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Alert modalities in connected and smart work zones to enhance workers' safety from traffic accidents using virtual reality (VR) experiments☆

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ABSTRACT

Connected and Smart Work Zones (CSWZ) represent the future of work zones, utilizing technology to enhance safety, efficiency, and productivity among workers. However, research on leveraging technologies to communicate hazards and systematically evaluate different alert modalities to enhance safety remains limited. Assessing and understanding such hazards from the worker's perspective is highly challenging, making virtual reality (VR) a promising solution that provides flexibility in assessing complex and influencing factors. In this paper, a set of 12 VR evaluation tasks for alert technology-assisted work zones are developed, encompassing various attributes by applying orthogonal design principles. Participants are exposed to these VR evaluation tasks, generating a dataset comprising 222 distinct scenarios. A proximity-based threshold is used to quantify a critical event based on worker and vehicle interaction orientations. The impact of different alert modalities (no alert, centralized, and personalized alert systems) on critical safety outcomes (reaction time and reaching safe region) using discrete choice modelling framework and kinematic behavior (temporal variation of evasive speed and relative distance) are comprehensively evaluated. The personalized alert consistently demonstrated its effectiveness by facilitating faster reactions and more effective evasive actions, significantly improving safety outcomes through a three-phase sequential motion pattern of acceleration, speed maintenance, and deceleration. This study provides a comprehensive assessment of the effectiveness of different alert systems, offering valuable insights for mitigating risks associated with intruding vehicles, especially in scenarios involving high vehicle speeds and worker involvement levels.

1. Introduction

Highway construction/maintenance jobs are considered one of the most unsafe occupations. During the recent five years in the United States, more than 150,000 roadside work zones related vehicle crashes were reported, leading to the fatal injuries of 6,185 workers (National Highway Traffic Safety Administration, 2021) and 113,535 drivers (Weng et al., 2016). Errant vehicle intrusion is one of the leading causes of fatalities in work zones (Awolusi & Marks, 2019; Thapa & Mishra, 2021). Reports show that approximately

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20 % of the US highway system is under maintenance/construction during the peak construction season, with more than 3,000 active work zones operating simultaneously (Construction Safety Council, 2008). Despite national efforts to reduce incidents in work zones by implementing stricter law enforcement (Nnaji et al., 2020), worker fatalities and injuries have increased by 44 % over the last decade (National Safety Council, 2020). Europe has also seen a significant increase, with about 15 % of total crashes attributed to work zones (Várhelyi et al., 2019). Similar to Europe, Australia, also experienced 16 % of crashes resulting from work zones (Australian Road Research Board, 2019). According to the World Health Organization (WHO), work zones contribute to approximately 20–30 % of all fatal crashes in construction areas worldwide. These statistics underscore the urgent need for concerted efforts to enhance work zone safety, especially lowering vehicle intrusion, and improved worker reaction time along with enhanced, and stringent enforcement measures.

Controlled field experiments conducted on vehicle intrusion in work zone showed that workers have a limited window of approximately five seconds to execute an evasive maneuver (Thapa & Mishra, 2021). Considering the crucial nature of the situation, it is essential to assess workers' evasive behavior and examine how advanced technologies can enhance their abilities in terms of escape skills, hazard avoidance, and other relevant factors within work zones. This helps determine how incorporating these technologies can enable timely communication, providing workers with valuable seconds, thereby further enhancing their safety.

According to the crash statistics in the US, numerous transportation safety and planning agencies have acknowledged work zone safety as a matter of utmost importance. As a result, there exists a strong need for enhanced safety devices and methodologies that can offer improved effectiveness and efficiency in mitigating work zone related hazards (Ozan, 2019). Advanced technologies can play an important role in facilitating timely alerts to the workers to appropriately act (Venthuruthiyil et al., 2023) and escape hazards, which can help promote the idea of a Connected and Smart Work Zone (CSWZ) (Park et al., 2017). CSWZ is a novel concept that aims to enhance the safety of workers and drivers near work zone that use technology to improve safety, efficiency, and productivity. The CSWZ can leverage advanced technologies such as connected infrastructure and workers' wearable devices to provide real-time monitoring, communication, and feedback with the stakeholders in work zones and with the drivers. By leveraging technology and real-time data, CSWZ has the potential to transform the construction industry and improve the overall construction experience. However, no systematic and empirical research has conceptualized the working of CSWZ with advanced alert systems and technologies in the context of worker safety. Common efforts adopted to improve work zone safety have primarily focused on the use of Work Zone Intrusion Alarm system from workers' perspective. The existing Work Zone Intrusion Alarm system usually has centralized operation (alert through lights and sirens in the work zone). This centralized operation adds an important limitation, which can possibly make the warning mechanism ineffective in a highly chaotic environment like roadside construction, highlighting the need for a personalized type of alert.

Traditionally, work zone related perceived hazards for workers in case of traffic intrusion have been explored by means of simple control field experiments (e.g., (Thapa & Mishra, 2021)), safety data sheet (OSHA), road safety dataset (see (Adeel et al., 2024)) and self-reported hazards (see (Abrar et al., 2017)). Simple control field experiments may lack the complexity and realism of actual work zone conditions, potentially leading to limitations in capturing the full range of hazards and their effects. Safety data sheets offer valuable information but may not always capture the nuanced perceptions and experiences of individuals working in the work zones. Self-reported surveys rely on participants' subjective interpretations and recollection, which can introduce biases and limitations in data accuracy, for example, biases form the experimenter effect (Iyengar, 2011), from the degree of familiarity with the situation (Patterson & Mattila, 2008), survey presentation (Näher & Krumpal, 2012). One of the major issues associated with these approaches is the potential incongruence between stated and experienced risks, as well as between stated and actual actions taken by workers. To address these limitations and gain a comprehensive understanding of work zone hazards, it is crucial to employ a multi-faceted approach that combines traditional methods with advanced immersive environments, such as virtual reality (VR). By leveraging VR and other advanced technologies, researchers and practitioners can create realistic work zone simulations that provide a more immersive and authentic experience for participants. This approach allows for the exploration of complex scenarios, the assessment of workers' responses and behaviors in a controlled environment, and the development of more effective mitigation strategies. Moreover, VR eliminates significant challenges associated with traditional field experiments involving vehicle intrusion in the work in the presence of workers. Rather VR facilitates a safer and controlled setting for analyzing worker response to various types of intrusions.

