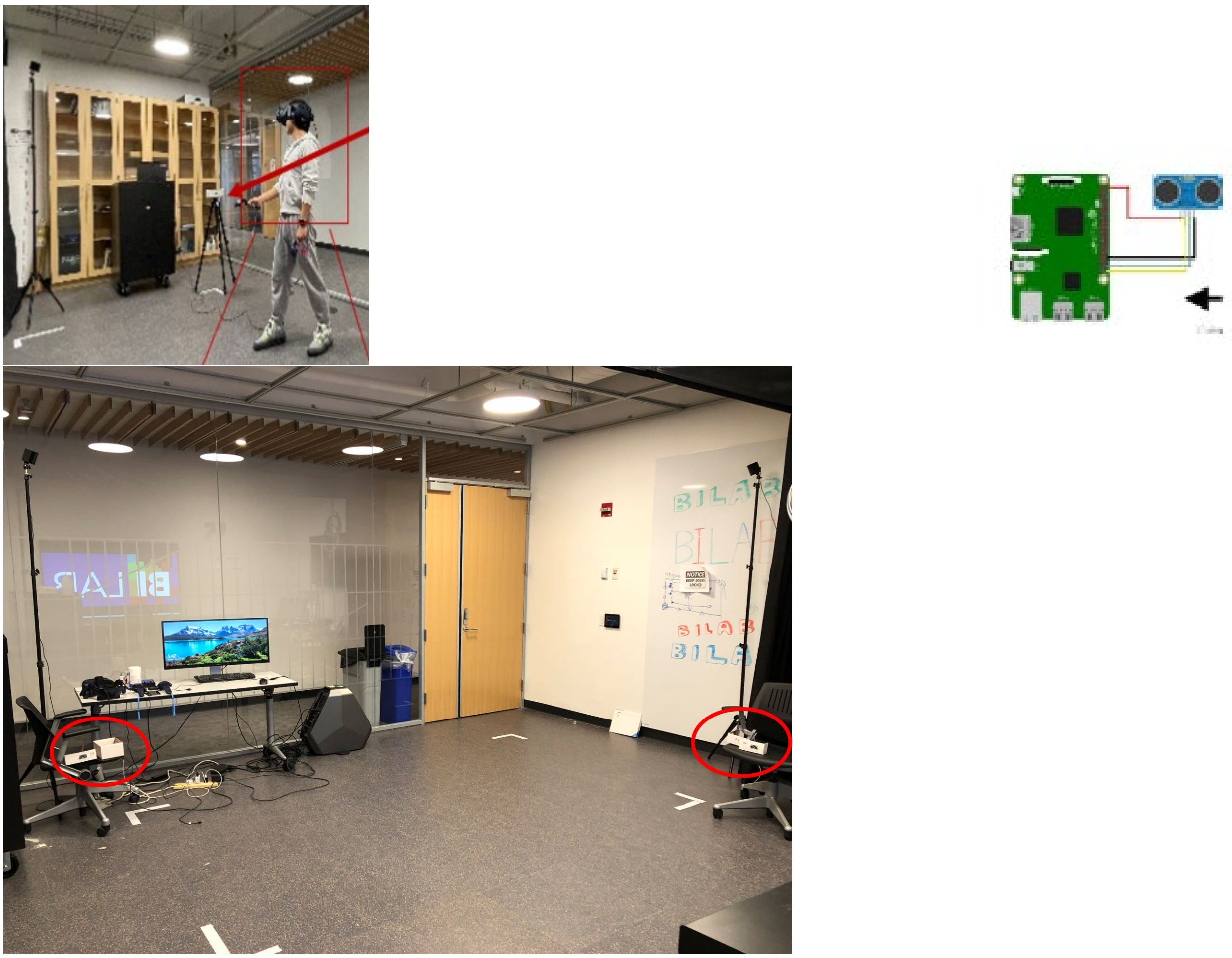

Figure 6: Photos of the four Raspberry PIs with ultrasonic sensors and how they are laid out in the physical lab indicated in red circles and arrows

6. Lab Setup for User Studies

As seen in Figure 7, the hardware setup for this platform consists of the VR hardware, which includes a system of headsets, controllers, and laser trackers, and the ultrasonic sensors installed on Raspberry PIs that can be used to measure distance between physical objects and the sensor. In the physical lab environment, four ultrasonic sensors were installed on four corners of the work zone spaces, where the subjects can freely move without triggering the perimeter alarm. The subjects expected to wear a VR headset that was connected to a VR client computer to run the VR environment from a game engine. The traffic simulation tool ran on a separate computer, which connects with the VR client using a proxy server.

