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WORK ZONE SAFETY: VIRTUAL REALITY-BASED TRAFFIC CO-SIMULATION PLATFORM FOR WORKFORCE TRAINING AND PEDESTRIAN BEHAVIOR ANALYSIS

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16. Abstract

First, an assessment was conducted to evaluate the suitability of VR in replicating reality and to compare worker behaviors in real-world and virtual environments. Second, an existing VR-based traffic co- simulation platform was enhanced by incorporating realistic worker and pedestrian behavior. This improvement allows for more accurate simulations of movement, including restrictions, tasks, and random movements. The platform also enables users to modify variables to adjust worker behavior. Finally, VR-based training modules were implemented and evaluated against traditional methods to enhance worker preparedness for hazards.

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WORK ZONE SAFETY: VIRTUAL REALITY-BASED TRAFFIC CO-SIMULATION PLATFORM FOR WORKFORCE TRAINING AND PEDESTRIAN BEHAVIOR ANALYSIS

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C2SMART Center is a USDOT Tier 1 University Transportation Center taking on some of today's most pressing urban mobility challenges. Some of the areas C2SMART focuses on include:

Urban Mobility and Connected Citizens

Urban Analytics for Smart Cities

Resilient, Smart, & Secure Infrastructure

Disruptive Technologies and their impacts on transportation systems. Our aim is to develop innovative solutions to accelerate technology transfer from the research phase to the real world.

Unconventional Big Data Applications from field tests and non-traditional sensing technologies for decision-makers to address a wide range of urban mobility problems with the best information available.

Impactful Engagement overcoming institutional barriers to innovation to hear and meet the needs of city and state stakeholders, including government agencies, policy makers, the private sector, non-profit organizations, and entrepreneurs.

DISCLAIMER

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EXECUTIVE SUMMARY

Work zones pose risks due to exposure to traffic and the potential desensitization of workers to hazards over time. To improve safety awareness, innovative intrusion alarm systems with wearables and other devices are being considered. Virtual Reality (VR) offers realistic simulations without exposing workers to real-world dangers, such as speeding cars or work zone intrusion. This report consists of three main parts. First, an assessment was conducted to evaluate the suitability of VR in replicating reality and to compare worker behaviors in real-world and virtual environments. Second, an existing VR-based traffic co-simulation platform was enhanced by incorporating realistic worker and pedestrian behavior. This improvement allows for more accurate simulations of movement, including restrictions, tasks, and random movements. The platform also enables users to modify variables to adjust worker behavior. Finally, VR-based training modules were implemented and evaluated against traditional methods to enhance worker preparedness for hazards.

Benchmarking studies in real-world and VR settings for worker responses to notifications show that workers display similar behaviors in both settings. The analysis included factors such as ambient noise and user heart rate to explore correlations with response times to alarm signals. The results showed that participants, across 90 trials in each setting, displayed similar response times in both settings, with a slight advantage for real-world scenarios (average response time to received notifications 2.43 s. vs. 2.59 s. in real and VR-based settings, respectively). The statistical analysis confirmed that the response times were not significantly different.

The existing VR-based traffic micro co-simulation platform has been significantly expanded to improve realism by incorporating pedestrian behavior and trajectories. This enhancement allows users to make realistic movements based on pedestrian speed and step length. Rule-based pedestrian behaviors, including movement restrictions, task simulations, and random movements, were simulated within the platform. Users can modify environment variables to adjust worker behavior, enhancing the platform's training capabilities. Additionally, a pre-trained behavior model accurately simulates pedestrian behavior using real trajectory and experimental data. These enhancements provide a more realistic and immersive experience, enhancing the platform's training capabilities for work zone safety and will be instrumental

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INTRODUCTION

Most recent crash data reveal that around 874 fatal crashes in the United States happened around work zones in 2021 alone, resulting in 956 fatalities (1). The data in the last decade also indicates similar trends with an average number of worker fatalities around 125 per year. The proportion of construction workers struck by fatal accidents in work zones takes up almost 50% of all pedestrians involved in work zone crashes, which makes construction companies experience high rates of complaints regarding work zone crashes (2). On the other hand, the institutional effort towards enhancing worker safety around work zones has largely focused on improving traffic control devices and work zone configurations to minimize confusion of motorists passing through the work zone and to limit collisions involving motorists (3). Efforts that result in better understanding of worker behaviors around work zones are in scarcity but needed. More recently, Virtual Reality (VR) presents opportunities and benefits in this area of work by simulating dangerous situations without causing actual harm to those who experience the situation. Previous research studies on the application of VR to transportation and construction industry safety behaviors show the potential to improve the conventional ways of safety training and workforce development (4-6).

Many of the technological design aids developed to improve work zone safety focus on influencing drivers' behavior, which is crucial for improving safety in and around work zones. Institutional efforts to improve work zone layout and configurations have been common, but there has been an increased emphasis on the application of safety-enhancing devices and techniques. These safety measures include various strategies to control the traffic speed, such as fixed or variable message signs, police enforcement, speed display trailers, flagging, and lane width reduction. Additionally, channelizing devices like cones, drums, barricades, flashing arrow panels, impact attenuator devices (TADs), and portable concrete safety shape barriers (PCBs) are employed (7). Furthermore, work zone layouts and speed limits are designed based on regulations set by the Federal Highway Administration (FHWA) (8). Intrusion safety alarm systems, such as SonoBlaster (i.e., impact-activated intrusion safety alarm system) (9), Intellicones (i.e., modular radio-based intrusion safety alarm system) (10), and Advanced Warning and Risk Evasion Systems (AWARE) (i.e., radar-based intrusion safety alarm system) (11), are also utilized. These intrusion safety alarm systems, along with training and the use of high-visibility Personal Protective Equipment (PPE), are among the measures implemented to enhance work zone safety for workers. Moreover, the hardware-in-loop (HIL) design, developed based on our earlier worker safety studies, incorporates various alarm signals and wearable devices (i.e., an Apple watch) to ensure safety.

Despite ongoing discussions and implementations of various measures for the safety of workers at work sites, workers continue to face exposure to traffic and the risk of being struck by vehicles, particularly in mobile and short-term work zones. Workers such as flaggers and surveyors often lack physical barriers between them and the traffic, making them more vulnerable to fatalities (12, 13). Additionally, the nature of their tasks requires them to focus on their job, which can limit their ability to perceive and respond to events in the background. To capture the attention of roadside workers, intrusion alarm systems have been introduced. These systems utilize audio and lightning features to effectively alert both drivers and workers to any intruding vehicles. However, one of the main challenges is ensuring that the auditory and visual cues from these systems do not blend with the existing signals in the work zone. As an alternative to the current visual and auditory warning systems, tactile sensory warning systems in work zones (14, 15). Hence, there is a need to understand how workers respond to different modalities of safety alarm systems in work zones. In the previous year, a comprehensive study was conducted using a VR-integrated platform with a hardware-in-loop (HIL) system to gather data on various user behavioral responses, motion data, trajectories, biological signs, and alarm response times. These datasets were helpful in figuring out what modalities are more effective for workers to respond to alarms (e.g., vibration better than sound, vibration+ sound being the most effective, longer duration with repetitions more effective than shorter duration ones). To evaluate the practical implications and quality of VR-based platforms, it is essential to compare user experiences in the virtual environment with those in the real world. Therefore, one of the objectives of this year's project was to assess the collected user data from the VR based platform, aiming to determine if the system's improvements based on the gathered data reflect reliable responses that can be expected in real-world settings.

Another objective of this year's project was to improve the VR-based traffic co-simulation platform with integrated pedestrian data/behavior. Significant efforts were made to enhance the realism within the VR platforms, particularly in developing scenarios and incorporating microscopic traffic flow simulations with pedestrian movement and response behaviors, which will be discussed in detail in this report. The advantage of VR systems for workforce training lies in their ability to simulate dangerous situations without subjecting workers or users to actual harm. The effectiveness of the VR system in representing reality with sufficient detail to facilitate user learning is crucial. Work zone operations, which demand attention to site-specific risk factors and adherence to general guidelines, serve as a prime example of the areas of focus. The third objective of this project was to assess the feasibility of using VR in safety training. A prototype was implemented to provide workers with learning content that addresses general safety concerns and guidelines related to roadway work zones. The evaluation aimed to gauge user receptivity to different VR applications. While further exploration is required to fully leverage such platforms for worker safety training, our findings indicate that the VR implementation serves as an exemplary model for enabling workers to engage in workplace safety and comprehend job sites without exposing themselves to the hazards of live traffic or interacting with motorists.

1. MOTIVATION

Studying safety in work zones presents a significant challenge due to the limited availability of comprehensive data and infrastructure for testing new technologies, particularly from the perspective of workers (15). Currently, there is no dataset that provides insight into the behavior of road workers when exposed to dangerous interactions with vehicles and their reactions to existing safety warnings. To truly understand the behavior of workers in work zone environments, their interactions with traffic, and their response to safety alarms (auditory, visual, or tactile), it is essential to accurately replicate the work zone environment, traffic conditions, and the various potentially dangerous interactions. However, physically recreating different work zone scenarios in a controlled setting requires significant financial, capital, and personnel resources. It involves expenses for vehicles, construction materials like fencing and equipment, hiring personnel to participate in and oversee the experiments, and finding a suitable location with the necessary infrastructure. Alternatively, sending participants to real work zones is not ideal, as it may create conflicts with working hours and increase their exposure to unsafe situations, posing a real danger to both participants and other road users. To address these challenges, Virtual Reality (VR) technology offers a viable solution.

VR has been successfully employed in previous studies to investigate work zone environments from the perspective of drivers. For instance, Bella (16) calibrated and validated a driving simulator to examine the effects of temporary traffic signals on traffic speeds in different areas of a work zone. The variation in speeding behavior within work zones under various scenarios continues to be a topic of interest in recent studies (17,18). Another application of VR in work zone safety is analyzing key factors contributing to work zone crashes (19). Despite the consistent use of VR technology in work zone safety studies, there is a gap in the literature concerning its application in understanding the behavior of construction and road workers within work zones, as well as calibrating emerging safety alarm systems based on workers' reactions to these systems. VR provides a highly realistic environment without subjecting participants to actual risks (20,21). The VR-based micro-traffic simulation platform designed in our earlier work was crucial to truly understand how workers behave in dangerous situations and various modalities of safety notifications.

Building upon the VR-based micro-traffic simulation platform described in the previous year's report, this project focused on benchmarking the behavioral data captured in the VR platform with the real-world settings, enhancing the realism of VR-based work zones with worker/pedestrian behaviors, and evaluating the feasibility of using VR in workforce development and safety training. We have replicated VR experiments in real-world settings and captured similar behavioral data to compare with the earlier experiment results conducted using our VR-based platform. We improved microscopic traffic simulations to incorporate random and diverse behavioral responses by pedestrians, utilizing open-source observational videos from external sources. We implemented standard safety training content targeting safety in roadway work zones and compared user experience with a focus group. We also reached out to industry stakeholders to capture their viewpoints on the value proposition of VR as a tool to deliver training and workforce development.

2. BACKGROUND

This study builds on and extends the research studies at the intersection of (1) VR in safety training and workforce development in the architectural, engineering, and construction (AEC) and transportation domains, (2) technologies used in work zone safety to sense and simulate vehicular and pedestrian traffic, and (3) Virtual Reality (VR), user comfort, and improvement of user safety awareness.

2.1 Previous Studies on Virtual Reality In Worker Safety Studies And Workforce Development In The AEC And Transportation Domains

The AEC industry involves high-risk conditions, including complex construction plants, heavy machinery operation, handling hazardous materials, and interactions with construction vehicles and road traffic (22). With safety being paramount, identifying the causes of incidents and improving safety performance has been a key focus for industry and academic stakeholders.