This study contributes to VR experiment design for work zone safety from a worker's perspective two significant ways. First, it develops a CSWZ in a VR environment that simulates critical safety scenarios. This environment incorporates advanced alert systems, such as personalized and centralized systems, providing realistic simulations of real-world alert mechanisms. Second, by employing orthogonal design principles, our approach allows for the efficient analysis of multiple variables and their interactions, ensuring that the most critical safety elements are explored within a manageable set of scenarios. The methodological advancement of this paper are: (i) development of an experiment design that is personalized to the construction and utility work context which emulates field conditions in a VR setting which can be modified as per user needs; (ii) analysis of critical event occurrences using relative distance between intruding vehicle and the worker escape trajectory using safety envelope procedure; and (iii) quantitative estimation of evaluating modalities that are most promising for the wearable safety alert system technology configurations that are assistive in designing CSWZ.

This empirical assessment aims to answer research questions on leveraging technologies in managing traffic intrusion-related hazards and improving worker safety, contribute to existing knowledge, and highlight the practical implications of implementing CSWZ.

1) How can we make the work zone "connected" and the workforce "smarter" with the application of alert modalities to communicate traffic intrusion-related hazards?

2) How effective will different types of alert modalities be in enhancing workforce safety?
3) The effectiveness of alert modalities on the workforce's involvement level in work zone activities, i.e., how different alert modalities assist as the workforce involvement in construction/maintenance activities increases?
4) What can be the behavioral and kinematic changes in the escape decisions of the workforce with the application of different alert modalities?

All the above-mentioned research questions aim to address the critical and challenging aspects of work zone safety from the workers' perspective, for which detailed data are very scarce, making it a highly challenging and unexplored research topic.

The paper is organized as follows: Section 2 provides a comprehensive review of the relevant literature concerning work zone safety from a worker's perspective and explores the application of VR in safety assessment. Section 3 presents the methodology employed, which is divided into four components, outlining the approach taken to address the research questions. Section 4 describes the development of VR experiments, and the collection of VR data specifically designed for this research. Section 5 presents the comparative analysis of the collected data, the estimation of models, and the resulting findings. Section 6 summarizes the discussion by comparing the study's results with existing studies, highlighting key insights in the context of work zone safety and alert system effectiveness. Finally, the paper concludes in the last section, offering insightful discussions and implications derived from the study's outcomes.

2. Literature review

The literature review has been divided into two parts. The first part provides insight into current and emerging technologies for work zone safety from the worker's perspective. The second part discusses applications of VR for worker safety with a special focus on work zones.

2.1. Advanced and emerging technologies for work zone safety

Common efforts adopted to improve work zone safety have primarily focused on improving drivers' behavior through speed control measures (Shaer et al., 2023; Thapa et al., 2024) and using the Work Zone Intrusion Alarm from workers' perspectives. Advanced alert technologies have emerged in recent years to improve the effectiveness of Work Zone Intrusion Alarm and enhance worker safety in WZ (Thapa & Mishra, 2021). The literature suggests that Work Zone Intrusion Alarm can be effective in improving worker safety and reducing the number of work zone accidents. These systems use advanced technologies, such as video analytics, GPS, Wi-Fi, RFID, and Bluetooth, to detect and alert workers and drivers of potential hazards. As these technologies continue to evolve, it is likely that Work Zone Intrusion Alarm will play an increasingly important role in improving construction worker safety. Currently, available Work Zone Intrusion Alarm technologies include Advance Warning and Risk Evasion, Worker Alert Systems, Alpha SafeNet, and Intellicone (Nnaji et al., 2018). Advance Warning and Risk Evasion utilizes radar-based technology to detect and monitor vehicle intrusions and worker locations, while Worker Alert Systems and Intellicone utilize pressure-activated tubes or lamp sensors that are triggered by an encroaching vehicle (Thapa & Mishra, 2021).

In a study conducted in Kansas, two cone-type intrusion alarm technologies, SonoBlaster and Intellicone, were evaluated for their effectiveness in temporary work zones (Novosel, 2014). The SonoBlaster system functions as an impact-activated, standalone unit that alerts workers to vehicle intrusions by emitting a loud, CO_2-powered horn blast upon impact. Intellicone, in contrast, is a multi-component system comprising portable site alarms and motion-sensitive smart lamps. When a smart lamp tilts beyond a set angle upon impact, it transmits a signal to the portable site alarm, which then activates an audio-visual alert to notify workers of the intrusion. The findings of the study indicated that workers displayed a positive outlook toward the implementation of these systems. However, it was observed that the setup process of the SonoBlaster technology posed certain difficulties, while the Intellicone alarms are deemed insufficiently loud to be effectively utilized in environments with high levels of noise. However, a very limited work zone is equipped with Work Zone Intrusion Alarm systems (Ozan, 2019). One of the major shortcomings of the existing alert systems is their centralized operation, which can possibly make the warning mechanism ineffective in a highly chaotic environment like roadside construction, highlighting the need for a personalized type of alert. Moreover, little is known about the effectiveness of the centralized type of alert system and none of the studies had systematically compared the effectiveness between the centralized and personalized alert system based on safety outcomes. Therefore, we aim to assess the current practices providing worker assistance in well-equipped work zones and explore the need to upgrade to a personal and customized warning and guidance mechanism that can improve worker's escape trajectory for maximum safety.

2.2. Application of VR for work safety in the context of work zone

Past studies have relied on visual stimuli such as pictures and videos for the exploration of human perception (Kalatian & Farooq, 2021). However, with the emergence of advanced VR environments, it has become feasible to conduct investigations on human perception and behaviors within highly controlled experimental settings. These technological advancements in VR offer new avenues for studying and analyzing the intricacies of human cognition and response, providing researchers with enhanced tools to examine behavioral dynamics in a more immersive and controlled manner (Bogacz et al., 2020; Farooq et al., 2018; Nie et al., 2021). Research experiments through VR have raised concerns regarding its level of realism and the extent to which its results align with real-life behaviors. Researchers have conducted studies comparing VR with real environment experiments to investigate such comparisons.

For pedestrian behavior, Bhagavathula et al. (2018) and Deb et al. (2017) found no significant differences between VR and real environments in terms of crossing intention, perception related to safety, risk, and distance, and objective and subjective measures. Kalantarov et al. (2018) focused on the body movements of pedestrians crossing in VR environments and found that wait time measures aligned with laboratory studies and field observations.