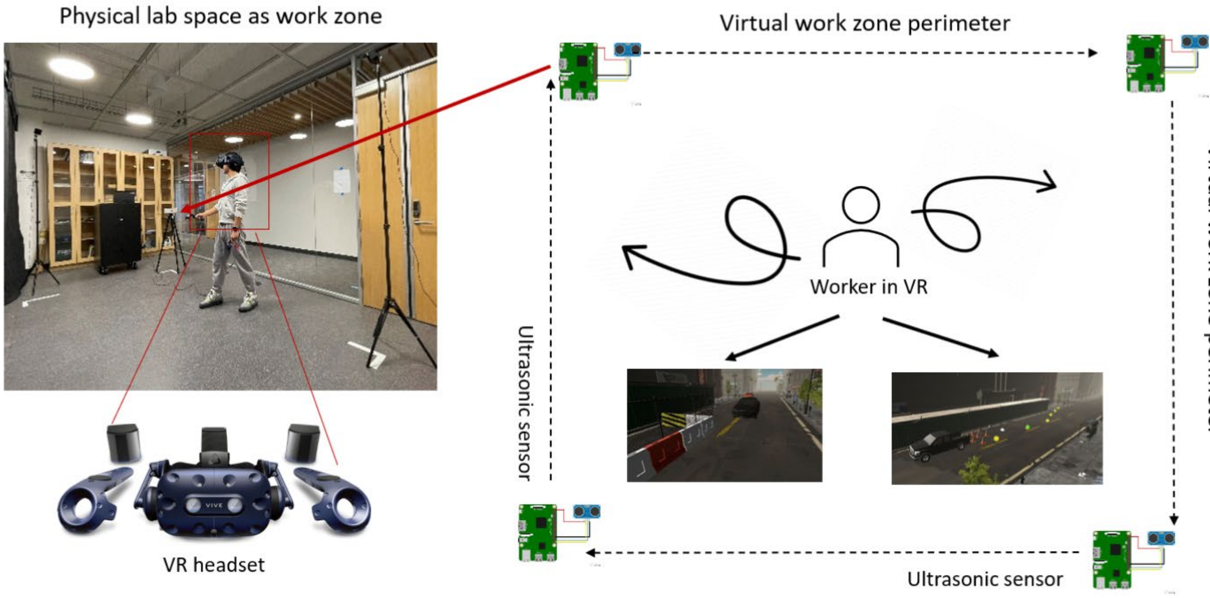

Figure 7: Hardware setup for the integrated platform including (a) VR hardware and (b) server and client hardware

The VR system used in this study is the HTC Vive Pro, with a resolution of (1440 x 1600) per eye and a refresh rate of 90 Hz, and a 110-degree field of view (Figure 7). The VR system occupies a physical space of 15 square meters (i.e., 3m x 5m) where users can walk around while wearing the headset and immersed in VR. The VR system is powered by a VR client, which runs a game engine Unity3D. The VR client is equipped with a six-core Intel CPU, 32 Gigabytes of RAM, and an NVIDIA GPU with 8 Gigabytes of VRAM. The traffic simulation client runs on a laptop equipped with a four-core Intel CPU and 16 Gigabytes of RAM. The VR client and the simulation client communicate through a proxy server. The VR client and the smartwatch (i.e., alarm hardware) connect through an application server. Finally, the monitoring hardware (i.e., ultrasonic sensors) and the traffic simulation tool connect through an application server. All servers are equipped with an Intel eight-core CPU with 16 Gigabytes of RAM and connects with clients using the TCP/IP networking protocol.

7. Implementation of the Integrated Platform: Modules 1 and 2

First year of this project resulted in three critical scenarios to be tested in VR settings with short term and mobile work zones. Scenario 1 includes the placement of traffic barriers to set construction perimeters at an urban intersection, representing a mobile work zone. For this, we used the intersection located at

Myrtle Avenue and St Edwards Street in Brooklyn Downtown. Scenario 2 included installing sensors/equipment on the side of an urban highway, representing intermediate-term work zone, and located on the Brooklyn-Queens Highway, close to Commodore Barry Park. Scenario 3 included surveying the road at an urban intersection, representing short-term work zone, and included a location at the intersection of Willoughby Street and Jay Street in Brooklyn Downtown.

The integrated platform was implemented to develop VR environments based on real-world work zones in downtown Brooklyn, NY (Figure 8a) representing Scenario 1, and Brooklyn Queens Highway (Figure 8b), representing Scenario 2. Screenshots from the VR environments are provided in Figure 8.

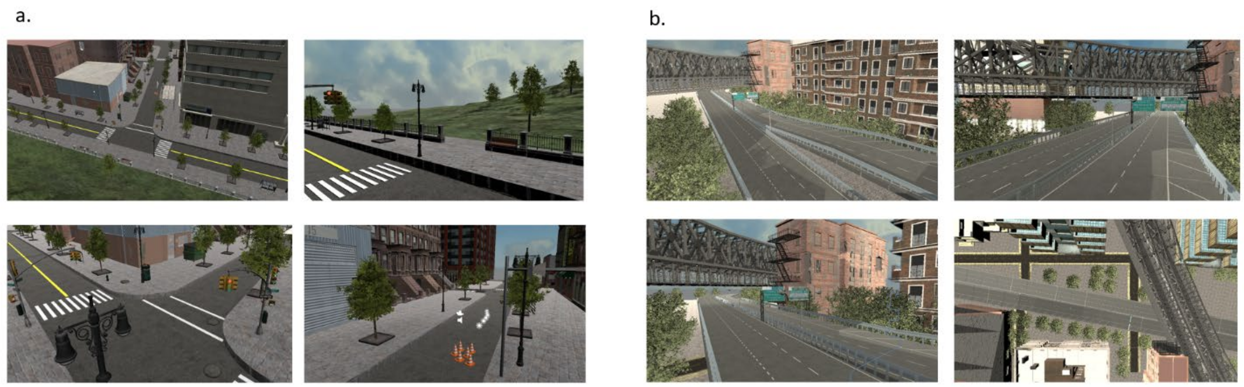

Figure 8: Snapshots from the VR environments, representing (a) a mobile work zone, and (b) an intermediate-term work zone