VR offers a distinct advantage by creating simulations of hazardous situations that allow users to learn about potential dangers without exposing them to real risks. Workers can enhance their knowledge of workplace safety without facing physical hazards. One notable application of VR is the generation of walkthroughs of construction sites, highlighting life-threatening hazards and empowering workers to evaluate safety measures. By training workers to recognize dangers in a simulated setting, accidents and injuries can be reduced. Previous research and practical applications have explored the use of VR for workforce safety training in the AEC industry. However, implementing such programs for practitioners and management has been limited by the initial cost (25). While VR training was found to improve workers' ability to recognize hazards associated with specific operations, its effectiveness for general site safety applications was limited (26). Studies have also examined the long-term retention of safety awareness acquired through VR training, reporting positive results (27,28).

In addition to its popularity in the AEC domain, VR has gained traction in transportation, particularly in studying interactions between autonomous vehicles and vulnerable road users, such as pedestrians and cyclists (29). Numerous studies over the past decade have used VR to investigate pedestrian behavior in virtual traffic scenarios, providing valuable insights into human responses to dangerous situations(30). VR-based platforms allow for the simulation of realistic traffic flow and the collection of behavioral response data. These data can be used for statistical modeling, such as survival analysis, or more advanced approaches like reinforcement learning to enhance alarm systems based on human responses (31,32). Consequently, the cross-disciplinary application of VR in addressing work zone safety concerns has become inevitable, given its relevance to both the AEC and transportation industries.

As mentioned earlier, safety training is an important aspect of construction projects, including work zones. Workers must be able to identify and respond appropriately to dangerous situations, such as intruding vehicles, to prevent injuries and fatalities. Cross-functional researchers focusing on both AEC and transportation aspects have recognized the need for enhanced safety training using emerging technologies like VR. For example, Roofigari-Esfahan et al. (2022) proposed an immersive instructor-in-the-loop, group-based VR training platform for road workers, allowing instructors to modify scenarios during training (33). However, developing realistic scenarios that accurately represent real-world situations and worker reactions relies heavily on the experience of instructors and training developers. In our previous publications and reports (9), we presented the development of a VR-based platform that faithfully reproduced an existing work zone, complete with simulated traffic calibrated using real-world data. This platform facilitated the study of road workers' responses to the imminent danger posed by high-speed vehicles intruding into the work zone. Such data can bridge the gap in realistic reproductions of hazardous situations that road workers encounter daily for training purposes, reducing reliance on human input. Moreover, successful integration of VR in the AEC industry requires collaborative efforts among researchers, industry professionals, and policymakers.

2.2 Previous Studies on Emerging Traffic and Pedestrian Simulation and Sensing Technologies in Work Zone Safety

As we delve further into the assessment framework of VR-based platforms, it becomes evident that "realism" is a crucial element for VR technology to fulfill its purpose and achieve the desired design outcomes. In the context of work zone safety, where the well-being of construction workers is often jeopardized by traffic and other on-site elements that pose risks or impede motorists' ability to detect and navigate safely, two essential components are necessary to accurately represent work zone configurations. Firstly, the systems implemented to ensure the safety of road workers in potentially hazardous situations, and secondly, the behavior of traffic surrounding the work zone. It is therefore imperative to comprehend the context in which these components are integrated within the Architecture, Engineering, and Construction (AEC) and transportation domains.

Among the systems aimed at enhancing work zone safety, aside from Temporary Traffic Control (TTC) measures, the use of intrusion alarm systems has gained prominence. These systems, guided by the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD), focus on minimizing risks and addressing site-specific or general hazards that could have severe consequences for workers (9,34). Proximity warning systems (PWS), utilizing radar, sonar, and alarm devices, have garnered attention from industry professionals and researchers. Work zone intrusion alarm systems (WZIAS), a type of PWS, can be categorized into three types based on the mechanism used for danger detection (35): Impact Activated System (IAS), Radar Activated System (RAS), and Pneumatic Activated System (PAS). However, the effectiveness of these intrusion alarm systems relies on factors such as time, distance, structural layout, and site location. Location-based detection technologies, including radar, sonar, and alarm devices, are employed to implement proximity warning systems (PWS) and improve workplace safety. These technologies have received significant attention from industry professionals and researchers alike. Different types of PWS have been employed to mitigate site-specific or general hazards that could potentially lead to life-altering accidents for workers in dangerous outdoor work environments (22,25). Work zone intrusion alarm systems (WZIAS) are categorized into Impact Activated System (IAS), Radar Activated System (RAS), and Pneumatic Activated System (PAS) and represent popular sensor-based solutions used to detect and address hazards, aiming to lower the risk of accidents and ensure worker safety.

Accurate and realistic traffic simulation is also a crucial consideration when developing a VR-based platform for work zone safety. Traffic simulation has traditionally been used to evaluate microscopic safety aspects of road design, primarily focusing on crash analysis and accident probability modeling (36). However, there is a lack of simulation models specifically designed to evaluate the traffic safety of non-lane-based heterogeneous traffic environments, which are prevalent in many developing countries (36). Similar challenges arise in mobile work zones located on narrow roads next to populated sidewalks, where traffic and pedestrian movements are unpredictable and heterogeneous. To create an accurate representation of the traffic environment, it is necessary to observe the random behaviors and trajectories of pedestrians and drivers, as well as their reactions to each other's locations. VR has shown promise in enhancing hazard recognition in construction by providing immersive environments for safety training (37). VR-based platforms enable the analysis of pedestrian-worker behavior around heavy machinery and offer valuable insights for hazard assessment and learning.

Microscopic traffic simulation plays a vital role in traffic research, offering intermodal traffic solutions and generating accurate representations of traffic flow and movement. While microscopic simulation may have slower execution speeds compared to macro and meso-scale simulations, advancements in research and tools have significantly extended its capabilities. The transportation research community widely utilizes the open-source tool called SUMO (Simulation of Urban MObility). SUMO enables the simulation of pedestrians using configurable models and provides various functions for traffic flow simulation, including routers, scenario-based modeling, demand importing, generation, and adaptation (38). By incorporating pedestrian simulation into microscopic traffic simulation, SUMO proves to be a valuable tool for accurately representing traffic, especially in situations where a significant portion of the road is occupied by pedestrians.

In this study, one of the three major objectives is to employ external resources such as videos of pedestrian movements to generate pedestrian traffic co-simulation, aiming to create realistic representations of traffic within the virtual environment. To achieve this, we utilize the SUMO microscopic traffic simulation tools, and in some cases, incorporate input data collected from earlier VR experiments, which included users' behavioral responses, such as motion and trajectories within the virtual environment. This approach opens up possibilities for developing a VR platform that simulates traffic not only by representing driving vehicles with different routes and trajectories but also by enabling interactive responses of vehicles to users' motion and locations. By generating realistic pedestrian and traffic co-simulations, we aim to create an accurate representation of the behavioral responses expected in real-world situations. The methodology employed to achieve this will be discussed in detail in subsequent chapters.

2.3 Previous Studies at the Intersection of Virtual Reality, User Comfort, and Improvement of User Safety Awareness

VR applications have shown significant potential in enhancing safety training and awareness in the construction and transportation industry. VR technology offers a unique advantage by simulating dangerous situations without exposing workers or users to actual harm. In the construction industry, which often faces high accident rates leading to project delays and cost overruns, the adoption of VR programs can help mitigate risks associated with construction projects and operations (39). However, to ensure the effectiveness of VR-based training or safety lessons, it is crucial to prioritize user comfort and deliver a high-quality experience (QoE) that incorporates utility and entertainment while avoiding cybersickness (40). Achieving a comfortable and engaging user experience is essential for the success and overall impact of VR platforms.

In the context of VR applications, user comfort evaluation may vary depending on the specific objectives of the assessment. While most research on VR has focused on gaming and entertainment, industrial applications, including safety training, have received comparatively less attention. Therefore, evaluating user comfort in VR requires a framework that considers not only comfort and experience but also usability, entertainment value, and mental effort required to complete tasks within the immersive virtual environment (IVE) (41,42). These evaluations can be guided by established usability principles outlined in this section. Additionally, this study aims to assess the application of VR in safety training for the architecture, engineering, construction (AEC), and transportation domain. Therefore, it is crucial to consider VR's ability to enhance worker safety awareness and replicate realistic environments within the VR-based training platform.

Greenfield et al. (2018) conducted a comprehensive evaluation of various VR platforms, including head-mounted displays (HMDs), mobile 3D and 2D displays, large immersive displays, and tablet PCs. Their findings highlighted the significance of characteristics such as field of view (FOV), virtual environment design, and physical constraints of movement in determining user comfort levels within VR systems (43). However, there is still a lack of research that provides a clear taxonomy outlining the main characteristics of VR systems and their influence on user experience (UX) (44). More recent work by Kim et al. (2020) proposed a taxonomy framework based on a meta-analysis of 393 unique articles, which classified VR systems according to target users, input and output device types, interaction attributes and task types, application domains, environmental attributes or platforms, and types of UX evaluation methods used (45).

To evaluate the practical application of a VR-based prototype, several studies assessing user experience in virtual environments were reviewed. Vlahovic et al. (2022) proposed a perception-based framework that considers multiple evaluation categories, considering the holistic concept of QoE (40). Figure 1 provides an example of an evaluation framework for user experience in immersive virtual environments (IVEs) that can serve as a basis for a follow-up user study as proposed in our study (40). This taxonomy was instrumental in re-designing of the VR-based platform as a tool for safety training and workforce development.

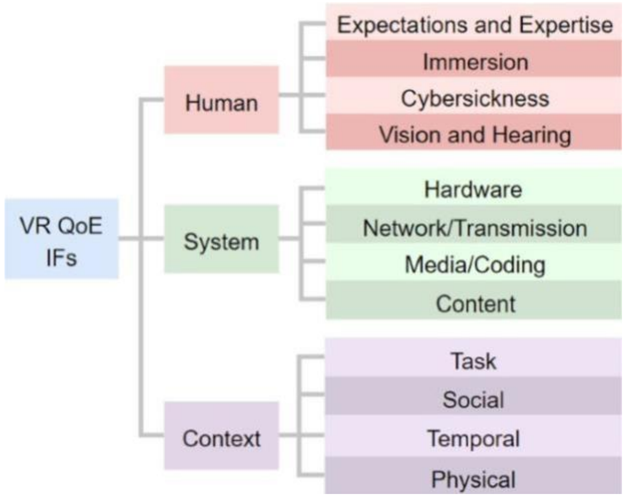

Figure 1: VR quality of experience influencing factors.

Moreover, in order to establish a strong link between the objectives and outcomes of the VR application study and the evaluation metrics, framework, and tools used, it is crucial for researchers to consider the target audience and align the evaluation methods accordingly. Survey questionnaires and open-ended interviews are widely employed in research studies focusing on the practical application of VR in industrial or educational settings, allowing for both quantitative and qualitative feedback. For instance, Lee et al. (2020) conducted a study where they applied a VR application with a 3D model to the architectural design review process for end users. Their findings demonstrated the effectiveness of the VR and augmented reality (AR) system in reviewing the visual elements of a building (44). These types of findings can serve as valuable insights in developing an evaluation framework for site-specific safety training programs in VR, especially when research objectives align closely with the purpose and domain of application.

Lastly, the content implemented within the VR platform itself plays a vital role in facilitating effective learning. A careful review of local and state guidelines, as well as relevant publications, was conducted during the design phase of the VR-based safety training prototype. This step was crucial in identifying the appropriate content necessary to achieve the objectives of the safety training program and enhance workers' awareness of workplace safety. It is essential to consider both site-specific elements and concepts related to work zone installations, as they contribute to a comprehensive understanding of safety in the AEC domain. By incorporating site-specific knowledge and aligning the evaluation methods with the objectives of the VR application study, researchers can develop a robust framework that ensures the effectiveness and relevance of the VR-based safety training program. This framework will not only enhance user experience but also contribute to the overall success and impact of the VR application in improving worker safety awareness in the construction and transportation industry.