VR technology has witnessed a surge in utilization within the construction industry, finding applications in safety assessment, simulation, training, and visualization. Usually, research for worker safety uses VR for safety training, safety planning (Albert et al., 2014), and safety inspection (Li et al., 2018). This is mainly because VR experiments provide flexibility to develop a realistic construction site environment with control of variability in the environment. Through VR, workers can engage with and gain insights from hazardous scenarios, all while avoiding actual risk and harm (Feng et al., 2021). Studies utilizing demonstration-based training methods in physical settings have found that VR-based training is a more efficient approach that requires fewer resources, poses minimal risks in simulating unsafe conditions, and demands less mental effort from trainees (Lin et al., 2011). Despite the widespread adoption of VR in worker safety, there is a limited number of studies exploring its application specifically for worker safety in work zones.

Lordianto et al. (2024) introduce "Hapti-met," a safety helmet with haptic notifications, tested in a VR environment to simulate real-world hazard interactions. Their findings suggest a significant decrease in collisions, highlighting the helmet's potential to enhance situational awareness and the application of VR to assess such safety technologies. Ye et al. (2024) review safety technologies in work zones, noting the extensive use of VR to create risk-free environments for technology testing. However, they pointed out that the depth of risk mitigation analysis is lacking, pointing out a need for more detailed assessments to inform safety device optimization. Building on this need for refined evaluation, Sabeti et al. (2024) examine the effectiveness of multimodal AR warnings on worker reaction times in both VR and real-world settings, noting differences in reaction times in VR and real-world settings. Despite differences, VR proves superior for replicating complex work zone dynamics for training purposes. Further supporting this, Scorgie et al. (2024) demonstrate that VR safety training distinctly outperforms traditional methods, offering a more effective approach to safety training in work zones. Qing & Edara (2024) focus on VR's application in work zone flagger training, demonstrating its capability to enhance engagement and training outcomes, thereby improving learning and adherence to safety protocols. Banani Ardecani et al. (2024) analyze the physiological impacts of work intensity on safety in VR environments. Their study provides insights into the internal effects of work conditions and suggests ways to optimize AR-assisted warning systems. By conducting a search on Scopus using

Table 1
Studies assessing hazards in work zone from workers' perspective using VR.

Authors	Objective	Hazard form	Major findings
Lordianto et al. (2024)	The authors assessed the impact of the Hapti-met (a helmet with haptic feedback) using VR experiments.	Intruding vehicle	The study findings indicate that there is a 9.8 % reduction in collisions with vehicles when participants are alerted by the Hapti-met system, as opposed to scenarios where no notifications are received.
Sabeti et al. (2024)	This study assessed the effectiveness of multimodal AR warnings on worker reaction times in both VR and real-world settings.	A potential vehicle intrusion in the work zone	The major finding of the study indicates that the haptic-visual warning system triggered the quickest response from participants. (32 participants)
Banani Ardecani et al. (2024)	This research assessed stress levels in roadway workers using physiological data who were subjected to multi-sensory AR-assisted warnings under different work intensities by utilizing VR experiments.	A potential vehicle intrusion in the work zone	A key finding indicates higher stress for workers engaged in moderate-intensity tasks, which provides valuable information for enhancing warning systems.
Kim et al. (2023)	The authors investigated personality traits influencing workers' accident susceptibility and their susceptibility to habituation to construction vehicle warning alarms in a work zone.	Construction vehicle	Workers with higher susceptibility to boredom exhibited reduced attention to warning alarms, resulting in an increased likelihood of accidents involving construction vehicles.
Ergan et al. (2022)	This study provides a comprehensive overview of integrating platform components for synchronous VR, traffic simulation, and sensor interactions, enabling hardware-in-the-loop capabilities.	Vehicular traffic intrusion	The outcomes provide a detailed roadmap for implementing the immersive and integrated platform, which can be utilized for conducting work zone safety studies in accordance with the provided guidance.
Roofigari-Esfahan et al. (2022)	The study introduces a training platform that incorporates instructor-in-the-loop and group-based VR training.	Construction equipment	VR modules simulate work zone environments, allowing customization and sharing training with others, enhancing training effectiveness and outcomes.
Kim et al. (2021)	The authors examine the effectiveness of VR as a behavioral intervention tool to assess the decline in vigilant behaviors resulting from habituation to workplace hazards.	Construction vehicle	The simulated accidents within the VR environment had a lasting impact in mitigating the effects of habituation on attention over the course of one week.
Aati et al. (2020)	Development of an immersive platform of a work zone that consists of a learning module.	Traffic flowing near the work zone	The learning modules were rated as realistic and effective by 97 % of users.
Zou et al. (2020)	Use of the VR module of the work zone to calibrate the synchronous wearable sensors with an alarm system for maximum worker attention.	Vehicular traffic intrusion	The calibration results showed that the participants demonstrated sensitivity to the modality and frequency of the alarm, but not its duration.
Golovina et al. (2019)	The authors developed an immersive VR environment to focus on near misses and collisions between construction workers and moving and static construction equipment.	Construction equipment	The findings illustrate the application of VR to assess safety and provide both the advantages and constraints of safety information that was previously inaccessible or challenging to collect.

the keywords *"Work Zone" AND "Virtual Reality"*, we got 26 research documents, of which only 10 studies assess worker safety in work zones using VR, as summarized in Table 1.

Among the studies listed in Table 1, only five studies (see (Ergan et al., 2022; Lordianto et al., 2024; Sabeti et al., 2024; Banani Ardecani et al., 2024; Zou et al., 2020)) focused on worker safety concerning traffic intrusions, which are the most common cause of fatal accidents for workers. However, Ergan et al. (2022) and Zou et al. (2020) lacked a detailed assessment of participants' evasive behaviour specifically related to traffic intrusions in the work zone. Their main objectives revolved around developing a platform that enables hardware-in-the-loop for synchronous VR, traffic simulation, and sensor interactions (Ergan et al., 2022) as well as calibrating alarm sensors based on static body movements and reaction time of only five participants (Zou et al., 2020). To our knowledge, the study by Sabeti et al. (2024) is the only research that has evaluated and compared the effectiveness of various advanced alert systems. However, their analysis primarily concentrated on assessing and comparing reaction times and did not explore kinematic and escape behaviours within work zones during traffic intrusions. This leaves a gap in comprehensively understanding how these systems perform in altering physical movements and safety maneuvers in critical situations. To achieve this, we introduce the concept of CSWZ, which aims to enhance worker safety by integrating advanced technologies that enable real-time data capture and feedback. By exploring the potential of VR technology within the context of work zone safety, this study aims to contribute to the existing body of knowledge and pave the way for future advancements in this field.