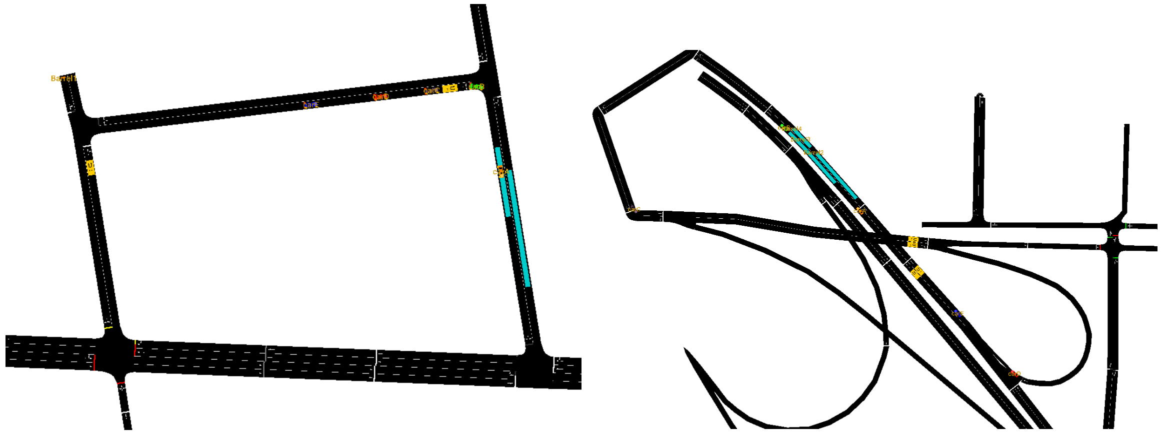

Figure 9: SUMO traffic simulations for (a)mobile work zone, and (b) intermediate-term work zone

The traffic simulation was implemented in SUMO, and the VR environment was developed in Unity 3D. The maps used in SUMO and Unity 3D was downloaded from OpenStreetMap and was kept consistent in both applications (Figure 9). Light blue rectangles on Figure 9 indicate zones where speeding and collision vehicles are monitored within SUMO and used to trigger alarms on the Apple watch.

Dangerous maneuvers by vehicles (rogue vehicles in SUMO) when passing the virtual work zone were manually designed to study the workers' behavior when facing dangerous interactions in VR. In the studied scenarios, a dangerous interaction can be caused by either a vehicle speeding or a vehicle invading the perimeter of a work zone, which corresponds to either activating a speeding or collision safety alarm. Once a dangerous maneuver by a vehicle is generated in SUMO (Figure 10a), the dangerous maneuver will be reflected in real-time in the VR environment (Figure 10b). An alarm will be triggered and the information regarding the alarm (i.e., alarm ID, alarm type, alarm time, vehicle causing the alarm, vehicle type) will be gathered (Figure 10b) then sent to a designated server handling its delivery to a smartwatch integrated into the platform.

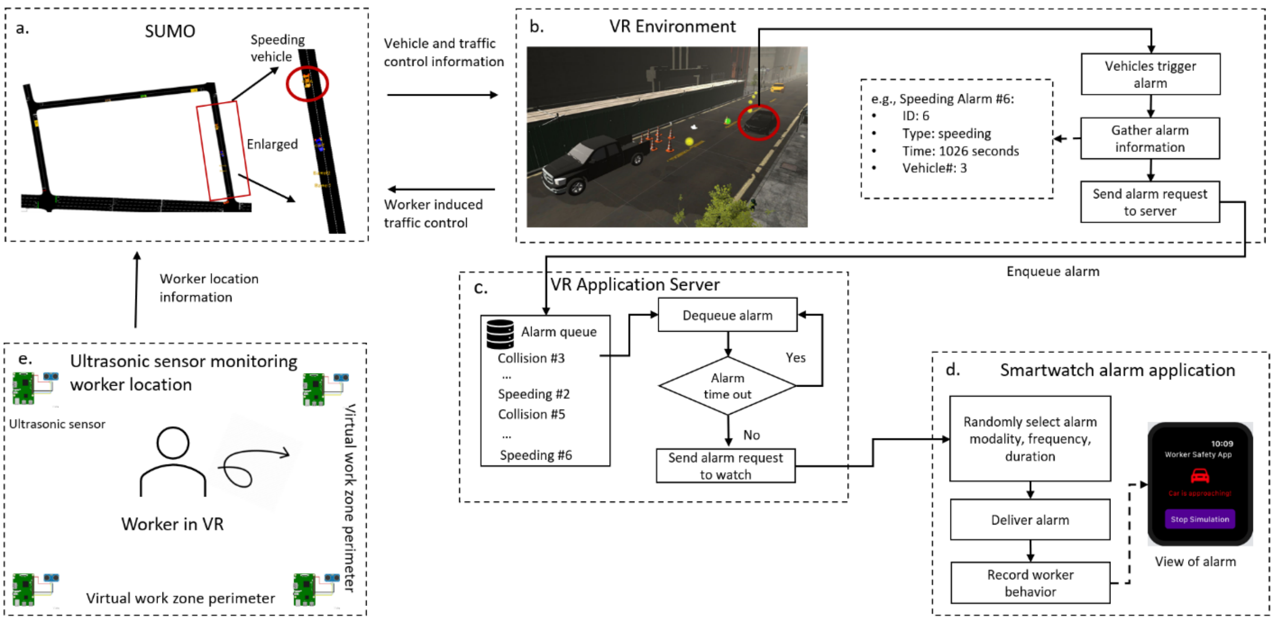

Figure 10: An overview of the alarm delivery system to send speeding and collision alarms to workers on a smartwatch

