Work Zone Safety: Benchmarking Studies between Virtual Reality-based Traffic Co-simulation Platform and Real Work-Zones

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Abstract— **The need for improvements in roadway work zone safety becomes increasingly pressing, with continuous accidents/incidents reporting around a thousand fatalities in the United States in 2021 alone. Though rare, efforts that lead to a deeper understanding of worker behaviors around work zones are necessary to increase safety of workers. Unlike long term work zones, short term or mobile work zones lack clear standards. Understanding worker behavior in such work zones is an integral part of the solution. However current means are ineffective due to simplicity in intrusion scenarios and/or lack of immersiveness of trainees in situations/scenarios where workzones are intruded. Our earlier work resulted in the development of an immersive Virtual Reality (VR) based traffic co-simulation platform with innovative alarming systems for work zone safety. However, there is still a need to understand whether the behaviors captured in immersive VR based work zones are representative of reality in terms of how they respond to received safety alarms. This work presents the findings of the same user studies performed on real and VR based work zones to compare worker behaviors in both settings. The results show that participants, across more than 90 trials (with 31 participants), had similar response times to received alarms in both settings (around 2.5 seconds) with a slightly faster reactions in real settings.**

I. Introduction

Analyzing the most recent roadway work zone crash data in the United States reveals 874 fatal crashes that happened around work zones in 2021 alone, resulting in 956 fatalities [1]. Data from last decade also indicates a similar pattern with an average of 125 worker fatalities annually. Moreover, short term and mobile work zones lack design standards, which increases the risk of crashes/intrusions. Worker behavioral data while facing dangerous situations around work zones are are essential to improve work zone safety, however it is in scarcity. Alarm systems, in various modalities (e.g., sound, visual, biometric), are deployed on sites to warn workers for approaching dangers; however, their response to these alarms are not systematically analyzed to suggest improvements. More recently, Virtual Reality (VR) based settings provide a high-fidelity environment to reproduce dangerous scenarios

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(a) Virtual reality based user study setup

(b) Real world user study setup

Figure 1. Overview of the experiment setup.

without any safety concerns. These VR settings can be enhanced with traffic co-simulation environments (e.g., Simulation of Urban MObility (SUMO) [2]), providing a natural traffic flow control and enable bi-directional information flow between VR and micro-simulators for immersive simulation of real interactions in work zones. Our previous work [12] introduces such a hardware in the loop mechanism to capture workers' attention before dangerous vehicles arrive- through an apple watch and various modalities of alarm signals sent.

However, there is still a gap to be bridged between virtual environments and the reality: understanding how representative the behaviors of workers are in virtual work zones to their behaviors in reality. To address this gap, we designed and implemented the same work zone incident scenarios both in VR and real world. Participants were instructed to execute tasks, such as picking up cones to create mobile or temporary work zones. In both settings, participants would receive warning alarms when there is immediate danger to them. We collected the reaction times to received alarms as well as captured their bodily movements (e.g., head turns, body positions).

The real incidents would be dangerous for the participants hence speeding model cars were used in the real-world experiments to avoid injuries of participants as there were expected collusions. The collected data has also contributed to system calibration to bridge the gap between virtual environment and reality. The main contributions of this work include:

- statistical comparison of workers' behavior between real world and VR environments, where the analysis confirmed that the response times of workers to received notifications are not significantly different when received in VR vs. in real world.
- a dataset on worker behaviors and a method of capturing such realistic behavioral data for calibration of virtual worlds designed for improving work zone safety with improved realism.

II. RELATED WORKS

A. Virtual Reality Use in Worker Safety Studies

The AEC (Architecture, Engineering, and Construction) industry encompasses hazardous conditions such as the operation of heavy machinery, the handling of hazardous material, and interactions with construction vehicles and road traffic[4]. Studies have demonstrated that the safety training of workers has a major impact on safety performance in construction projects, highlighting the need of ensuring safe working conditions, facilities, and equipment [5]. VR has emerged as a promising tool to integrate novel safety training of workforce [6]. Related studies have shown the long-term retention of safety awareness acquired through VR training, reporting positive results [7][8]. VR has gained traction in transportation domain as well, particularly in studying interactions between autonomous vehicles and vulnerable road users, such as pedestrians and cyclists [9]. Several studies over the past decade have utilized VR to examine pedestrian behavior in virtual traffic scenarios, yielding valuable insights into human responses to perilous situations [10]. VR-based platforms facilitate the simulation of realistic traffic flow and the gathering of behavioral response data. These data are applicable for statistical modeling, such as survival analysis, or more sophisticated methods like reinforcement learning, aimed at improving alarm systems based on human reactions [11,12].