3. BENCHMARKING STUDIES TO COMPARE REAL-WORLD AND VIRTUAL REALITY-BASED STUDIES

3.1 Study Design and Protocol for the Real-world Benchmarking Study

The objective of this task was to determine if Virtual Reality-based captured behavioral data on responses to notifications are similar to what is expected in real-world settings. Therefore, we replicated one of the scenarios (Scenario 1) in real-world settings and statistically evaluated the response times of workers to the received notifications. The real-world benchmark study was conducted using the same setup and hardware that was developed in an earlier study to gauge workers' naturalistic response to haptic alarm signals through a hardware-in-loop (HIL) system (31,32). The design and implementation of the real-world study were completed in four months. Figure 2 provides an overview of the experimental steps composed of design, recruitment, implementation, and data collection and analysis. Required factors to be satisfied for the experiments for each step are also provided in Figure 2. The experiment required a reserved area where the speeding toy cars could be used while participants were conducting the tasks assigned to them.

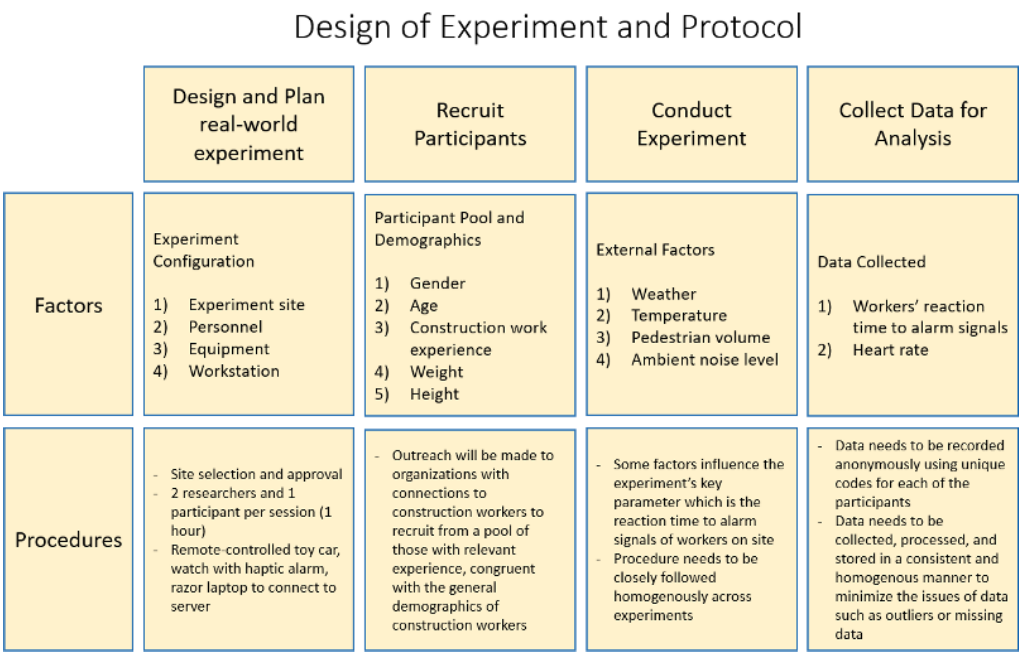

Figure 2: The design process of experiment design and implementation.

The proposed scope of data collection of the real-world study included the external environmental factors (e.g., site accessibility, weather) as well as the key parameters of research defined as reaction time to received alarms and heart rate measures. Table 2 provides the list of parameters that were controlled and measured during the experiments.

Table 1: Key parameters measured and tracked during real-world experiments.

	Variable name	Descriptions
Key parameters captured	Reaction time	The time that one takes from getting the haptic or sound alarm from a wearable alarm device, herein referring to the Apple Watch, to the point when the participant gives a response by stopping the alarm by pressing on the screen of the smartwatch
	Inter-beat interval (IBI, heart rate)	The time interval between individual beats of the heart; the data is measured by using E4 application provided by Empatica
External factors tracked	Ambient noise	The level of ambient noise in the area is a factor potentially influencing participants' reactions and is considered in the experiment design
	Temperature	Daytime temperature recorded at each experiment
	Number of pedestrians on site	Number of participants counted during the time of the experiment to record on the varying factors in the external environment in real-world settings

The experiment took place at the NYU Tandon School of Engineering campus, replicating Scenario 1 described in earlier reports (31,32). In this scenario, an unstructured work zone was temporarily defined by workers using traffic cones. The task presented to users involved picking up the six traffic cones (channelizing devices) from the ground and arranging them to create a simple lane closure for a mobile work zone. To mimic the virtual environment, the real-world study replicated the setup by placing six channelizing devices (traffic cones) on the side of the road. Participants were instructed to pick the cones and place them on the markings on the ground. To simulate oncoming traffic, a remote-controlled scaled-down car was used. The car was operated by a researcher who drove it in a loop toward a designated point, triggering an alarm signal.

In this design, the remote-controlled car approached the work zone from a distance of 100 feet. As the car reached a point where it was 30 feet away from the work zone, another researcher signaled the haptic and sound alarm using an application installed on a connected laptop. For continuity of seamless data collection, it was essential to ensure that the laptop remained connected to the server and campus Wi-Fi to facilitate a smooth execution of the experiment. Any issues related to the transmission of alarm signals or Wi-Fi connectivity needed to be addressed promptly in case they arose during the experiments. Figure 3 provides a visual representation of the entire experiment setup for this specific scenario.

Figure 3: The experiment set up and the location.

Throughout the study, a total of 31 participants took part in the real-world benchmarking experiment, conducting a total of three trials per participant to collect data on user heart rate and alarm reaction times. These measurements were obtained using the hardware-in-loop (HIL) system.

Description of the Data Captured: The raw data captured during the experiment is stored in JSON format on the server. The recorded items, as illustrated in Figure 4, follow a specific order: 'Timestamp', 'From' (indicating the source of the signal or response), and 'Event' (providing notes on the types and nature of events that occurred during the experiments). As shown in Figure 4, the data recorded is in raw form and is mixed with the VR experiments' data recorded on the same server. This raw data is preprocessed to consolidate the real-world trials and separate the VR experiment data.

	Timestamp	From	Event
0	2022-12-08 14:37:53.101391	VR	Received car approaching alert, mode=3, id=1000
1	2022-12-08 15:53:05.098288	Watch	Start Simulation
2	2022-12-08 15:53:07.437488	VR	Received car approaching alert, mode=4, id=1004
3	2022-12-08 15:53:13.064067	Watch	Stop Simulation
4	2022-12-08 15:53:13.163635	Watch	Stop Simulation
...	...	...	...
2417	2023-03-03 16:17:46.166644	Watch	1398
2418	2023-03-03 16:18:00.004425	Watch	1398
2419	2023-03-03 16:18:01.272071	Watch	1398
2420	2023-03-03 16:18:07.359187	Watch	Stop Simulation
2421	2023-03-03 16:18:07.388183	Watch	Stop Simulation

Figure 4: Raw data stored in the server, starting in December 2022.

Firstly, the data was filtered by dates to extract only the recordings from the real-world benchmarking study, which took place outside of the 6 MetroTech Center academic building. We ensured that there were no concurrent VR and real-world experiments occurring on the same dates. Figure 5 presents a snapshot of the extracted data.

	Timestamp	From	Event	date_full
465	2022-12-21 10:45:55.646213	Watch	Start Simulation	2022-12-21
466	2022-12-21 10:46:01.850254	VR	Received car approaching alert, mode=1, id=1015	2022-12-21
467	2022-12-21 10:46:03.393368	Watch	1015	2022-12-21
468	2022-12-21 10:46:04.060460	Watch	1015	2022-12-21
469	2022-12-21 10:46:04.313220	Watch	1015	2022-12-21
...	...	...	...	...
2417	2023-03-03 16:17:46.166644	Watch	1398	2023-03-03
2418	2023-03-03 16:18:00.004425	Watch	1398	2023-03-03
2419	2023-03-03 16:18:01.272071	Watch	1398	2023-03-03
2420	2023-03-03 16:18:07.359187	Watch	Stop Simulation	2023-03-03
2421	2023-03-03 16:18:07.388183	Watch	Stop Simulation	2023-03-03

Figure 5: Raw data filtered by dates of real-world study events.

Any missing or anomalous data points resulting from server or experimental errors were excluded from the dataset. Additionally, sanity filters were applied to remove any values that were outliers. The duration of each experiment was calculated by subtracting the timestamps for the start and end times. Trials with a duration of less than 30 seconds were eliminated from the dataset. Furthermore, any data points that deviated more than 50% range from the mean were considered outliers and removed for both the vehicle travel time between the start point and the warning zone, as well as the user's naturalistic response time to received alarms.

The remote-controlled vehicle's travel time was recorded by subtracting the timestamp when the vehicle started moving from the starting point (100 ft apart line in Figure 6) from the timestamp when it reached the line 30 ft apart from the work area (also indicated in Figure 6). The user's naturalistic response times were recorded as timestamps whenever the user tapped on the watch screen to respond to the haptic alarm. The alarm was manually triggered each time the vehicle passed the 30 ft apart line from the work area. For each trial, the vehicle's speed was measured and recorded, while a total of two to five alarm signals were generated randomly during each trial, depending on the variations in participant and vehicle movement throughout the experiment.

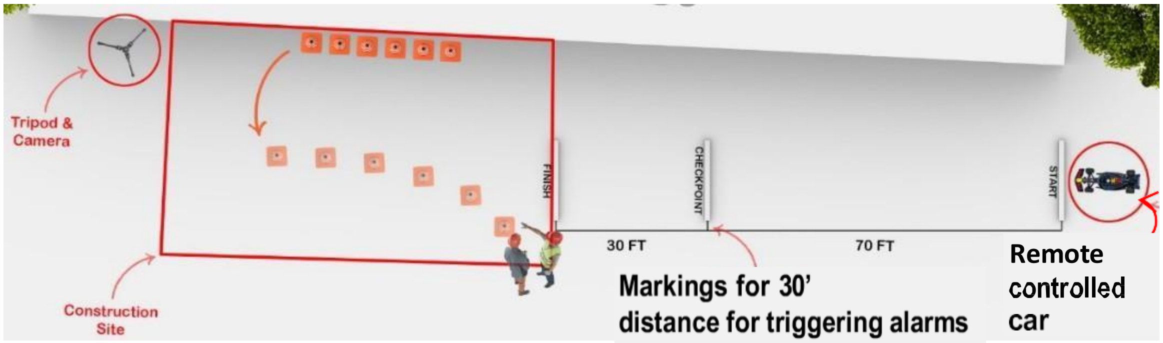

Figure 6: Markings on the real work zone.

The raw data from the server was further processed to assign a unique ID number to each participant, ensuring the anonymization of the data points. With a total of 31 participants, all timestamps recorded were labeled with the corresponding trial number and alarm number. The labeling was necessary as multiple alarms would signal to participants during each triggering event. In each experiment, participants completed three trials, during which they performed the task of defining the boundaries of a short-duration work zone using six traffic cones. Within each trial, participants experienced a total of two to five triggering events, resulting in the corresponding number of alarms. A comprehensive record of each timestamp captured during the real-world benchmark experiments is stored. The metadata about the recorded data is provided in Table 2.

Table 2: Metadata* of the captured data.

Column	Description
userID	Random ID number assigned to each participant
t1_alarm1_sent	Timestamp of the first alarm of trial 1 is sent by the system
t1_alarm1_received	Timestamp when the first alarm of trial 1 is received by a participant
t1_alarm2_sent	Timestamp of the second alarm of trial 1 is sent by the system
t1_alarm2_received	Timestamp when the second alarm of trial 1 received by a participant
t1_alarm3_sent	Timestamp of the third alarm of trial 1 is sent by the system
t1_alarm3_received	Timestamp when the third alarm of trial 1 is received by a participant
t1_alarm4_sent	Timestamp of the fourth alarm of trial 1 is sent by the system
t1_alarm4_received	Timestamp of when the fourth alarm of trial 1 is received by a participant
t1_start	Timestamp of trial 1 start time
t1_stop	Timestamp of trial 1 end time
vehicle_70ft_t1	Vehicle travel time for 70 ft: from the start point to the 30 ft point at trial 1
t1_duration	Duration of trial 1 for each participant in 'mm:ss' format
t1_duration_sec	Duration of trial 1 in seconds
t1_rt1	Response time to alarm 1 of trial 1
t1_rt2	Response time to alarm 2 of trial 1
t1_rt3	Response time to alarm 3 of trial 1
t1_rt4	Response time to alarm 4 of trial 1

**: shown only for the first trial. The same naming convention has been used for the remaining two trials, where 5 alarms were received/sent for the last two trials.*

Data Analysis and Descriptive Statistics: The number of data samples remaining after removing outliers is displayed appear in the count (N) column of Table 3. These samples are used to generate the histograms of data for the trial durations and the response times of the participants (Figure 7 and Figure 8 respectively). However, the plot representing the duration of the experiments shows a slight right skew, indicating that a few participants took considerably longer than the average time to complete the assigned task of placing six cones around the boundary of the work zone. This observation is illustrated in Figure 7.