A dangerous situation can also be caused by the worker stepping out of bounds of the work zone perimeter (Figure 10e), which corresponds to a perimeter alarm. When the subject triggers the perimeter alarm, the worker location information will be sent to the traffic simulation tool for the simulation to adjust traffic movement. In the meantime, the alarm information will be sent to the VR application server (Figure 10c), which maintains a queue of all active alarms and sends the alarm in the order of receiving them. Once the VR application server sends out an alarm, the smartwatch application (Figure 10d) will randomly generate a combination of alarm characteristics (i.e., alarm modality, frequency, and duration), then notify the worker wearing the watch. The reason for randomizing the characteristics of the alarm is to examine how these different combinations can affect the behavior (i.e., read or dismiss the alarm) of the worker.

The task for the workers in the first scenario is to set up a perimeter for a mobile work zone at an urban intersection (Figure 11). Workers are expected to put six orange traffic cones unloaded from a truck (in a red circle in Figure 11) in pre-determined locations to finish setting up the perimeter. This task was chosen based on the findings of previous studies regarding mobile work zones without a structured perimeter having one of the highest incident rates [31]. Furthermore, the selection of this task also eliminates the possibility of test subjects performing heavy physical workload to ensure the adherence to the institutional review board (IRB) requirements. In VR, designated locations of the traffic cones are marked using blinking yellow spheres. Once a worker finishes putting one traffic cone, the corresponding location will have a steady green sphere to signal the worker that the cone is in place. After all traffic cones are put in place, the worker will be notified of the completion of the assigned task. Details of the simulated steps are provided in Figure 12a.

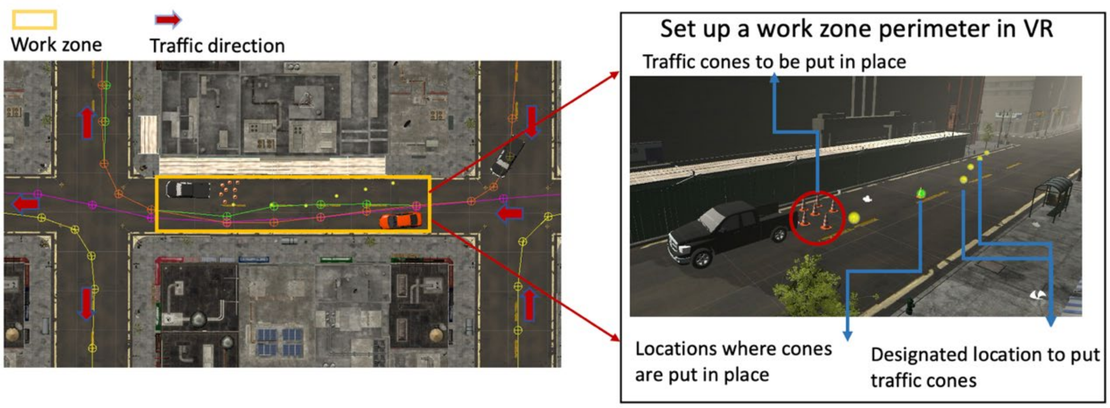

Figure 11: A bird-eye view of the virtual work zone from Scenario 1 and the construction worker tasks in the virtual work zone

As the workers completing the task of setting up the work zone perimeter, vehicles are moved based on the simulated results from SUMO. On the other hand, once a traffic cone is put in place, the VR environment will signal the cloud server that a traffic control device is put in place, and the location of this cone will be transferred to SUMO, causing the traffic pattern to change in SUMO, and in turn, changes the vehicle movements in VR.

Specific tasks to be included in Scenario 2 included installing road monitoring sensors for highway traffic monitoring. Based on videos of highway sensor installations and discussions with domain experts, the research team has developed a sequence of tasks that participants will perform in VR for Scenario 2 and how worker task completion will be tracked and visually communicated in the VR environment (Figure 12b).