B. Virtual Reality Use in Human Behavioral Data Collection

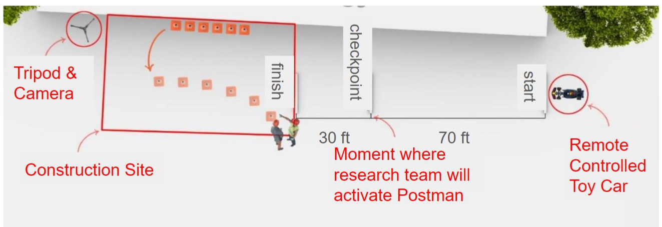
Studies on autonomous vehicles and their interactions with pedestrians on shared spaces have mainly utilized VR [13]. Several related data have been captured on participants, such as participant position, head rotation, and gaze point while in VR. However, limitations on how realistic the environment in virtual settings needs further exploration. Regarding driver behaviors, studies also utilized VE to capture driver data on simulated scenarios [14]. For example, DReyeVR, a platform aimed at democratizing VR for driver research, serves as a driver data collection tool by implementing eye-tracking function [14]. However, limitations include the lack of vehicle control and comprehensive experiments. In order to forecast human intentions and maximize semi-autonomous vehicle operation, studies also combined VR-captured human behaviors with machine learning approaches [15], providing insights into human-robot interaction and VR-based data collection.

III. METHODOLOGY

A. System design

The objective of this work was to determine if worker behavioral data on responses to received safety notifications are representative of what is expected in real-world settings. Therefore, we designed and implemented a workzone scenario [12] both in VR and in real-world settings and statistically evaluated the response times of workers to the received notifications (see Figure 1). The work zone scenario we utilized is not covering a long-term work zone scenario, where typically heavy equipment or construction activity are involved within structured boundaries. This research aims to improve worker safety in mobile and short-term work zones where workers are exposed to working conditions in an unprotected way. So, these mobile work zones in terms of safety concerns and construction tasks, are close to reality. The scenario included setting up a mobile work zone using traffic cones to define a work area for short term construction tasks such as asphalt patching and digging. The details of the VR based experiment setup and the scenario is provided in [12]. Participants used a head mounted display to interact with the virtual roadway and traffic, and a smart watch to receive safety notifications when incidents/ accidents were expected (Figure 1). Traffic volume and trajectories were simulated in SUMO and received in VR through a bi-directional information flow enabled in this integrated platform.

For the real-world version of this scenario, the same work zone setup task was given to participants and approaching traffic was represented with a model car, controlled by the research team (Figure 1). A reserved area including a span of 100 feet was needed where the speeding model cars could be used while participants were conducting the tasks assigned to them. This area has been selected around the campus where the research team works and has only pedestrian and bike traffic instead of real traffic (Figure 2b).



(a) Bird eye view of the experiment setup

(b) Markings to guide participants for placement of traffic cones, an image of the model car, and the location of the experiment site

Figure 2. Real-world work zone setup.

An unstructured work zone was temporarily defined by workers using traffic cones in real-world settings (Figure 2a). 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. Participants were instructed to pick the cones and place them on the markings on the ground. To simulate the incoming traffic, a remote-controlled scaled-down car was used (Figure 2b). The car was operated by a member of the research team, who drove it in a loop toward a designated point using the same route and speed for each trial, triggering an alarm signal. In each trial, the remote controlled car started at a 100 feet distance from the participants where the work zone to be defined and a first alarm would be issued when the car is at 30 feet distance to the boundary of the temporary workzone. The alarms are received as warning vibrations on the smart watch to notify participants, and participants are expected to acknowledge the receipt of them through tapping on the watch. Captured timestamps were recorded on the research server via a WIFI connection enabled on site.

B. Data collection

The experiment took place at the NYU Tandon School of Engineering campus. The study involved 31 participants, including professionals dedicated to enhancing worker safety in construction projects, alongside graduate civil engineering students. Participants included a construction safety training provider, two construction professionals, a public sector expert in infrastructure, and a technology startup consultant, all focused on improving worker safety in construction projects. All remaining participants were graduate construction engineering students. Among the participants, we had 21 male and 10 female participants, with an age range between 17 and 30. During both the VR and real-world experiments, each participant conducted a total of three trials to collect data on alarm reaction times. During real world user studies, 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 2a) from the timestamp when it reached the line 30 ft apart from the work area (also indicated in Figure 2a). When the user pressed the watch screen to respond to the haptic alert, his or her response time was recorded as a timestamp. Responding to alert signals allows workers to prevent dangerous vehicles, leading to improved work zone safety. The alarm was manually triggered each time the vehicle passed the 30 ft apart line from the work area. For each trial, a total of two to five alarm signals were generated randomly during each trial. Although the route and speed of the car are the same during each trial, the speed of participants in completing the assigned task (placing cones to define a work zone boundary) is not the same. So, depending on their task durations, the trials showed variations in completion time, hence the variations in the number of alarms each participant received during a trial. Each participant however received at least two alarms. Figure 3 shows how participants worked on their tasks during the experiment.