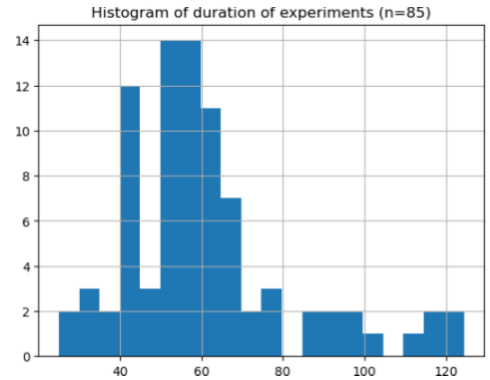

Figure 7: Distribution of experiment duration across all trials.
Y-scale: count; X-scale: duration of trials in seconds.

As shown in Figure 8, the response time counts accumulated around the 2-3 seconds time frame. Descriptive statistics about the response time is provided in detail in Table 4.

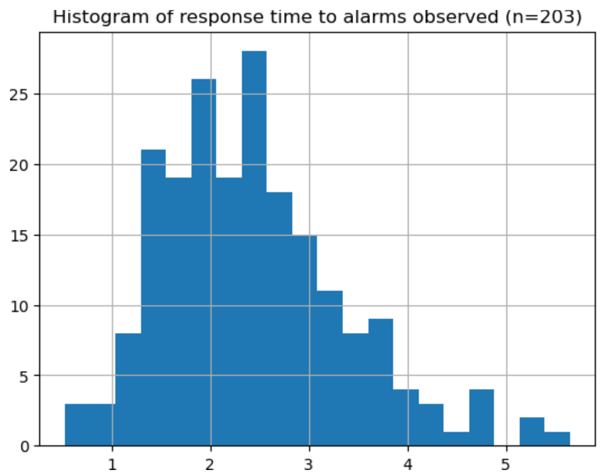

Figure 8: Distribution of response time over all alarms
Y-scale: count; X-scale: response time in seconds.

Descriptive statistics were calculated for the captured data, as presented in Table 4. The statistics were computed based on a total of 93 real-world study trials, encompassing 31 participants who completed 3 trials each. During the experiments, ambient noise data and the participants' heart rates were measured and recorded at one-second intervals. This additional data will be analyzed later (not part of the scope of this project) to examine potential correlations between the user's heart rate, ambient noise levels, weather conditions, and other factors that may influence the worker's response time to alarm signals.

Table 3: Descriptive statistics of data captured during real-world experiments.

	N**	Mean	St.Dev	Min	Max
Response time (sec)	203	**2.43**	0.93	0.52	5.65
Trial duration (sec)	85	61.46	21.23	25.01	124.50

**Vehicle speed is calculated using time it took the remote car to travel a distance of 70 ft.*

*** N: number of datapoints; not consistent, as outliers were removed by applying a 1.5 quarter range to the raw dataset; rounds of trial were not used for sampling and all trials were treated independently.*

The final dataset was calculated using the timestamps recorded at various stages of a participant's trial, such as the vehicle start time from the 100 ft line, the participants' response times to alarm signals, and the instances when an alarm was generated by the system. The calculations included the duration of each trial experienced by a participant, the response times of participants to each alarm signal across all trials, and the vehicle speed calculated from the vehicle travel time of 70 ft at the beginning of each trial. To determine the vehicle speed, the travel distance was divided by the travel time, resulting in the vehicle speed in feet per second. This value was then converted to miles per hour and presented in Table 3. The average response time to notifications during real-world experiments is 2.43 seconds. The main reason for conducting these real-world experiments was to compare the participants' response times to alarms with their response times in VR experiments conducted in the previous year. We assumed that the behaviors exhibited by the participants in VR experiments were indicative of their behaviors in real-world settings. Consequently, we formulated a null hypothesis stating that "the behaviors of individuals towards safety notifications in real-world settings differ from their behaviors in VR settings."

Table 4 provides the results of the participants' response times to notifications received in VR settings. On average, participants responded to a given alarm in 2.59 seconds when they received those alarms in VR settings. Given that the average response time to alarms in real-world settings was 2.43 seconds, the average response time of participants to the received alarms in real-world settings was observed to be slightly shorter (the difference is around 0.6 seconds) than the average response time to received alarms in VR-based experiments. The results of the t-test indicated that the response times observed in both settings of the experiments were not statistically significantly different, with a p-value of 0.22.1 As a result, the null hypothesis was rejected, suggesting that there is no substantial difference in the behaviors of individuals when exposed to VR vs. real-world settings.

Table 4: Descriptive statistics of data captured during VR experiments (Work Zone Safety-III project).

	N**	Mean	St.Dev	Min	Max
Response time (sec)	30	**2.59**	0.75	1.05	4.21

4. ENHANCEMENT OF VR BASED TRAFFIC CO-SIMULATION PLATFORM WITH WORKER BEHAVIORAL MODELS

4.1 VR-Based Interactive Traffic Simulation Platform in a Nutshell

The following description of the Integrated Platform between Virtual Reality (VR) and Simulation of Urban MObility (SUMO) traffic simulations was established in the previous study periods and was available to be deployed in the lab space at NYU Tandon School of Engineering. Therefore, the only task to improve the traffic simulation in VR would be to update and generate a transportation simulation model separately to be integrated later in VR following the same steps described in the following section describing the hardware-in-loop system (HIL) that integrates user interface, traffic simulation and VR. The platform has been detailed in previous publications and reports (31,46).

In a nutshell, the integrated platform enables a two-way flow of information between traffic simulation tools and VR environments using a cloud server. The platform consists of three components: traffic simulation tools (e.g., SUMO) for realistic traffic patterns, VR environments (e.g., Unity3D) for visualizing work zone scenarios, and cloud servers for information relay. These components work together to generate realistic traffic flow in VR. The platform utilizes a feedforward path to transmit simulated traffic information from the simulation tool to VR and a feedback path to bring traffic control changes from VR back to the simulation tool. SUMO and Unity3D are chosen as the tools for traffic simulation and VR implementation, respectively. TraCI protocol enables communication between SUMO and the cloud server, while a custom API called TSVRI facilitates communication between VR environments and the cloud server. Each component of the platform is reminded to the readers briefly below (31,46):

- SUMO (Simulation of Urban MObility) (38): SUMO is an open-source, microscopic, multi-modal traffic simulation software used to address various transportation problems, including traffic management, evacuation, signal control, and safety analysis. It models individual vehicles with defined routes and simulates their movement through a road network. SUMO is cost-effective, highly flexible and modifiable, and supported by user groups, forums, and documentation. SUMO has been used for simulating traffic behavior and studying the effects of different factors on traffic conditions in this study. The software allows for scenario creation by setting initial conditions and adjusting parameters based on the study's objectives. Previous studies have also used SUMO to evaluate variable speed limit control methods, dynamic traffic light changes, and vehicular ad hoc networks (VANETs) assisted by Roadside Units (RSUs) (47-49). SUMO takes input data that includes a road network consisting of nodes, edges, junctions, and signals obtained from OpenStreetMap (50), as well as traffic demand information gathered from real-world traffic observations. The output of SUMO provides vehicle-based information like speed and position, as well as traffic control information such as traffic signal states. This information is sent to a cloud server through the TraCI API.
- TraCI (Traffic Control Interface) (51): TraCI is a key component that allows external applications to interact with SUMO in real-time. It enables customization and control of various simulation objects, such as vehicles, traffic lights, and road infrastructure. TraCI also facilitates the integration of SUMO with Unity3D to create VR environments.
- VR Environment: The VR environment development involves two steps. First, the road network is imported from a mapping service like OpenStreetMap into both SUMO and Unity3D. Second, detailed 3D mesh objects representing the work zone, such as buildings, streetlights, scaffolds, and signages, are added using point cloud data generated by a laser scanner. This process creates a realistic representation of the work zone in the VR environment.
- Information Flow: The platform establishes a client-server interaction using TCP/IP networking protocol to enable a two-way information flow between the VR environment and the traffic simulation software (52,53). Real-time simulated vehicle and traffic control information from SUMO are sent to the cloud server and then forwarded to Unity3D, where

vehicles in the VR environment move based on the simulation. Conversely, changes in the VR environment, like the placement of barriers or cones, are captured and sent back to SUMO to adjust the ongoing simulation.

- Hardware-in-the-Loop Integration: The platform includes a hardware-in-the-loop integration, where a worker safety system is connected to the VR environment. The safety system monitors worker location using sensors and provides alarms through devices like smartwatches when dangerous situations are detected in the VR environment. Application servers facilitate the relay of information between the VR environment, traffic simulation software, and the worker safety system.

By combining SUMO, Unity3D, and hardware integration, this platform enables realistic traffic simulations, worker safety analysis, and user studies in VR environments for work zones. This platform has been expanded since the last effort to incorporate pedestrian behavior into the traffic co-simulation.

4.2 Enhanced Platform: VR-based Traffic Micro Simulations with Integrated Pedestrian Behavior

Prior studies have utilized VR-based scenarios; however, the integration of pedestrian simulation into the virtual environment has not been achieved yet. To bridge this gap, we have developed a pedestrian integration scheme by modifying the codes used in SUMO to recognize participant locations as worker behavior within the system (Figure 6). The incorporation of pedestrian simulation into the virtual environment offers several potential benefits. Firstly, it enhances the accuracy and realism of the simulation by replicating the movement and behavior of real pedestrians. Secondly, it enables the evaluation of the impact of pedestrian behavior on traffic flow, which is critical for developing effective transportation planning and management strategies. Thirdly, it provides a safer and more cost-effective way to conduct experiments involving pedestrian behavior as it eliminates the need for actual pedestrians during the testing phase. Lastly, it facilitates the development and testing of intelligent transportation system applications that specifically focus on pedestrian safety and mobility. This enhancement represents a potential approach for improving the virtual environment by more accurately replicating real-world behavior and environments observed in short-duration work zones surrounding roadway construction sites.

Task 1: The first task of the research is to simulate workers' movements in the work zone area and control the movements according to the interaction orders. This is the key preceding step of VR-based co-simulation because, in the control loop, workers' actions from the VR environment will be sent to the SUMO environment. The SUMO environment needs a framework to control workers' movements based on direct signals. The following steps have generated this framework: 1) change the worker control status; 2) combine the TraCI commands to move the worker by direct orders. To modify the worker control status, we took over the control from the default simulation model, which allowed us to send direct signal control orders for each simulation step based on interactive activities. The movement of the worker was controlled using the TraCI commands, which allowed us to specify the pedestrian's position, speed, and direction. Specifically, we used the following TraCI functions to control pedestrian movements (some of the functions are optional, depend on the task requirement):

- **traci.person.getPosition(personID):** This function retrieves the current position of the pedestrian with the specified ID.

- **Traci.person.moveToXY(personID, edgeID, lanePosition, x, y, angle, keepRoute):** This function moves the pedestrian to the specified (x,y) position on the specified edge and lane.
- **Traci.person.setSpeed(personID, speed):** This function sets the speed of the pedestrian to the specified value.