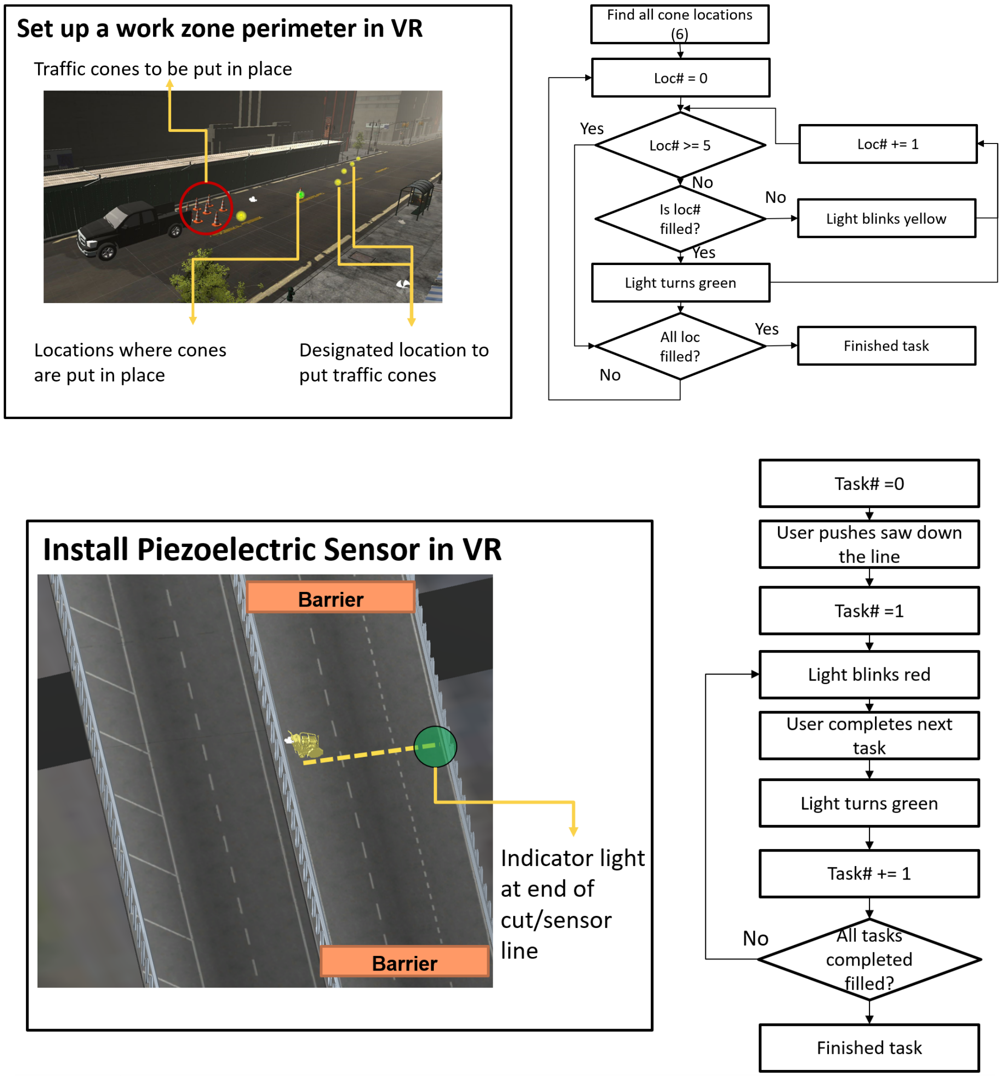

Figure 12: Flowchart of the simulated actions in (a) Scenario 1 and (b) Scenario 2

Flow of events in Scenario 2 includes pushing a saw-cutting machine into the road surface from one side of the road to the opposite side, installing a piezoelectric sensor cable (which is typical of weighing stations and traffic monitoring) by virtually drawing along the groove made earlier by the saw-machine, pouring sealant over the sensor, and troweling the seal flat (Figure 13). Indicator lights and floating text instructions in VR provide guidance to participant on these tasks.

Figure 13: Flow of events in Scenario 2 in VR

8. Initial Alpha Tests, Results and COVID Impact on User Studies

The research team had received approval from the IRB with the certification number IRB-FY2020-3946 and had done initial alpha tests pre-COVID19. The alpha-tests were done with five participants (mean age = 29.5, SD = 2.5, 60% males, 40% females) to study the effectiveness of this platform, which is measured by a quantitative analysis of the behaviors of the workers towards safety alarms (i.e., read or dismiss the safety alarm) and a qualitative survey (questions and results are shown in Table 2). All participants had previous experiences with VR systems, and none of them had experience with working in physical work zones, so these participants were categorized as novice workers (Figure 14: .

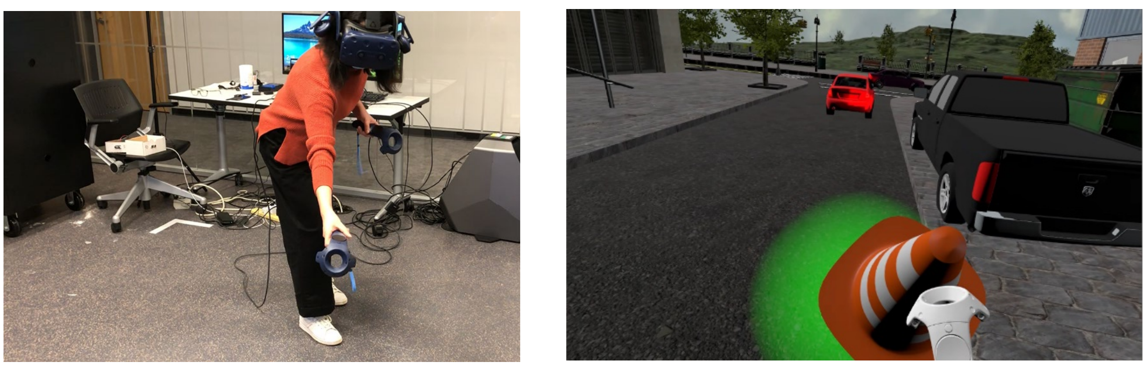

Figure 14: Alpha-tests (a) participants during experiments, (b) view from the VR headset

8.1 Quantitative analysis of the workers behaviors towards safety alarms and qualitative analysis of workers' survey results

During the alpha experiments, the responses of towards the safety alarms delivered in various modalities, frequencies, and duration were monitored and analyzed. The safety alarms were delivered in two modalities, as vibration and visual safety alarms. Safety alarm frequency was set as either three safety alarms per 20 seconds or six per 20 seconds, and the safety alarm duration was set as either one second or three seconds. The initial testing hypothesizes that the behaviors of workers (i.e., read or dismiss the safety alarm) will be statistically significantly different when safety alarms are sent in different modalities, frequencies, and durations. The hypothesis was tested using a paired t-test with a significance level of 0.05. From the t-test results, it is apparent that the participants were sensitive to (i.e., the behavior of participants towards the safety alarm being statistically significant) the safety alarm modality and frequency but not the duration. The alpha test has shown that the integrated platform is ready to be used in larger experiments and can provide relevant data in understanding behavior of road workers' towards notification systems.