3. Methodology

The methodology section for this paper is divided into four parts. The first part dealt with the conceptualization of CSWZ in the context of traffic intrusion and the working of an alert system to communicate potential hazards to the workers. The second part explores the development of CSWZ in an immersive environment like VR to provide realistic scenarios with varying important attributes to understand work safety. The third part empirically assesses the effectiveness of different alert modalities at the aggregate level by collecting experimental data from the developed VR evacuation tasks. The effectiveness assessment of alert systems is evaluated: 1) comparing the body reaction time, 2) defining the critical event based on the captured positional data, and 3) developing discrete choice models based on the potential outcome of evasive behaviour. The last part of the analysis presents detailed insights into evasive behaviour by comparing the temporal variation of participants' kinematic data and estimated positional data through VR evacuation tasks. The overview of the methodology of the study is presented in Fig. 1.

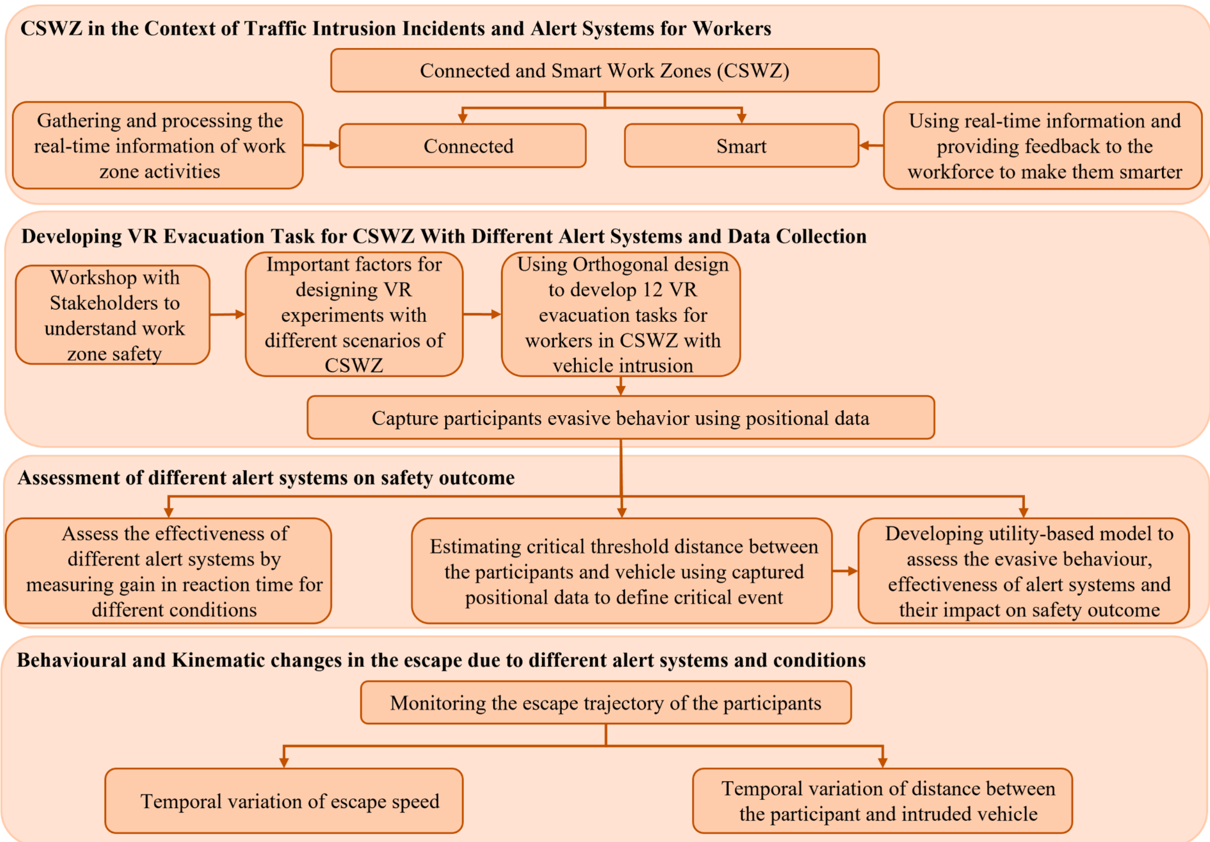


Fig. 1. The methodological framework of the study.

3.1. Conceptualizing the working of CSWZ in context traffic intrusion hazards

This study characterized the CSWZ by connecting the work zone with advanced technologies to capture real-time data of vehicles and make the workers smarter with the feedback provided by collected real-time information. In Fig. 2, we presented the working principle of CSWZ for this study. Firstly, a controller device will be placed in the advance warning region of the closure lane, which will detect potential vehicle intrusion (see Fig. 2**a**). If a vehicle crosses the controller device, then the controller will trigger the alert systems (either centralized or personalized) in the work zone and communicate the potential intrusion hazards to the workers present in the work zone (see Fig. 2**b** and Fig. 2**c**). The personalized alert can notify the worker through a personalized message displayed via a pop-up notification on the wearable, accompanied by a siren audio signal for heightened alertness. This provides them additional seconds before the vehicle actually enters the work zone to act prudently and plan their evasive behaviour. The controlled field experiments conducted by Thapa & Mishra (2021) investigated the potential, reliability, and accuracy of hazard-communicating devices with similar functionalities in detecting vehicles and delivering timely and effective alerts and warnings to the workers.