To simulate the movement of pedestrians, we allowed them to move in four different directions (forward, backward, left, right) and calculated the moving distance based on the average walking speed of a person (4.92 ft/s by default) multiplied by the simulation time step length. By utilizing these TraCI functions, we were able to accurately simulate pedestrian movements and behavior within the VR- based traffic co-simulation platform. A demo was generated based on the scenario, where workers are tasked with Scenario 1. One "worker" is simulated in the scenario near the work zone, and his/her movements can be controlled by pressing keyboards. Each press can move the worker by a limited distance according to the actual pedestrian speed and simulation step length. Four directions are available (forward, backward, left, right), and the pedestrian can walk freely across the sidewalk and driveway.

Task 2: The next task is to simulate rule-based pedestrian behaviors in the SUMO environment. The rule consists of three parts: 1) movement restriction areas, 2) task simulation, and 3) random movements. The movement restriction defines the areas where workers can move, including sidewalks, driveways, and work zones. Once the pedestrians("workers") reach the boundaries of these areas, they are compelled to return. The restriction area needs to be set by the user in Python script according to the real data of the work zone. The task simulation rule defines specific tasks for the workers to mimic real workers in an actual work zone, such as circling between two points in the work zone. The random movements rule generates diverse behaviors, including unsafe movements like walking in and out of the work zone and jaywalking across the driveway.

In the task simulation component of the pedestrian behavior simulation, users can adjust the behavior of the simulated workers and work zone features by modifying the environment variables. These environment variables include:

- **Moving frequency (float, [0, 1]):** This variable defines the proportion of time that workers spend moving and stationary. Users can adjust this value to simulate workers who are constantly on the move or workers who spend more time at specific locations.
- **Work focus point (vector, [x, y]):** This variable allows users to set a specific point within the work zone that will attract workers to move to or stay at that point. This can be useful in simulating workers who are focused on a particular task or location within the work zone.
- **Compliance level (float, [0, 1]):** This variable defines the probability of out-of- boundary movements. Users can adjust this value to simulate workers who are more or less likely to deviate from their designated work zone areas.

By adjusting these environment variables and utilizing TraCI functions to control the movement and behavior of the simulated workers, users can create more realistic and accurate simulations of pedestrian behavior within the VR-based traffic co-simulation platform.

Task 3: The third task of this research project involves simulating pedestrians using a pre-trained behavior model that leverages real trajectory data and experimental data collected from our previous VR tests. A generative pre-trained model can be utilized to simulate pedestrians' behavior within the VR- based traffic co-simulation platform. Generative models can be used to generate realistic pedestrian trajectories that can be used as inputs to the SUMO simulation environment.

We are using Generative Adversarial Network (GAN) to generate realistic pedestrian trajectories based on real trajectory data and experimental data collected from previous VR tests. The GAN consists of two networks: a generator network that generates new trajectories and a discriminator network that determines whether a given trajectory is real or generated. To train the GAN, real pedestrian trajectories can be used as the training data. The generator network is trained to generate new trajectories that are indistinguishable from the real ones, while the discriminator network is trained to differentiate between real and generated trajectories. Once the GAN is trained, the generator network can be used to generate new pedestrian trajectories, which can be fed into the SUMO simulation environment to simulate pedestrian behavior.

However, the quality of the real trajectory data and movement data collected from previous VR experiments is not satisfactory, as it contains a lot of noise and unreal behavior. This can result in a suboptimal GAN model that fails to generate realistic pedestrian trajectories. To address this issue, we plan to collect more open-source workers' and pedestrians' trajectories to supplement the existing dataset. By incorporating more diverse and high-quality data into the training process, we aim to improve the GAN model's performance and generate more realistic pedestrian trajectories that can be used as inputs to the VR-based traffic co-simulation platform. This will enhance the realism and accuracy of the pedestrian behavior simulation and improve the platform's overall effectiveness.

Figure 9 delineates the correlation between the rule-based control model and the Generative Adversarial Network (GAN) based trajectory generation model. The training of these models incorporated both actual trajectories and those produced through VR experiments. Components of the output generated by the rule-based model, such as the safety boundary, task-oriented behavior, and random movements, can be utilized not only in the training of the GAN-based models but also within the simulation environment.

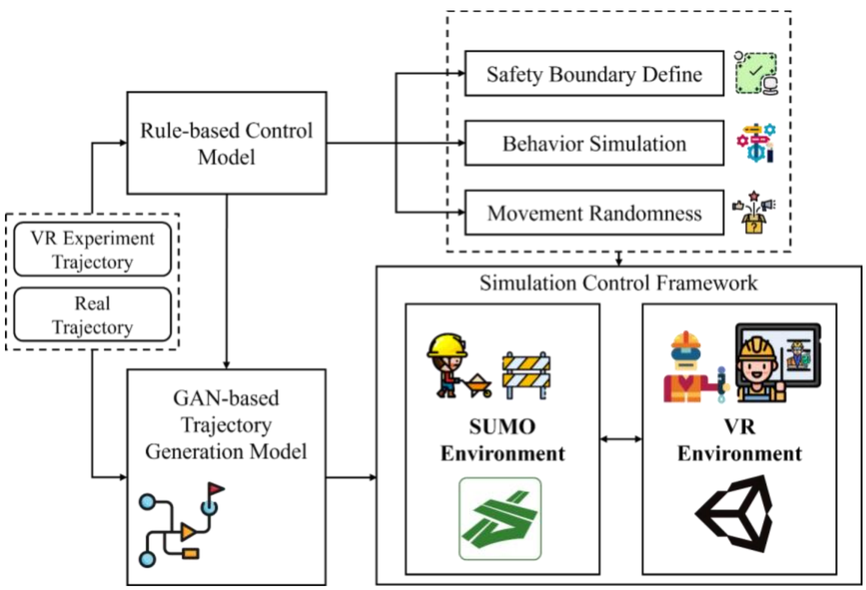

Figure 9: Implemented system to incorporate worker behaviors into the SUMO and VR integrated.

5. VIRTUAL REALITY AS A WORKFORCE DEVELOPMENT AND TRAINING TOOL

This section provides the outcomes of the research task on evaluation of VR as a workforce development and training tool. The work that has been performed to develop the VR based training platform has been presented first, followed up with the captured perspectives of professionals about this opportunity of using VR in safety training.

5.1 Stakeholder Interviews from AEC Industry Professionals on the views of Virtual Reality Applications

5.1.1 Introduction

This task aimed to capture the perspectives of industry and government professionals from the Architectural, Engineering, Construction industry on the application of Virtual Reality (VR) for workforce development. We have identified five subject matter experts and interviewed them to gauge their interests in the deployment of the technology for workforce development and understand their viewpoints. The interviewees were contacted and recruited from the network of the PIs and are executives and technology officers at major companies that present demonstrated interest in adopting new technologies for enhancing worker safety, as well as public sector transportation professionals who provide guidelines for safety to be followed. The interview questions were composed of three parts: 1) General views on VR/AR application for workforce development and safety training, 2) value experts see in using VR/AR platforms to increase safety awareness of their construction workers, and 3) a set of use-cases where the VR platforms can be expanded for workforce development and safety training (i.e., content identification for future VR implementation). A summary of the stakeholder interviews is presented anonymously in the following section.

Participants included a safety training provider, two construction professionals related to worker safety, one public sector expert who oversees construction projects which encounter real-life cases where workers are exposed to dangers from oncoming traffic or vehicle movements around work zone operations on the road, and a professional from a technological startup and a consultancy firm that takes on innovative approaches to bringing novel technologies to improve worker safety for construction projects. The comprehensive list of questions, covering three areas of investigation, is summarized in Table 5.

Table 5: Stakeholder interview questions.

Introduction	
Q1	Could you please introduce yourself and your work, how long have you worked in the industry and your current role?
Part 1. General views on VR/AR application for workforce development and safety training	
Q2	What do you think about Virtual Reality being used as a platform for providing safety training for roadway workers?
Q3	Do you have any experience or knowledge of Virtual Reality being used in worker safety training in your practice or industry? Please give a few examples if so.
Q4	What are advantages or incentives of adopting VR platforms to augment current worker safety training platforms/methods?
see in using VR/AR platforms in increasing safety awareness of construction workers	
Q5	What are some value propositions you can state for VR platforms for improving worker safety awareness?
Q6	What specific scenarios you can think of where VR can enhance worker safety training?

VR platforms can be expanded to include workforce development and safety training	
Q7	What level, grade, types of workers do you see are most prone to workplace hazard, where bringing better workplace training program is required?
Q8	What are some workplace hazard situations where it is difficult to train workers due to difficulty of demonstrating a hazardous situation, where it would be appropriate to bring in VR equipment? Please provide specific examples.

5.1.2 Interview Results

The stakeholder interviews conducted with professionals from various sectors involved in worker safety training and construction operations provided valuable insights into the potential adoption of VR technologies. The interview results can be summarized as follows:

- Site safety professionals, who provide training to workforce, indicated that the conventional training would involve classroom lectures and on-site demonstration, involving the potential risk of hazards and accidents that may occur in lieu of any common mistakes or mishandling of equipment. Some demonstrations will require a mock setup of operation sites where the workers will be assigned to learn how to use the actual tools and equipment involved as well as some of the site-specific characteristics of the construction work. The professionals responsible for providing safety training expressed limited knowledge and awareness regarding the application of VR technologies. They emphasized the need for VR platforms to be comfortable and attention- grabbing for users. While there was strong agreement on the usefulness of VR for multiple screenings of work operations and its potential to enhance safety, emphasis was on the need for realistic representation of job sites within the immersive virtual environment.
- Local government plays a crucial role in establishing and overseeing safety procedures in transportation and construction. Public servants may often oversee and inspect the various construction sites on roadways that require safety treatment and installation. A general view held regarding the nature of dangers extant on roadways is that drivers show erratic behavior and the general movement of vehicles do not always follow the usual trajectories when there is a change of circumstance on the road. As earlier versions of VR implementations show static or the same simulated trajectories of cars in virtual environments, the perception was that the traffic behavior will not be realistic. This work resulted in a platform where VR is co-simulated with real traffic flows, trajectories, volume, and composition of traffic on the intersections simulated in VR with random erratic behavior by drivers. Given this simulation platform, this concern of the professionals is addressed. Even if the assumption was that VR would not provide realistic traffic simulations, the interviewee indicated that VR would still be useful for beginners to get started with safety training for roadway construction. For deployment of such technology-based training platforms in agencies, the cost associated with adoption and compliance with regulatory standards has been highlighted as important components for consideration.
- Professionals from construction companies in supervisory or managerial roles expressed skepticism due to previous failed attempts to adopt VR for workforce development and safety training. While the discussion of such technological adoption is still open to question and further investigation among AEC firms, a major obstacle faced by construction companies in taking innovative approaches to adopting VR technologies was the cost considerations

including the initial cost of purchasing the equipment and putting such practices at scale. Regulatory hurdles like compliance with OSHA standards are another component of the difficulty of adopting wearables or novel technologies that include wearable equipment and VR technologies, as use of them will sometimes require OSHA approval, which is a difficult regulatory authority from which to gain approval. The major area of work in site safety that construction companies are interested in is improving the realism of VR to replicate the site as closely and in as much detail as possible so the learning would be useful in actual operations. The big challenge of work zone operations is to keep workers alert to the imminent danger they are exposed at a constant rate on the roadways; humans tend to get comfortable even in a dangerous setting over time. This is still a major task for worker safety training. Technological solutions to solving the issue of improving workers' safety awareness may be an area of work for VR technicians as well.

- Viewpoints of companies that leverage technology were positive as compared to construction professionals. The interviews highlighted that the high risks faced by utility workers near power lines are significant and can result in casualties and life-altering injuries. Like other interviewees, the emphasis was on developing VR platforms that closely replicate the specific characteristics of the job site. When the VR products are in use, they will assuredly benefit those who receive such safety training on the job site. However, the economic and regulatory feasibility of such a product will result in another level of concern once there is an agreement on the technological adoption.

In conclusion, the interviews revealed a mixed perspective on the adoption of VR technologies for worker safety training and job site simulations. While there were reservations and skepticism based on past experiences and cost considerations, there was also recognition of the potential benefits of VR in enhancing safety and training outcomes. The emphasis on creating realistic job site simulations emerged as a common theme across sectors. Future developments in VR should focus on addressing these concerns and challenges to increase acceptance and feasibility among stakeholders. The simulation capacity of VR to give experiential learning of the site without posing users with actual physical danger offers potential success for the technology and the platform to achieve better outcomes in worker safety training.