The goal of the survey was to gauge participants' impression of the VR work zone environment, and the level of realism they perceived when in VR. The survey extends previous VR studies survey questions for understanding the human experience in VR as compared to physical environments [54,55]. The survey was separated into four parts: experience with VR, control in VR, distractions in VR, and the sense of realism in VR. The questions were presented as a ranking question for the participants on a 5-point Likert scale. The range for the 5-point Likert for each question is shown in Table 2. Results from the survey suggest that the participants could adjust to the VR environment quickly (3.60) and found the actions initiated in VR to be responsive (3.80) and found the experience in VR resembles the real-world (3.60). However, during the experiments, participants did find the control mechanism used (e.g., hand controllers, keyboard, mouse) to be distracting of their experience (2.20), and they were still aware of the surroundings in the physical space even in VR. Finally, the participants rated highly of the realism of the VR environment (3.60) and found it similar to the physical environment (4.00).

Table 2: Questions in the survey regarding experience in VR

Questions	Mean (SD)
Experience	
How familiar are you with VR technologies? (1-not familiar, 5-very familiar)	3.40 (1.34)
Control in VR	
How quickly did you adjust to the virtual environment experience? (1-slow, 5-quick)	3.60 (1.52)
How responsive was the environment to actions that you initiated or performed? (1-not responsive, 5-very responsive)	3.80 (0.84)
How much did your experiences in the virtual environment seem consistent with your real-world experiences? (1-not consistent, 5-very consistent)	3.60 (0.55)
Distractions in VR	
How distracting was the control mechanism? (control mechanism is the device you interact with the VR environments, e.g., VR hand controllers, keyboard, mouse), (1-not distracting, 5-very distracting)	2.20 (1.30)
How aware were you of events occurring in the real world around you while performing the assigned tasks in the virtual environment? (1-not aware, 5-very aware)	2.60 (0.55)
Realism in VR	
How realistic and natural was your sense of moving around in the virtual environment? (1-not realistic, 5-very realistic)	3.60 (1.14)
How difficult was it to move the traffic cones in the virtual environment compared to the physical environment? (1-not difficult, 5-very difficult)	1.40 (0.55)

How similar did you feel the virtual environment was to the physical environment? (1-not similar, 5-very similar)	4.00 (0.71)

For future work, further user tests will be conducted to validate the initial results with a larger subject pool. These tests will include employees of several different transportation companies (both public and private), various age groups (in working age), positions, and work experiences (from novice road workers to high-level administration and engineering). This research will provide a better understanding of road workers' responses to safety alarms delivered in different techniques. In addition, this platform can be used in other environments. For instance, one can incorporate pedestrians in the traffic simulation to understand pedestrian crowd dynamics or decision behavior of people selecting a queue. It can also be used to understand the interaction of vehicles and pedestrians while crossing a street, jaywalking, and bicyclist behavior studies.

Due to the COVID restrictions this year, in-person user studies could not be pursued. While the in-person user studies are still suspended by the IRB review office due to the pandemic, we have continued to evaluate the quality of the data captured through the HIL integrated platform. As a result of the beta tests, we have observed patterns that resulted in adjustments in the platform to reduce noisy data collection. These included the followings:

- **Ultrasonic Sensors Sensitivity and Range:** Currently the ultrasonic sensors are recording the distance to the nearest detected object and sending signals to a server whenever that distance is less than 80 cm. This was decided as an adequate temporary setting since sensors are currently reading distances between 90 - 300 cm at ambient conditions. This range means that the ultrasonic sensors are currently recording very noisy data that may produce false positives in detecting when the worker in VR has left the physical space perimeter. Future implementations of these sensors will consider a prolonged presence (a couple seconds) of readings shorter than 80 cm, multiple ultrasonic sensors at one edge of the perimeter, or to add other sensors (e.g., cameras) as additional input to reduce false alarms.
- **Virtual work zone size reduced to fit within the physical lab perimeter:** During initial tests of the VR platform for the urban work zone perimeter, where a worker must place 6 cones in specific locations, it was found that workers would have to move beyond the physical perimeter to place all 6 cones. For beta testing, this requirement was decreased to placing 3 cones in a smaller area that would match the scale of the physical lab space. Next step is to rescale the VR environments to make sure 6 cones can be reached in the physical lab perimeter. The HTC Vive can detect about 5*5 meter squares, so we want to maximize that physical space to accommodate as much virtual environment as possible.

Such issues are eliminated before conducting real experiments with students and NYC DOT affiliated workers once the IRB in-person experiment are possible.

9. Outreach Activities

- The team presented a poster at the 2021 Annual Meeting of the Transportation Research Board: Launching a New Century of Mobility and Quality of Life (Figure 15).