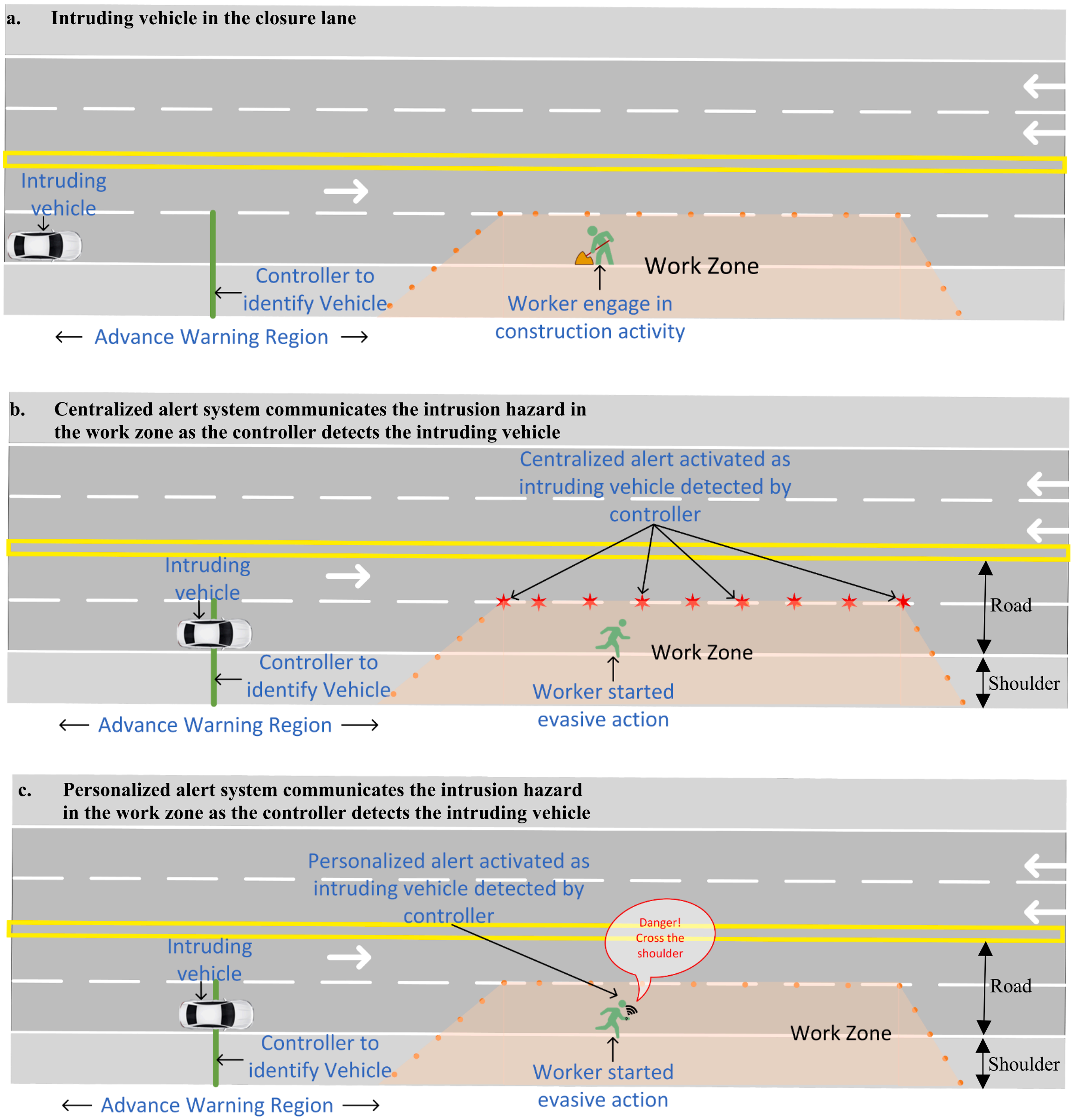


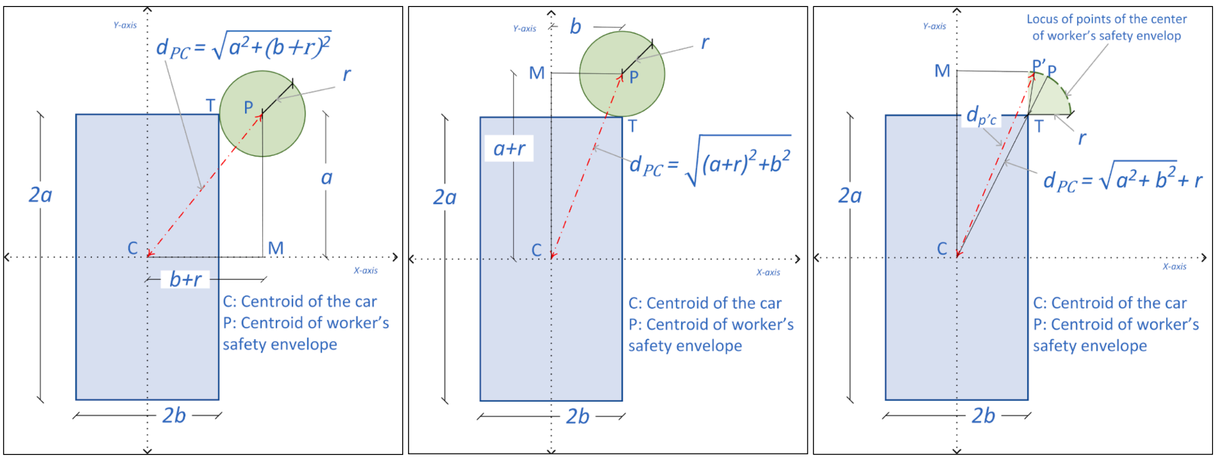
Fig. 2. Conceptualizing the working of different alert systems for CSWZ.

3.2. Developing VR evacuation tasks for CSWZ

The development of an immersive VR environment for CSWZ majorly includes two segments: 1) insights on important attributes of the work zone, which are associated with worker safety; 2) development of VR scenarios by considering the important attributes of the work zone in addition to the alert systems. For insights into important attributes of the work zone, we organized a collaborative Work Zone Safety Workshop, funded through a planning grant from the National Science Foundation. The workshop brought together 32 participants representing a diverse range of expertise in worker safety. Attendees included members from worker association organizations, work zone setup organizations, technology and standards development groups, academic institutions, and relevant government agencies. Specifically, three participants represented worker associations, while technology-focused organizations contributed ten members from three groups. Two organizations involved in the work zone and utility setup added 7 more attendees. The remaining 12 participants were researchers and academicians from three universities, specializing in work zone and construction safety and the application of virtual reality for safety assessments. The discussions from the workshop highlight current challenges, future vision, and the need to make work zones safer, smarter, and connected using advanced technologies. The safety and well-being of workers in the work zone is the primary concern for worker association organizations and other stakeholders. The workshop provided useful insights into the different factors affecting workers' safety in traffic intrusion-related incidents. Based on these insights, we considered different important attributes and used orthogonal design to develop different scenarios of the immersive VR environment for CSWZ. The VR experiment is methodically structured into two distinct phases to ensure comprehensive participant familiarization and precise data collection. Initially, participants underwent a familiarization task, introducing them to the virtual work zone's environment and the functionalities of the VR system. Subsequently, they engaged in three VR evacuation tasks aimed at evaluating the effectiveness of different alert systems: no alert, a centralized alert system, and a personalized alert system. These tasks were conducted in a simulated emergency scenario to rigorously test each system's responsiveness. Positional data for both participants and any intruding vehicles were recorded at high frequency—every 0.1 s—leveraging the VR system's advanced tracking capabilities. After completing the experiments, participants provided their socio-demographic information, previous experiences with VR technology, and feedback on the evacuation tasks through a detailed questionnaire. Further comprehensive details of the data collection process are thoroughly described in Section 4.