5.2 Content identification for VR-based safety training

In order to develop a prototype for VR-based workforce training, the research team conducted a comprehensive assessment of training programs and modules available from government agencies and certified training providers listed on the Department of Transportation (DOT) and Federal Highway Administration (FHA)'s web-based guides. These resources were categorized into nine different groups, encompassing various durations, content, and providers. The team focused on identifying training content relevant to the existing VR scenarios, with a particular emphasis on the following categories: design for work zones, short-duration work zones, traffic control in work zones, and worker safety. Additionally, the standard training programs cover a wide range of topics including inspection of work zones, intelligent transportation systems (ITS), law enforcement, management of work zones, and nighttime work zone operations. Design for work zones courses, for instance, spanned from six hours to three days and covered topics such as work zone strategies, advanced work zone management, design and operation of work zone traffic control, and strategies for work zone traffic analyses. Advanced courses delved into detailed standards, guidelines, and principles of temporary traffic controls, as well as constraints and opportunities related to work zone analysis using transportation modeling approaches.

For short-duration work zones, training modules and resources were available in various formats, ranging from less than 30 minutes to two-day workshops. These modules focused on field personnel involved in the planning, selection, application, and operation of short-term work zones tailored to specific roadway conditions. Specialized training materials addressed distinctions between short-term work zones and maintenance activities in rural and urban areas. In terms of traffic control, which requires detailed instructions and guidelines to ensure the safety of drivers and roadway construction workers, the Department of Transportation website(4) offered a plethora of courses and training materials. Lastly, worker safety resources covered overlapping topics, emphasizing the importance of considering work zone design, traffic control, and maintenance to ensure overall safety.

The resources identified by the DOT were available in various formats, including PowerPoint presentations, workshops, lectures, and instructional videos on platforms like YouTube. Some training modules were presented as interactive websites, allowing learners to navigate through specific topics using options or menus. Figure 10 showcases examples of training courses presented as interactive websites and printable documents. Access to interactive websites offering flagging operations or work zone setup using traffic control devices was available through external providers, some offering free access while others required fees (54-56).

Figure 10: Examples of training modules available on external sources.

In the process of content identification for the VR-based workforce training prototype, Scenario 1 served as the benchmark. This scenario involved workers placing six traffic cones along work zone boundaries, which aligns with the elements commonly found in worker safety training materials, particularly the 2009 Manual on Uniform Traffic Control Devices (MUTCD) guideline. The standard training content covers various aspects related to worker safety on construction sites, including the installation of safety devices on roads, traffic control training such as flagging procedures, and general precautions that workers need to be aware of during road construction activities. The specific program and modules may vary slightly depending on the providing agency, with training durations ranging from a few hours to several days.

For the implementation of a VR training module, it was important to ensure that the duration of the prototype module did not exceed one hour. This duration was chosen to make it comparable to conventional training formats such as instructional videos, lectures, or presentations. The identified content, which matched the requirements and constraints of the prototype, underwent a detailed analysis before being finalized for VR implementation. Researchers evaluated the suitability of the content for worker safety training, its relevance to the existing VR scenarios, and its overall applicability to safety training. A summary of the identified content and the evaluations conducted by the researchers is provided in Table 6.

Table 6: Content identification for VR-based safety training and evaluation chart.

Topic	Title	Source	Duration	Format	Suitability	Applicability for VR	Final selection to include
Design for work zones	Set up and take down of Roadside work zones	Online search	NA	Web learning contents	Suitable for individual training	Relevant, yet not specific on implementation as the materials are composed of paragraphs/pictures	**Yes**
	Design and operation of work zone traffic analyses	Training course	1-day	Classroom	Need to purchase through NHI	Hard to access	No
	Advanced work zone management and design	Training course	3 days	Classroom	Need to purchase through NHI/ Long	Hard to access and too lengthy	No
Short-duration work zones	Work zone technician manual	Training course	1 day	Classroom	Free course from Missouri DOT	No longer accessible/ source from local government	No
	Temporary traffic control for short duration activities	CD-ROM	5 Hours	ATTSA	No longer available	Hard to access	No
Traffic control in work zones	Uniform Traffic control devices (MUTCD) part 6: Temporary traffic control	ATSSA	NA	PowerPoint Slides	Suitable for individual or group training	Relevant, yet too general for VR lacking situational learning contents	**Yes**
Worker Safety	Work zone safety and flagging tutorial (NY)	Cornell Local Roads Program (57)	NA	Online self-study/ recorded webinars	Suitable	Relevant	**Yes**

From the identified training content related to work zone safety, three conventional training materials were selected for our VR-based worker safety training application. These materials include an overview of temporary traffic control devices, work zone clear zones, buffer spaces, positive protection devices, and hazard identification. The training platform consists of three sections: 1) hazard identification, 2) identification of temporary traffic control devices, and 3) order of installation for short-duration mobile work zones.

To replicate the current practice of delivering safety training to workers, we developed an interactive set of lecture slides. These materials resemble a toolbox, offering downloadable PDF instructions with graphics and images for topics such as hazard identification and work zone setup and takedown. The same content was used to create the VR-based training prototype, which is illustrated in Figure 11.

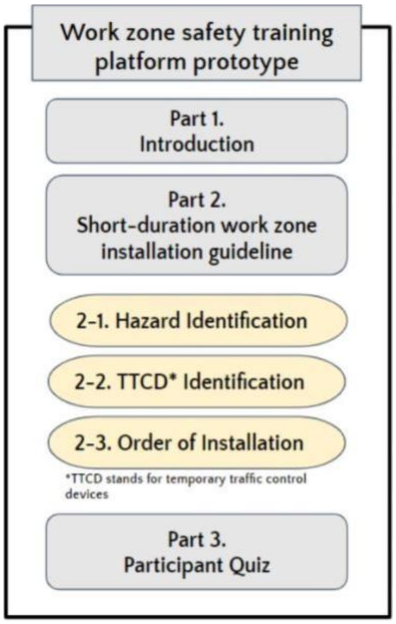

Figure 11: Structure of the VR-based worker safety prototype. Contents taken from the conventional training resources.

This VR-based training prototype allows workers to experience real-life scenarios in a simulated environment, providing them with a more immersive and engaging way to learn crucial safety skills. To allow for a better understanding of the benefits of VR-based training, we have also included a comparison between our prototype and more traditional training platforms in Table 7. This comparison highlights the main differences between the VR-based training prototype, including how they differ in content, duration, format, software applications used, and hardware devices used.

Table 7 Details of VR-based and conventional work zone safety training platform implementation.

		VR-based training platform	Conventional training material (PowerPoint presentation)
1	Content	Identical content that starts with a quick introduction to work zones followed by three modules: 1) hazard identification, 2) temporary traffic control device (TTCD) identification, 3) order of installation, and the final quiz to assess the knowledge acquired from all three modules.	
2	Duration & Description	1 HR (*The training will contain the safety training content outlined in Figure 6)	
3	Format	Virtual environment allowing participant interactions with objects/scenes with sound instructions	Lecture Video recorded by instructor (played by research administrator)
4	Applications Used	Unity	Video Lecture
5	Device needed	VIVE Pro connected with PC (Razer laptop)	A PC with a media player application for a recorded PowerPoint Lecture

We drew inspiration from previous research studies conducted in the area of worker health and safety, which aimed to utilize VR for safety training purposes. These studies shared a common objective of simulating hazardous conditions in a virtual environment, allowing participants to experience and learn about potential dangers without exposing them to the same risks found in real-world settings [26-28]. Examples of how the virtual environment is set up for each module are demonstrated in the storyboard created, based on Scenario 1 (i.e., installation of cones to define a work area in a busy urban street) from the earlier project (Figure 12).

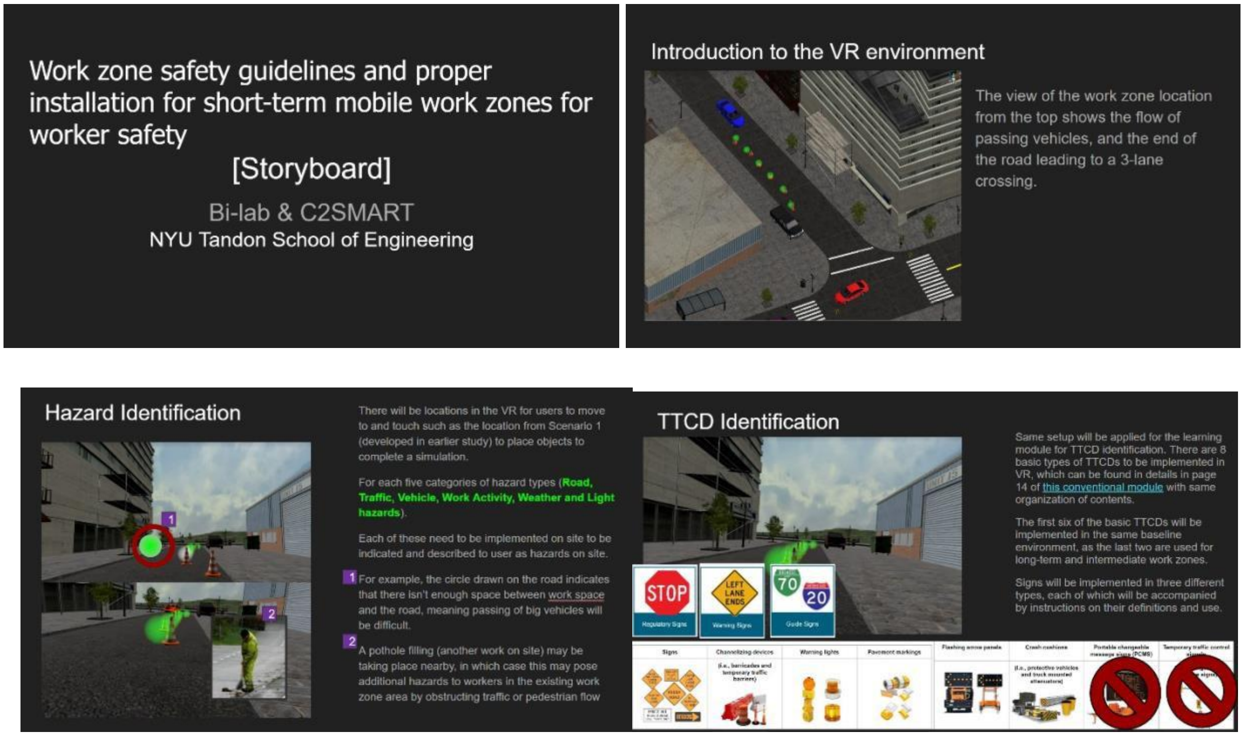

Figure 12: Examples from the storyboard created for implementing VR-based safety training.

6. TASK 3: VIRTUAL REALITY AS A WORKFORCE DEVELOPMENT AND TRAINING TOOL

6.1 Virtual Reality-based safety training prototype

6.1.1 Lab Setup and Equipment

As seen in Figure 12, the hardware setup for this platform consists of the VR hardware, which includes a system of headsets, controllers, laser trackers, and the ultrasonic sensors installed on Raspberry Pis that can be used to measure the 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 could freely move without triggering the perimeter alarm. The subjects would wear the 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.