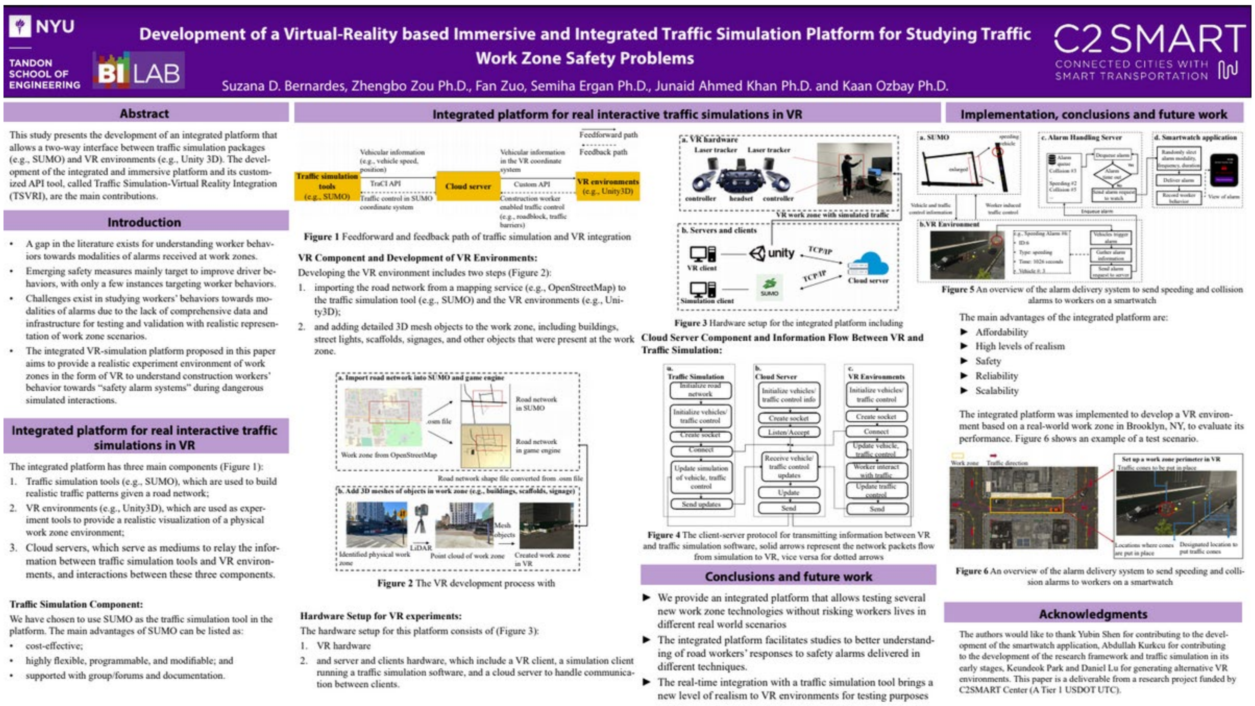

Figure 15: Poster presented at 2021 TRB Annual Event (virtually)

- The team submitted a journal paper on this work, with the following citation: Zou, Z., Bernardes, S. D., Zuo, F., Ergan, S., and Ozbay, K. (2021). “An integrated approach to enable Hardware-in-the-loop for realtime VR, traffic simulation and sensor interactions: An Application in work zone safety”. *Journal of Advanced Engineering Informatics*.
- The team submitted a publication to 2020 TRB annual meeting, with the following citation: Bernardes, S. D., Zou, Z., Zuo, F., Ergan, S., Khan, J. A. and Ozbay, K. Development of a Virtual-Reality Based Immersive and Integrated Traffic Simulation Platform for Studying Traffic Work Zone Safety Problems. Submitted for presentation and publication to TRB Annual Meeting, Transportation Research Board.
- 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. The citation

includes: Zou, Z., Ergan, S., (2020). An Integrated Approach to Capture Construction Workers' Response towards Safety Alarms using Wearable Sensors and Virtual Reality. C2SMART webinar series, presented on May 26th, 2020.

- The research project's overview is presented online at: http://c2smart.engineering.nyu.edu/behavioral-analysis-with-integration-of-vr/
- The research team created a database hosted at C2SMART's PostgreSQL server for storing the data collected in real-time by the sensors implemented for virtually delimiting the bounds of the work zone based on the physical environment of the lab. The database also serves as backend for the VR + Traffic simulation platform. The database is restricted access for now, only the research team has the credentials to insert and retrieve data from it.

10. Outcomes

Increased understanding and awareness of transportation issues

Long-term (i.e., more than 3 consecutive 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. 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.

Increase in the body of knowledge

The research team has identified that HIL is a key technique for increasing the realism of the VR experiments, as it can collected data on the physical environment and adapt it to the VR environment for better reproducing the work zone environment and for improving the special awareness of the participants. The research team also identified the suitable types of sensors to be used in work zone safety monitoring, which can be used in future implementations. However, the HIL technique still present challenges that the research team is trying to tackle. For example, reproducing the interface between connected vehicles and Roadside Units are difficult to implement due to the cost and dimensions of the resources needed to do so.