3.3. Assessment of advance alert systems based on safety outcome

The assessment of different alert systems in communicating the hazard potentially due to the intruding vehicle can be analyzed based on reaction and safety outcomes. Firstly, we compared the body reaction time to start an evasive action based on the alert systems. To further, understand the degree of potential hazard due to the intruding vehicle, the proximity of the intruding vehicle is evaluated. Here the proximity analysis is important mainly due to two reasons: 1) as the interaction between the participants and vehicle is in a virtual environment, we cannot quantify and report the collisions because there is no actual collisions between the vehicle and participants, and 2) proximity will help assess the near misses collisions using such VR experiments, which are usually not recorded/reported or analyzed for safety assessment in WZ. Using the captured positional data, the proximity analysis is performed, and a critical event is defined (see section 4.3.1). Based on the attribute of the VR evacuation task for the CSWZ, discrete choice models are developed to assess the occurrence of a critical event.



a. Safety envelope interaction at the corner of the longer side **b. Safety envelope interaction at the corner of the shorter side** **c. Safety envelope interaction at the corner**

Fig. 3. Safety envelope intrusion based on different orientations, considering the maximum distance between the vehicle's centroid and the worker.

3.3.1. Defining critical event based on the proximity of an intruding vehicle

When a vehicle intrudes into a work zone, the interaction between the vehicle and the safety envelope of the workers can be very critical and can have serious consequences. The safety envelope of a worker in a work zone can be defined as the space around the worker that is needed to ensure their safety while they are carrying out their tasks. The size of the safety envelope can vary depending on many factors, including the type of traffic environment like speed and type of vehicle, the type of road or intersection, the characteristics of the individual like age, and the type of work being done. For example, if a vehicle comes too close to the worker or passes off can make them feel threatened, and their sense of safety may be compromised, causing the worker to become disoriented, panicked, or even fall into the path of the vehicle. To assess the degree of hazard, we analyse the intrusion of a vehicle into the safety envelope of the roadside workers, which provides insights into conflict-proximity estimation. The critical event occurs when the safety envelope is compromised, either by the vehicle entering it or touching it. As the data captured during the VR evacuation task are the temporal variation of positional data of the centroid of the participant and the centroid of the intruding vehicle, our interest lies in assessing the temporal variation of distance between the participant and the vehicle.

Fig. 3 illustrates a conflict scenario (a critical event), where the vehicle (blue rectangular object, with centroid *C*, length *2a*, and width *2b*) just touches the safety envelope (green circular object, with centroid *P* and radius *r*) of the worker. Firstly, we assess the boundary condition of the critical event, where the distance between the centroids of the vehicle and the safety envelope (d_{PC}) is maximum and the safety envelope is considered to be intruded. This occurs when the interaction between the vehicle and the safety envelope occurs at the corner point of the vehicle (farthest point of the vehicle from the centroid, point T in Fig. 3**a**). This makes the corner point of the vehicle act as a tangent to the safety envelope with two possible conditions (Fig. 3**a** and Fig. 3**b**).

The estimation of d_{PC} for configuration presented in Fig. 3**a** and Fig. 3**b** are given in Eq. 1 and Eq. 2, respectively.

$$d_{PC} \text{ for Fig. 3}\mathbf{a} = \sqrt{(a)^2 + (b+r)^2} \tag{1}$$

$$dPC \text{ for Fig. 3}\mathbf{b} = \sqrt{(a+r)^2 + b^2} \tag{2}$$

Other than this, there exists a configuration, as depicted in Fig. 3**c**, where the d_{PC} is maximum and the critical event occurs. To demonstrate this, we allow the centroid of the safety envelope (*P*) to move around the corner of the vehicle (*T*), making *P* follow a circular path (the locus of *P* as a green dashed circular curve in Fig. 3**c**) with a radius *r* (equal to the radius of the safety envelope). Let us assume a point *P'* on the locus of the centroid of the safety envelope and form *ΔCTP'*, where *P'C* is the distance between the centroids of the vehicle and the safety envelope ($d_{P'C}$), $CT = \sqrt{(a)^2 + (b)^2}$, and $TP' = r$ (radius of safety envelope). Using the triangle inequality theorem for *ΔCTP'*, which states that for any given triangle, the sum of two sides of a triangle is always greater than the third side, which can be written as presented in Eq. 3.

$$P'C < CT + TP' \text{i.e.}, d_{P'C} < \sqrt{(a)^2 + (b)^2} + r \tag{3}$$

However, if the centroid (C) and corner (T) of the vehicle, and the centroid of safety envelope (*P*) are collinear then d_{PC} is estimated as presented in Eq. (4), which is always greater than any other possible configuration for the critical event to occur.

$$d_{PC} = \sqrt{(a)^2 + (b)^2} + r \tag{4}$$

This discussion provides the maximum possible distance between the centroid of the vehicle and the safety envelope for which the safety envelope of the worker is considered as intruded. The threshold distance is determined based on the dimensions of the intruding car, with a length of 3.8 m and width of 1.6 m, resulting in values of $a = 1.9$ m and $b = 0.8$ m. Additionally, a safety envelope radius of $r = 0.84$ m is assumed, equivalent to half the average arm span. Applying Eq. (4), the threshold distance is calculated as 2.9 m. During the VR evacuation task, if the distance between the car's centroid and the participant's centroid falls below this threshold, it signifies the occurrence of a critical event, which is used for further analysis.