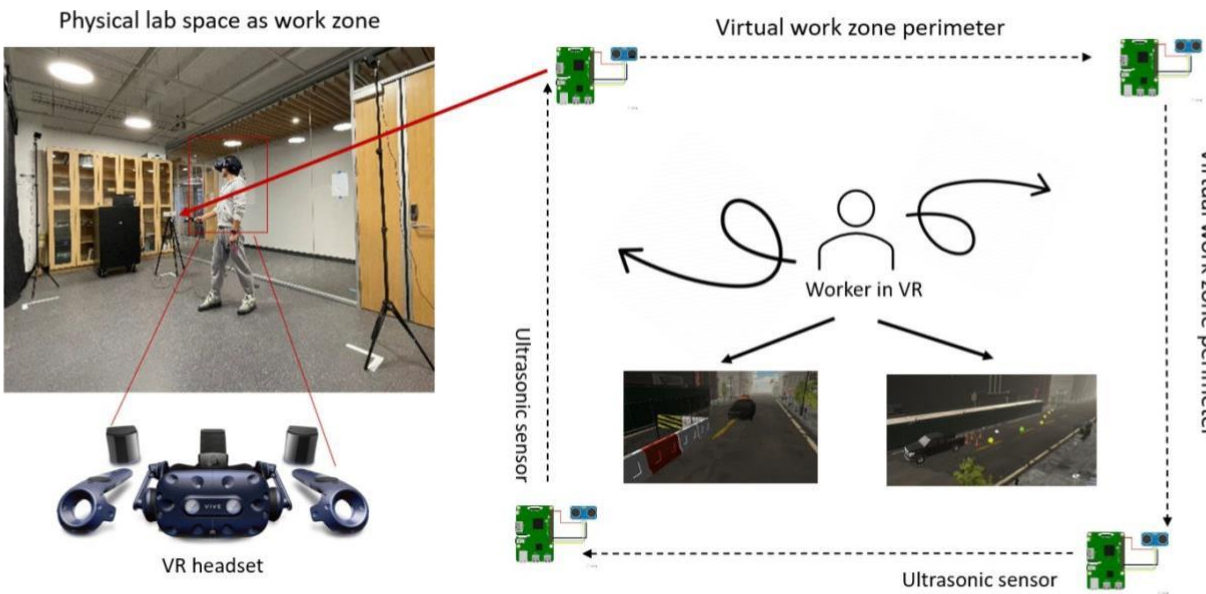

Figure 13: Hardware setup; integrated platform with (a) VR hardware, (b) server/client hardware.

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 13). 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, 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 connect with clients using the TCP/IP networking protocol.

6.1.2 User Study and Test of VR-based Safety Training Program

The initial content identified in the planning phase (Section 3.3, Figure 1) has undergone revisions to create a simplified demo version. This demo contains three different interactive learning modules focused on site-specific hazard identifications for installing a short mobile work zone on a narrow road near NYU's Brooklyn campus. The objective of this prototype is to evaluate the effectiveness of a site-specific interactive safety course, which has been designed to enhance the learning outcomes of the content when delivered through the novel VR platform. However, it is important to acknowledge that the key features employed in the prototype may have varying effects on participant comfort and learning effectiveness, depending on their receptivity to VR. To gather more user experience data and insights on application of VR on various contexts, a brief user study has been designed. This study aims to assess knowledge retention of the lessons presented in the VR-based worker safety training, followed by a survey to collect general feedback on the user experience and their perspective on the potential of VR applications in safety training within the AEC domain.

To finalize the worker safety training prototype, several key features were incorporated. The prototype focused on site specificity, meticulously replicating a road site near NYU Tandon's Brooklyn campus. The interactive learning modules were designed to be motion-based and consisted of three distinct hazard identification lessons tied to traffic cones placed on one side of the road. The immersive virtual environment (IVE) provided an audio-based explanation of each hazard as users interacted with the traffic cones. To enhance realism, scene-specific effects were integrated into the IVE, demonstrating what these hazards would look like in the real world. The platform included three types of hazards: ***weather hazard, traffic hazard,*** and ***road hazard*** (Figure 14). The weather hazard module addressed the unpredictable nature of weather conditions, emphasizing the need for operators to monitor and assess these conditions to prevent potential accidents. The traffic hazard module focused on the flow of traffic on-site, highlighting the importance of continuous monitoring by operators. The road hazard module highlighted any objects or structural components on the road, such as hills or curves, which could impact traffic flow and pose additional risks to workers.

During the modules, audio descriptions of the hazards were played through the user's headset, synchronized with the corresponding motions and scenes in the IVE. For example, when users initiated the "weather hazard" module, rain would begin falling in the virtual environment. Similarly, the "traffic hazard" module would feature a car approaching the site from behind. Lastly, for the road hazard module, objects surrounding the roadway, such as trees or streetlights, would be highlighted in red to indicate that the road may be too narrow for traffic to pass once the work zone is installed. By incorporating these elements, the final version of the worker safety training prototype aimed to provide an engaging and realistic learning experience, enabling participants to effectively identify and understand various hazards encountered in roadway work zones.

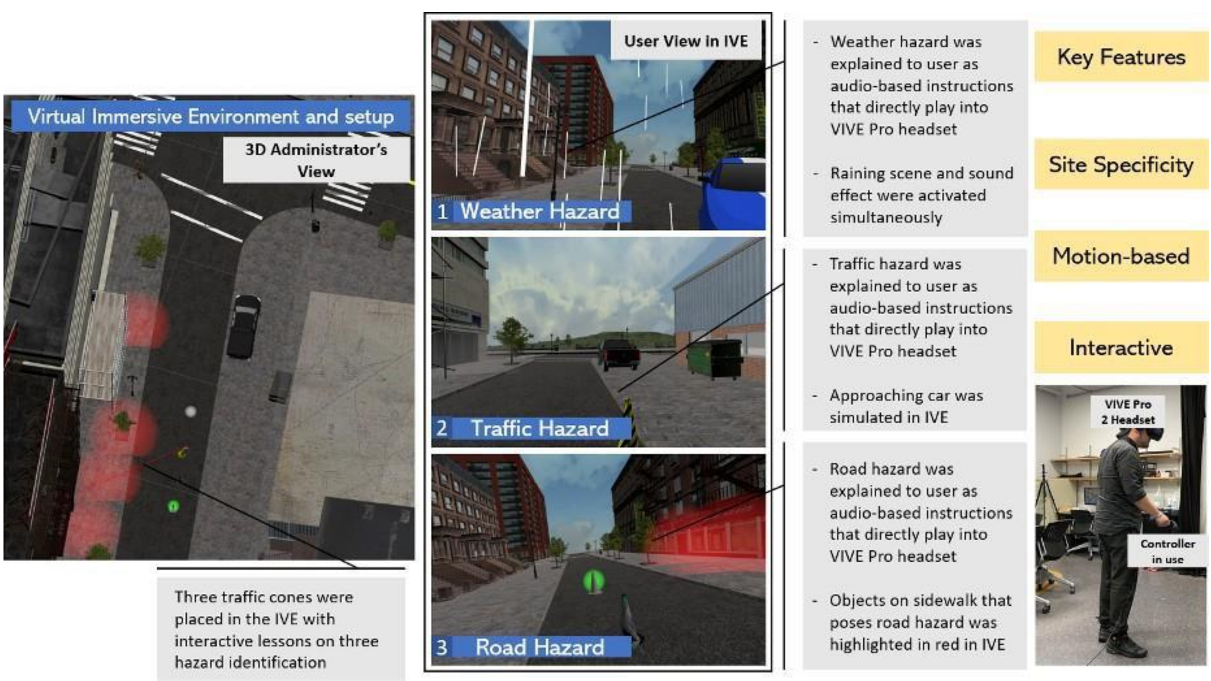

Figure 14: Final layout: work zone safety site-specific hazard ID demo version and key features.

The study period was insufficient to launch the prototype at scale and conduct comprehensive user studies comparing the performance of learners across different learning objectives in both traditional and VR-based platforms for safety training. However, the research team organized a half-day workshop with a small group of participants who had varying levels of knowledge regarding work zone safety. The user study included six participants, all from the Department of Civil and Urban Engineering. The group consisted of two female participants and four male participants, with two participants in their 20s and the remaining four in their 30s. Participants' self-reported exposure or awareness of work zone safety ranged from 1 to 4 on a 5-point Likert scale. Similarly, their knowledge of VR technologies varied from minimal (1) to expert (5). The user comfort and experience during the study were highly satisfactory and entertaining, as indicated by the survey responses and general feedback collected from the participants. However, in terms of learning and safety training through VR, improvement opportunities were pointed out to increase the effectiveness of the module in helping users grasp the various safety-related guidelines and concepts introduced. For example, one participant noted that as the module instructions were played simultaneously with the effects taking place in the IVE, it was challenging to pay attention to the audio instructions while being completely immersed in the VR environment. Such feedback can inform the future versions of the platform aimed at enhancing worker safety training on job sites resembling the one implemented in our platform.

In summary, the overall feedback on the learning experience in VR from the small group of participants was positive, with anticipation that such a platform will lead to better training outcomes in the future. Although the brief user study did not explicitly compare the learning outcomes of conventional training with the VR-based module, most participants provided positive feedback on the effectiveness of the interactive features introduced in VR for learning and content delivery. This aligns with insights shared during stakeholder interviews, indicating that VR appears to be a valuable tool at the entry-level, increasing interest in safety training by providing realistic experiences. The study presents a positive outlook, affirming that VR undoubtedly offers an engaging and captivating platform for introducing users to job sites and the content for learning itself. However, to assess long-term memory retention and the overall effectiveness of delivering lessons through VR in safety training, further work and more comprehensive user studies are necessary to provide conclusive insights that can benefit both users and industry stakeholders.

7. OUTREACH ACTIVITIES

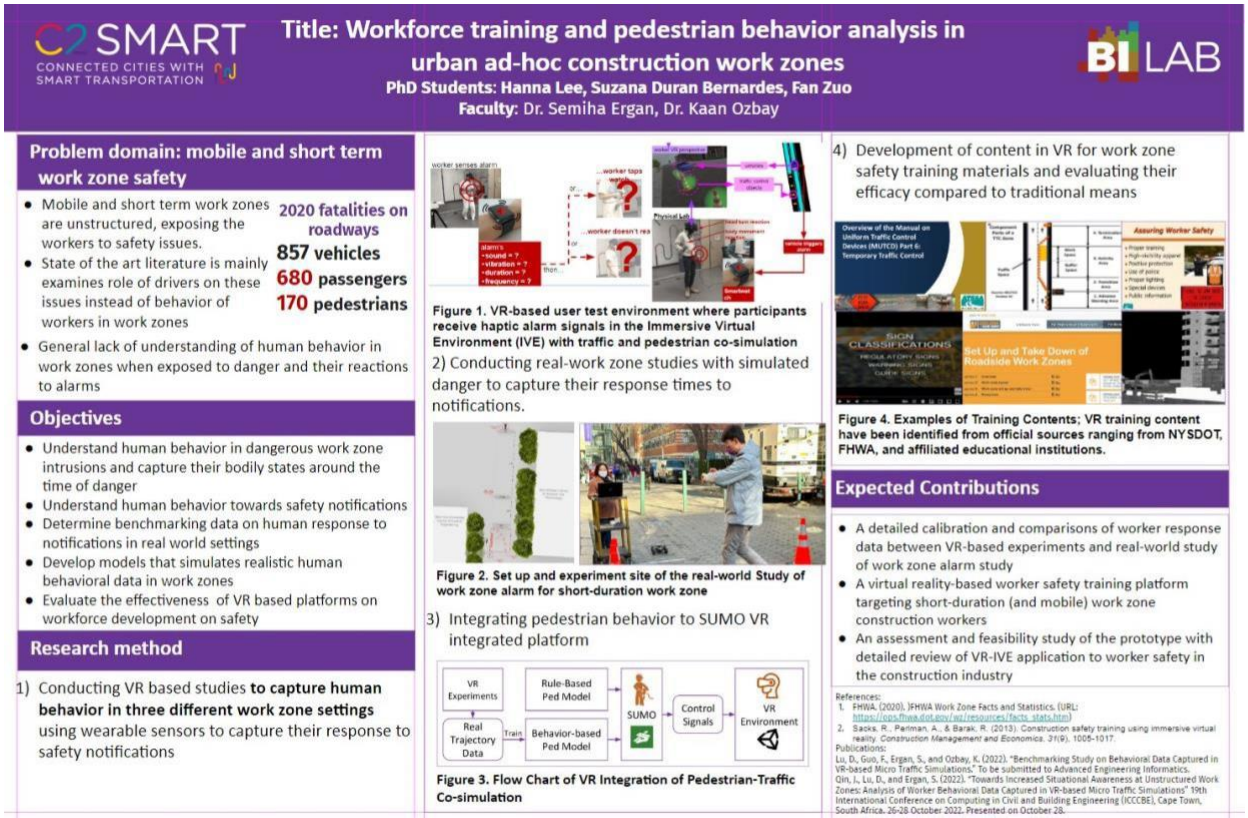

Figure 15: Poster presented at 2022 NYU Urban Research Day.