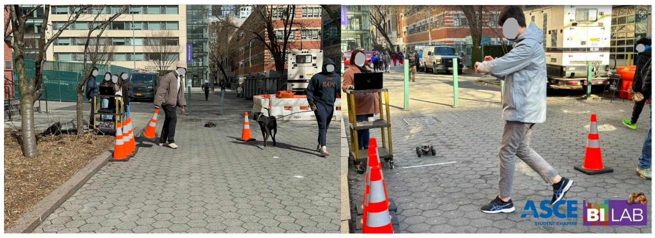


Figure 3. Behavioral data collection in the real-world scenario: Participant picks up cones to create the mobile work zone(left); participant reacts to alarms from a wearable device.

IV. RESULTS AND DISCUSSION

A. Meta data process

The raw data captured during the experiment is stored in *JSON* format on a server. The recorded items 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). 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. There are 5 alarms per trial and 3 trial per participant. Table 1 shows some data patterns collected in each trial.

Table 1. Examples of data items captured during experiments

Data type	Descriptions
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 of the second alarm of trial 1 is sent by the system
t1_start	Timestamp of trial 1 end time
t1_stop	Timestamp of trial 1 end time
t1_rt1	Response time to alarm 1 of trial 1
vehicle_70ft_t1	Vehicle travel time for 70 ft: from the start point to the 30 ft point at trial 1

B. Data Analysis and Descriptive Statistics

The data has been cleaned and removed for outliers. These samples are used to generate the histograms of data for the trial duration and the response times of the participants in Figure 4. The experiment duration plot, on Figure 4 left, exhibits a little right skew, suggesting that some participants required significantly more time than average to finish the job of placing six cones around the work zone area. On Figure 4 right, the response time counts accumulated around the 2-3 seconds time frame. The real-world statistics were computed based on a total of 93 real-world study trials, encompassing 31 participants who completed 3 trials each. The results of the participants' responses to notifications in virtual reality situations are shown in Table 2.

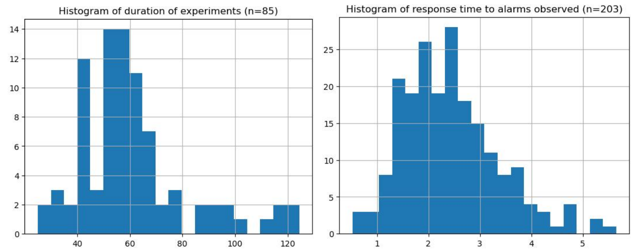


Figure 4. Left: Distribution of experiment duration across all trials; Y-scale: count; X-scale: duration of trials in seconds. Right: Distribution of response time over all alarms; Y-scale: count; X-scale: response time in seconds.

When alarms were sent to participants in VR environments, participant reacted to them in 2.59 seconds on average. The average response time of participants to received alarms in real-world settings was found to be slightly shorter (the difference is approximately 0.16 seconds) than the average response time to received alarms in VR-based experiments, given that the average response time to alarms in real-world settings was 2.43 seconds. There are a few possible reasons why VR environment leads to a 0.6 second delay compared with the reality: wearing of the VR head mount display (HMD), difficulty of touching the smart watch screen when holding VR controllers, and frame rates and motion sickness. This difference can be counted as the lag between real vs. VR settings. Discovering the gap between reality and VR assists the design and calibration for VR-based simulation, increasing the realism of the experience.

Table 2. Response times * 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.

Data type	N**	Mean	St.Dev	Min	Max
Response time (sec) real world	203	**2.43**	0.93	0.52	5.65
Trial duration (sec) real world	85	61.46	21.23	25.01	124.50
Response time (sec) VR experiment	30	**2.59**	0.75	1.05	4.21

V. Conclusion

This study compares and validates the data collected from VR based studies as compared to real-world settings for worker response times to notification alarms in roadway work zones. The results show that behavioral data captured in VR settings are representative of how workers would behave in real world work zones in terms of response to received safety notifications. Results indicate that the user experience and response times in VR and real-world environments did not differ statistically significantly. The authors acknowledge that although vibration sensors could be a much more suitable sensor as compared to visual and sound versions in construction settings, smartwatch based acknowledgement of alarms might be limiting for accurate capturing of response times. In the VR based scenario, a visual acknowledgement on the VR interface via the controllers can be implemented to eliminate lags in response times. This finding highlights the potential of VR technology in successfully replicating real-world situations, validating that behavior of participants in VR and real world are statistically similar. This is particularly significant with regard to involves worker safety, as VR can replicate dangerous scenarios without actually putting workers in danger or causing them injury. The comparison will also be beneficial for design and calibration of VR environments. During the experiments heart rate of workers and ambient noise data have been captured and the implications of such factors on worker responses and performance will be examined as part of the future work.

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