3.3.2. Modelling framework for assessment of different safety outcomes

Studies used random utility theory and developed discrete choice models to analyse choice scenarios and safety outcomes through VR experiments (Arellana et al., 2020; Bogacz et al., 2021). For this study, there are three possible outcomes of the VR evacuation task for CSWZ, which are 1) the occurrence of a critical event (close proximity encounter with an intruding vehicle), 2) reaching a safe region (moving out of the work zone and crossing shoulder), 3) occurrence of the no-critical event but still in work zone environment. The utility of an outcome consists of two components, which are: an observed or deterministic component (V_{ps}) and a random error component (ε_{ps}). The general formulation of utility for individual '*p*' and safety outcome '*s*' is given in Eq. (5), and the deterministic component of utility is given in Eq. (6).

$$U_{ps} = V_{ps} + \varepsilon_{ps} \tag{5}$$

$$V_{ps} = \beta_a X_a \tag{6}$$

where β_a is the coefficients vector and X_a is the attributes vector, which includes attributes of alternatives, and socio-economic characteristics of participants. If the random error terms are assumed to follow Gumbel distribution, and independently and identically distributed over the individuals, outcomes, and scenarios, the probability (P_{ps}) of observing outcome '*s*' by an individual '*p*' can be modelled using multinomial logit (MNL) model. P_{ps} can be estimated as shown in Eq. (7). (Train, 2002) can be referred to for detailed discussions on the MNL model.

$$P_{ps} = \frac{e^{V_{ps}}}{\sum_{n=1}^{k} e^{V_{pn}}} \tag{7}$$

The likelihood of the MNL model is given in Eq. (8), which is maximized to estimate the parameters.

$$L(\beta_a) = \prod_{p}\prod_{s}(P_{ps})^{D_{ps}} \tag{8}$$

where $D_{ps} = 1$, if safety outcome *s* is observed, and 0 otherwise. Conventional practice takes the natural logarithm of the likelihood function to simplify the computations.

3.4. Assessing evasive behavior

Evasive behavior plays a crucial role in enhancing safety by referring to the actions taken by workers to avoid danger when confronted with vehicle intrusions within the work zone. Previous studies based on controlled field experiments have indicated that workers typically have approximately five seconds to perceive the threat and initiate an evasive response in the work zone (Thapa & Mishra, 2021). In this research, we seek to investigate how the evasive behavior of workers is influenced and guided by advanced alert systems that provide them with pertinent information. Our objective is to assess the impact of these alert technologies on workers' response patterns during VR evacuation tasks. To achieve this, we analyze the collected positional data to capture behavioral aspects, such as the initiation of evasive behavior, as well as kinematic characteristics, such as the speed profiles of participants and relative distance profiles. By examining these parameters, we can gain insights into the effectiveness of alert systems for different working conditions in facilitating and shaping workers' evasive actions. The detailed analysis and results are presented in section 6.3.

4. Experiment and data collection

4.1. VR experiment development

In addition to the human factors, the evasive behavior of the workers subjected to vehicle intrusion in the work zone depends on various factors related to the work zone and the traffic environment. Based on the organized work zone safety workshop, these important factors are summarized and presented in Table 2 and are used for the development of the VR evacuation tasks. For designing the VR evacuation tasks, the factors and their combinations are considered to provide realistic immersive VR environments of CSWZ, which will be used to assess the subject's response to varying CSWZ conditions. Considering all possible attributes' combinations would result in many evacuation tasks. Therefore, we use the orthogonal design principle, which is one of the efficient experimental design methods (Louviere et al., 2010), to create 12 VR evacuation experiments of CSWZ with vehicle intrusion that have varying levels of the considered attributes (see Table 2).

The level of alert systems considered are 1) No alert system, 2) Centralized Alert System (CAS), which alerts the participants with sirens (lights and sound) about vehicle intrusion in the work zone and 3) Personalized Alert System (PAS), which alerts the participants with personalized notification (display alert with sound). In the VR experiments, the PAS can notify participants through a personalized message displayed via a pop-up notification within the VR environment, accompanied by a siren audio signal for heightened alertness. We implemented the alert systems using a controller placed in the VR environment. The controller is strategically placed in the advance warning region of the closure lane (see Fig. 2). The cars are generated randomly on the road from far away from the work zone area. One of the randomly generated cars is the actual intruding vehicle, programmed to travel consistently in the closure lane without deviation. Upon detection of this vehicle by the controller device, an immediate signal is sent to activate the selected alert system. The developed VR environment had the interface to select the type of alert before starting the experiment. The alert system in

Table 2
Important attributes of the WZ and traffic environment for VR evacuation tasks.

Attributes	Possible conditions	No. of levels
Speed of intruding vehicle	• 13.5 m/s (30 mph) • 20 m/s (45 mph) • 27 m/s (60 mph)	3
Location of the worker in the work zone	• Work activity • Buffer area	2
Activity being conducted by the worker in work zone	• Assisting co-worker • Performing a construction activity as main worker	2
Presence and type of alert system	• No alert system • Centralized Alert System (CAS; Sirens on cones) • Personalized Alert System (PAS)	3

the developed VR setup is inspired by the functionality of the Pneumatic Pressure Activated System, which consists of a pneumatic trip hose sensor with a signal transmitter, a site alarm, and personal alarms for workers. The sensor is designed to detect pressure on the hose after it has been runover by an intruding vehicle across the lane closure (Gambatese et al., 2017; Thapa & Mishra, 2021; Wang et al., 2011). This allowed the participants to receive real-time feedback and be alerted to potential intrusion, providing them with additional time to plan their evasive behavior and take appropriate action. Once the errant vehicle crosses the controller, it is programmed to barge the traffic cones, enter the work zone, and eventually come to a stop at the end of the work zone. This simulated a traffic hazard-like situation in the VR environment, allowing us to test the effectiveness of the alert system and workers' response to potential hazards.

For this study, we developed the CSWZ for intermediate-term work zones, which are typically set up for roadwork that happens during daylight for more than a day but up to 3 days. To begin with developing the VR environment for CSWZ, there is a need to identify a highway site and add the design detail of the site to Unity to develop 3D VR scenarios. Based on the interaction with the stakeholders in the work zone safety workshop, the work zone set organizations suggested that despite sufficient and standard warning signs many times due to the horizontal curvature of the roads, the vehicle intrudes the closer lane where the work zones are set up. Because of this reason, a road segment from the Chapman Highway in Seymour, Tennessee (35.8658, −83.6595), as shown in Fig. 4, is selected. This is an undivided highway with high horizontal curvature. For the VR environment of CSWZ, the road alignment characteristics are similar to that of the selected highway. The CSWZ is located on the curve of the highway. The developed work zone layout follows the guidelines of the work zone filed manual developed by the Tennessee Department of Transportation (2021) for the right lane closure of a multi-lane undivided highway. The 12 VR evacuation tasks with varying levels of considered attributes are developed for this highway site and an example of the VR environment of the work zone is depicted in Fig. 4. The CSWZ VR environment covered a 360-degree view of the work zone site around the participants. The sound and wind movement are also included in the simulation to account for the auditory and visible (waving grass and leaves) cues that are usually experienced by workers in real life on a highway. For a better experience importantly, the auditory cues are simulated such that the noise of the vehicle increases as it comes closer to the participant.