This work addresses a specific problem of creating realistic representation of work zones as virtual environments in VR. To that end, the realistic representation of traffic patterns in VR and the feedback of user behavior from VR to traffic simulation are desired. The scientific advance of this work mainly pertains to the automation of this two-way information flow between the traffic simulation and VR environments. With the rapid deployment of VR in multiple aspects in the AEC industry (e.g., construction safety, design improvement, quality control), the need for realistic representations of construction projects in all stages of the project life cycle (e.g., design, construction, maintenance) has propelled the growth of commercial VR software suites (e.g., irisVR, insiteVR) that are capable of presenting as-planned or as-built models in the VR format. These software suites either focus on the presentation of design models in VR, or the link between multiple users to enable team communication for collaborative decision making. When comparing to a game engine, which is the choice of this study for VR environment development, these platforms (1) provide the same high level of realism when material information of the model is present; (2) requires less computational cost because the software can run on cloud servers and minimize local computing needs; and (3) are relatively easy to implement and integrate with existing software since users can simply upload their designed model to the cloud server of the software platforms for visualization and communication purposes. However, these software suites (1) lack the flexibility to enable communication between the VR environments and traffic simulation; (2) are hard to extend with other sensor hardware if HIL solutions are desired; and (3) are closed-sourced, which prohibits other researchers/practitioners to build on top of their solutions to add more functionalities.

We have found four prominent traffic simulation tools that have VR feature or the capability of interfacing with game engine packages: PTV AISIM [38], Paramics [39] , AIMSUN [55], and SUMO [14]. All of them are widely trusted and used by academia and industry when developing traffic models. In addition, they all have the capability of building microscopic traffic models, which are used in this study. Microscopic traffic modeling describes each individual vehicle (e.g. trajectories, speed, acceleration, braking and lane-changing behavior) and their interactions, whereas macroscopic traffic modeling describes the traffic flow and its aggregated dynamic variables (e.g., traffic density, flow, mean speed, and speed variance)[56]. All four packages allow the calibration of the traffic model parameter to achieve highest accuracy of the traffic patterns, which can be validated through the use of real-world traffic data. They can all be integrated to Unity 3D game engine. However, the first three are expensive commercial packages and do not allow as much customization of the traffic model components and communication between them and the VR environment. Meanwhile, SUMO is open-source and allows maximum customization of both the traffic modeling and communication with the VR environment. The customization quality of SUMO also makes it easier to allow the implementation of physical sensors and hardware to the integrated platform, as its whole interface is fully programmable by the user. The disadvantage of adopting a fully programmable, open-source package is that its implementation is more complex than some of the other packages. This setback is, however, easily overcame by the wide availability of tutorials and documentation online. The outcome of this study, in addition to the contributions already presented, will help to reduce the complexity of implementation of SUMO models to VR environments by developing a complete integrated platform.

Improved processes, technologies, techniques, and skills in addressing transportation issues

The research team had developed an approach to bring realistic traffic simulations conducted in the simulation tools (i.e., SUMO) into the VR environments in real-time. We extended the initial SUMO-VR information loop to include hardware in the loop component, where work zone safety hardware can be tested in a realistic environment with real-time traffic simulated in VR and real-time worker behavior feedback from VR to SUMO. The proposed approach can fundamentally change the way of traffic being simulated in the VR environments, and improve the realism of the VR environments by providing a more realistic traffic from SUMO simulations.

Adoption of new technologies, techniques, or practices

The research team has adopted three main technologies as of the date this report has been submitted:

- VR Technology for visually reproducing real work zone environments into an immersive 3D environment.
- Traffic simulation integrated to the VR environment for reproducing real traffic conditions, so the participant can have a more realistic experience.
- Feedback from VR environments to traffic simulation to influence traffic patterns caused by worker behaviors in VR.
- HIL for creating a virtual bound of the work zone in the VR environment based on the physical dimensions of the lab. This will help with tracking the localization of the participant in the VR environment.

11. Conclusion and Future Work

Hardware-in-the-loop has shown great potential in testing sensors for alarming construction workers for safety in virtual environments (e.g., virtual work zone) instead of physical systems (e.g., physical work zone). To achieve realistic traffic patterns in the vicinity of traffic work zones, traffic simulations can be conducted to control vehicle movements. In this study, we developed an integrated platform that allows a two-way information flow between the virtual work zone and the worker safety system. The intention of replacing the physical work zone with a virtual work zone is to provide a realistic experiment environment to understand construction workers' behavior towards safety alarm systems during dangerous simulated interactions without putting workers in physical harm. Our prototype version of the integrated platform was implemented using an actual mobile work zone located at an intersection in downtown Brooklyn, NY. The implementation showed that the proposed platform can be used to connect a traffic simulation tool (i.e., SUMO) and a VR environment (i.e., Unity3D) to enable traffic control in VR and user behavioral intervention of traffic patterns in traffic simulation. Compared to the existing alternatives that present similar functionality, our integrated platform has shown advantages in terms of better flexibility of communication between VR and traffic simulation, higher extensibility to add other sensors for testing, and the nature of open source that enables other researchers to build on our platform.

For future work, user tests will be conducted using the developed platform to conduct behavioral studies towards modalities of notifications at work zones. These tests will include employees of several different transportation companies (both public and private), various age groups (in working age), positions, and work experiences (from novice road workers to high-level administration and engineering). With user studies, this research will provide a better understanding of road workers' responses to safety alarms delivered in different techniques. In addition, this platform can be used in other scenarios. For instance, one can incorporate pedestrians in the traffic simulation to understand pedestrian crowd dynamics or decision behavior of people selecting a queue. It can also be used to understand the interaction of vehicles and pedestrians while crossing a street, jaywalking, and bicyclist behavior studies.

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