- The team presented a poster at the 2022 Urban Research Day at NYU CUSP (Figure 15).
- Conference paper on "Towards increased situational awareness at unstructured work zones: analysis of worker behavioral data captured in VR-based micro traffic simulations" to International Conference on Computing in Civil and Building Engineering (ICCCBE) by Daniel Lu and Semiha Ergan.
- Conference paper on "Predicting roadway workers' safety behavior in short-term work zones" to European Group for Intelligent Computing in Engineering Conference (EG-ICE) by Daniel Lu and Semiha Ergan.
- Conference paper on "Urban Work Zone Detection and Sizing: A Data-Centric Training and Topology-Based Inference Approach" to IEEE ITSC 2023 by Fan Zuo, Jingqin Gao, Kaan Ozbay, Zilin Bian, and Dan Zhang.
- The research team held a joint event with NYU Tandon ASCE Student chapter on March 3rd, 2023 for a recruitment of students to participate in the real-world benchmark study conducted and a poster presentation as an introduction to learning about the ongoing study design and the past work from the lab (Figure 16).

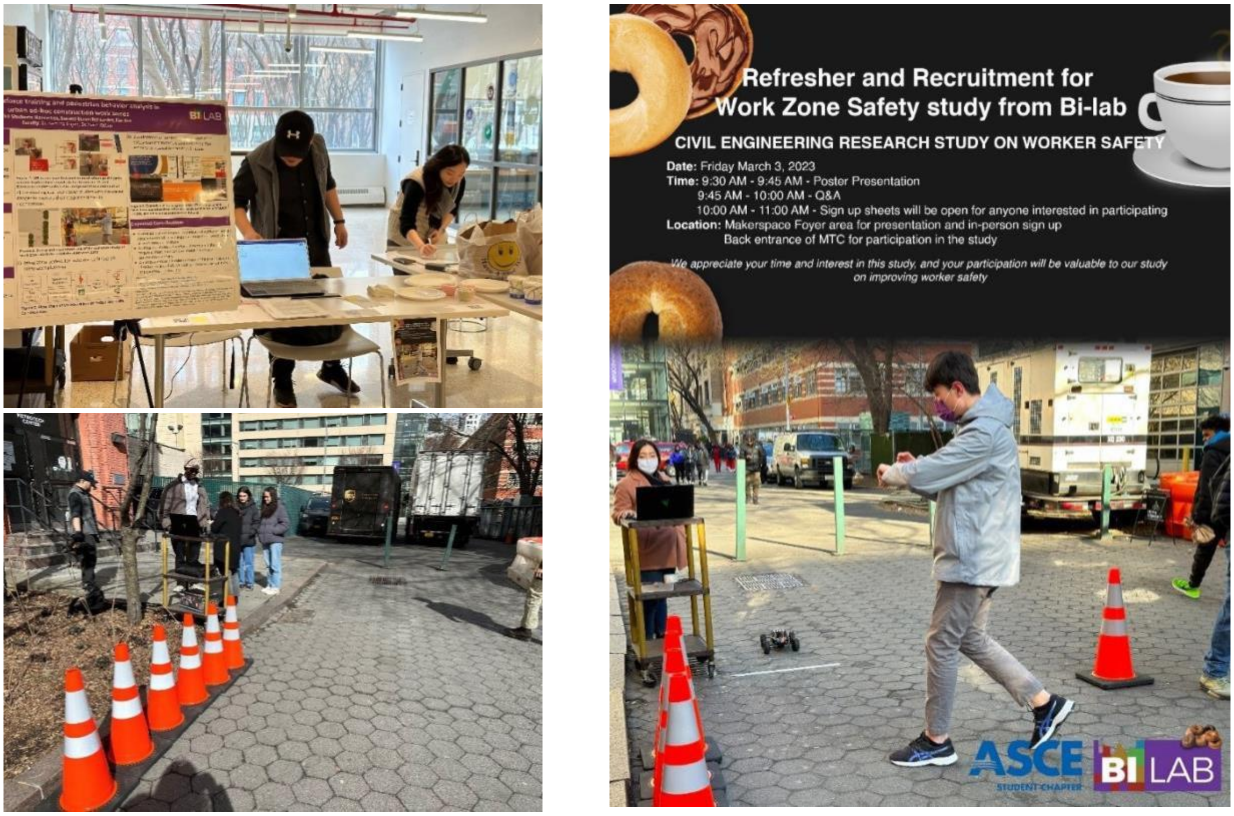

Figure 16: Photos of the ASCE student chapter event at NYU for recruitment of participants.

- The research team created a dataset collected from the real-world experiments and published the benchmark data on CIP.
- Stakeholder interviews were conducted between January and May of 2023.

8. OUTCOMES

8.1 Increased understanding and awareness of transportation issues

A review of safety training content from public sources such as DOT and FHWA revealed much work to be done in improving and ensuring safety for workers on construction sites, with the industry reporting the largest proportion of fatal injuries from traffic accidents. The industry insights provided to the research team through the series of stakeholder interviews were useful in noting that workers tend to get comfortable with the inherent high-risk exposure during work operations. Therefore, the managers and supervisors on site are always interested in different strategies and tools to keep the workers alert to the dangers on site throughout the operation. The industry has employed strategies such as regular inspection by executives on all project sites to keep workers alert. The general safety guidelines and standards that apply to work zone road installations were documented and analyzed for content identification of VR-based safety training for construction workers to develop as a prototype to be tested for a user study. There are five different types of hazards to be identified and inspected on site before installing a work zone: 1) Weather hazard, 2) road hazard, 3) vehicle hazard, 4) traffic hazard, and 5) work activity hazard. Further, for work zone installations, the operators should be aware of the different equipment that needs to be utilized to keep workers safe during operation; much of these can be found in the 2009 MUTCD Guideline published by the DOT. The simplest mobile work zone will employ just several traffic channelizing devices like traffic cones and warning signs indicating an active work zone as well as letting the motorists know where the work zone ends. The installation of different temporary traffic control devices (TTCDs) used for work zones will be installed in the order closest to the oncoming traffic to the furthest facing traffic.

8.2 Increase in the body of knowledge

In this year's study, one of our primary objectives was to validate the previously developed work zone alarm systems and determine if the workers' response time to the alarms would be consistent between the real-world setting as experienced in the Virtual Reality (VR) platform. The findings from this study are crucial in expanding the application of VR-based platforms as tools for providing training and development of the workforce. The outcomes also inform the design of future notification systems where the right configuration of alarms can be sent for increased safety awareness of workers at roadway work zones.

In addition, the existing VR-based traffic micro co-simulation platform has been significantly expanded to improve realism by incorporating pedestrian behavior and trajectories. This enhancement allows users for realistic movement based on pedestrian speed and step length. Rule-based pedestrian behaviors, including movement restrictions, task simulations, and random movements, were simulated within the platform. Users can modify environment variables to adjust worker behavior, enhancing the platform's training capabilities. Additionally, a pre-trained behavior model accurately simulates pedestrian behavior using real trajectory and experimental data. These enhancements provide a more realistic and immersive experience, enhancing the platform's training capabilities for work zone safety and will be instrumental in future user studies.

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

VR holds great potential for worker safety training by offering experiential learning without subjecting individuals to physical harm. A prototype application of VR-based worker safety training was developed, incorporating standardized content from existing safety training sources. The prototype focuses on hazard identification, temporary traffic control devices, and the order of installation for short-duration mobile work zones. Initial user feedback indicates the effectiveness of the interactive VR features, although further studies are needed to assess long-term content retention and overall effectiveness. Subject matter experts in public and private institutions endorsed the potential of VR for training and workforce development due to its cost-effectiveness and efficiency in implementation.

The outcomes of this study will inform future research, utilizing the VR-based traffic co-simulation platform to develop worker behavior models, design new wearable notification systems, and evaluate the VR-based training content more comprehensively.

8.4 Adoption of new technologies, techniques, or practices

The research project has resulted in significant advancements in four key areas including the cumulative outcomes from the earlier years. These advancements are as follows:

- VR Technology: The team has successfully utilized VR technology to visually recreate real work zone environments in an immersive 3D setting. This allows participants to experience a realistic work zone environment virtually.
- Traffic Simulation Integration: By integrating traffic simulation into the VR environment, the team has been able to replicate real traffic conditions and change those conditions while participants interact with the virtual environment (e.g., on the spot lane closure). This enhancement provides participants with a more authentic and immersive experience during training.
- Feedback Loop: The research team has established a feedback loop between the VR environment and the traffic simulation. This integration enables the influence of worker behaviors in the VR environment on traffic patterns, creating a more dynamic and realistic training experience.
- Hardware-in-the-Loop (HIL): The team has implemented HIL technology to create a virtual boundary for the work zone in the VR environment. This boundary is based on the physical dimensions of the lab and facilitates participant localization tracking within the VR environment.

Additionally, the research project includes the following components in the adoption of new technologies:

- Comparison of Real-World and VR-Based Response Time: A benchmark comparison is conducted between the response time of the previously developed HIL haptic alarm system in real-world scenarios and its response time in the VR environment.

- Microscopic Traffic Simulation with Pedestrian Behavior: The traffic simulation is enhanced to incorporate components of pedestrian behavior and reaction. This integration further enhances the realism of the traffic simulation integrated with VR.

VR-Based Work Zone Safety Training Prototype: The project includes the development of a VR-based work zone safety training prototype. This prototype features interactive modules that introduce users to three different types of hazards specific to site conditions, allowing participants to identify and respond to these hazards.

Overall, the adoption of these new technologies, practices, and methods in the research project has paved the way for improved work zone safety training and evaluation methods.

9. CONCLUSION AND FUTURE WORK

This year's research efforts have contributed to a deeper understanding of the application of Virtual Reality (VR) technology in the work zone safety domain. The objectives set for this project were successfully achieved, yielding valuable insights on multiple fronts.

Real-world benchmarking study. By collecting workers' alarm response times in real-world scenarios, we were able to compare and validate the data collected from earlier VR-based studies. The results indicated that there were no statistically significant differences in user experience and reaction times between VR and real-world settings. This finding highlights the potential of VR technology in successfully replicating real-world situations, particularly in the context of worker safety, where VR can simulate dangerous scenarios without exposing workers to actual risks or harm.

Pedestrian movement integration. We integrated pedestrian movement into the traffic simulation using SUMO, creating a more realistic co-simulation of traffic and pedestrian behaviors. This enhancement further enhances the realism and authenticity of the VR environment.

Feasibility of using VR for worker safety training and workforce development. Through stakeholder interviews, prototype implementation, and a user experience survey, we conducted a comprehensive feasibility study of VR-based worker safety training. The findings informed the development of a prototype that focused on hazard identification using interactive modules and traffic cones as VR objects. The overall feedback from the user experience survey was positive and enticing, highlighting the benefits of VR in safety training for construction workers. However, it was also noted that the effectiveness of learning may be compromised if the content delivery primarily relies on visuals, as participants may become distracted and overlook important details. This insight emphasizes the importance of carefully designing the learning platform in VR to balance immersive experiences with effective content delivery.

In summary, VR offers a promising platform for experiential learning, providing comfort and entertainment to users while capturing realistic components through advanced technologies. However, for the successful application of VR in safety training and education, further research is needed. This includes conducting comparative studies between conventional platforms and VR, as well as assessing the impact of different VR features on user learning. While this study represents an initial attempt to explore these aspects, it is constrained by time limitations and a small user sample size. A more comprehensive study in the future will yield greater insights and strategies for leveraging VR technologies across various industries.

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