4.2. *Experiment execution and data collection*

For the VR experiment, an Oculus Quest 2 stand-alone VR headset is used, enabling participants to interact within the virtual environment. The VR experiment is developed using the Unity platform, running on a workstation equipped with an NVIDIA GTX 1060 graphics card and an Intel i7 processor, ensuring robust processing power for rendering complex simulated environments. To enable seamless wireless transmission of graphics data, the experiment utilized the Oculus Air Link feature, which transmitted simulated data from the workstation to the VR headset via a Wi-Fi router. This high-performance router provided the necessary stability for smooth, real-time data sharing, which is critical for maintaining the immersive quality of the simulation. The wireless setup, facilitated by the Air Link, allowed participants unrestricted movement within the VR environment by eliminating any physical limitations that wired connections could impose and enabling better assessment of participant responses in a controlled laboratory setting. Participants are provided a brief overview of the study and are introduced to the experiment setup and data collection process. The lab experimental area for the VR evacuation task covers about 55 m^2 (5 m width and 11 m length), where the participant is allowed to move. Once they understand the overview of the experiment their consents are collected. The complete experiment is divided into two phases: 1) a VR familiarization task and 2) a series of VR evacuation tasks. The familiarization task is intended to familiarize participants with the VR and the working conditions in the virtual CSWZ, which will be facilitated by a brief introduction to the VR system and its features. The familiarization task includes observing the CSWZ virtual environment and working on the alert systems. Once, the participants complete the familiarization task, a response for a short survey questionnaire is collected. This will help assess any VR sickness or discomfort for the experiment and the level of familiarization evaluated from responses to questions about the available construction equipment in the CSWZ, the presence of a centralized alert system, and the activities of other workers in the CSWZ. This process will ensure that participants are familiarized with the VR environment and the working of alert systems. Participants are required to

Fig. 4. Virtual environment development for CSWZ replicating curved road alignment.

achieve an 80 % accuracy rate in this survey to proceed. We found that only four out of 74 participants needed to repeat the familiarization task to reach the requisite understanding level.

Following the familiarization task, a participant is required to complete a set of three VR evacuation tasks, making the participant expose to three different alert systems (task 1: with no alert system; task 2: with the centralized alert system; task 3: with the personalized alert system). The task sequences are randomized across alert systems, which can help mitigate any potential learning effects that could bias the results. This randomization ensures that each participant's experience and prior knowledge equally influence all alert systems, without giving undue advantage to any specific alert system (PAS, CAS, or No Alert). For capturing the actual reaction and behavior upon vehicle intrusion in the work zone, participants are clearly provided with the purpose of the study, i.e., to assess the impact of alert systems in a CSWZ. However, participants are intentionally kept unaware of the timing of the intruding vehicle. This approach ensured natural responses and behaviors, which are not influenced by prior knowledge of the vehicle intrusion, allowing for a more realistic and reliable evaluation of the alert systems' effectiveness in enhancing safety. In a VR evacuation task, the participant decides to escape the vehicle intrusion area and tries to cross the shoulder safely (see Fig. 5) in the virtual environment of the CSWZ. For a specific task, the CSWZ environment is characterized based on the speed of vehicle intrusion, the location of the participant in the CSWZ, the level of involvement in construction activities, and the alert system. The set of three VR evacuation tasks is selected from the developed 12 VR evacuation tasks. Each participant is exposed to these selected tasks, which encompass different levels of work zone environment attributes associated with each alert system. In the VR evacuation tasks, we assigned roles to participants to simulate various responsibilities within the work zone. Specifically, one attribute involves distinguishing between participants acting as 'main workers' and those serving as 'assistants to the main workers.' Main workers are tasked with counting boulders within the work zone, an activity designed to simulate task-focused attention. In contrast, participants designated as assisting co-workers are placed in proximity to another simulated worker who is actively engaged in clearing a hole. Similarly, different combinations of 3 tasks are completed by other participants, indicating that 4 participants exhausted the 12 developed VR tasks. After completing the VR experiment the participants are asked to fill out a questionnaire to provide their socio-demographic information, previous experience with VR technology, and current experience with the VR evacuation tasks.

Participants are recruited from engineering departments on campus, as they represent a potential future workforce in the construction industry. Recruitment is carried out through physical flyer postings on campus and online platforms, including WhatsApp, Facebook, and Instagram. The selection criteria included participants with normal vision or corrected-to-normal vision, normal hearing, and unrestricted walking ability, without any disabilities or heart disease. A total of 74 participants, with a median age of 27 years, are included in the data analysis as their data is fully captured. Prior to participating in the experiments, informed consent is obtained from all participants, and they are informed that they could withdraw from the study at any time if they experience any discomfort. The experimental procedures followed the guidelines and approval of the Institutional Review Boards of The University of Memphis.

5. Results

5.1. Body reaction time

In this study, the reaction in the body to initiate the evasive plan is assessed by analyzing the potential movement of participants, which is captured using estimated velocity derived from changes in positional data after sending the alerts. The body reaction time ($\Delta t^{p}_{bodyreaction}$) is defined as the time difference between the moment the intruding vehicle crosses the controller (controller present in the VR environment, which sends an alert if present in the VR evacuation task) and the time when the participant responds by increasing their movement speed by at least 0.5 m/s, resulting in a noticeable change in their movement speed. This provides insights into a participant's response and initiates an evasive action to avoid potential hazards. The box plot in Fig. 6 reveals significant differences in median body reaction times across the three alert systems: no alert, CAS, and PAS. The median reaction time for the no alert system is 4.3 s, indicating a relatively slower response to the simulated intruding vehicle. In contrast, the CAS exhibited a substantially reduced median reaction time of 2 s, demonstrating an improvement in workers' responsiveness to the intrusion hazard.

Remarkably, the PAS demonstrated the shortest median reaction time of 1.3 s, indicating the fastest response compared to the other

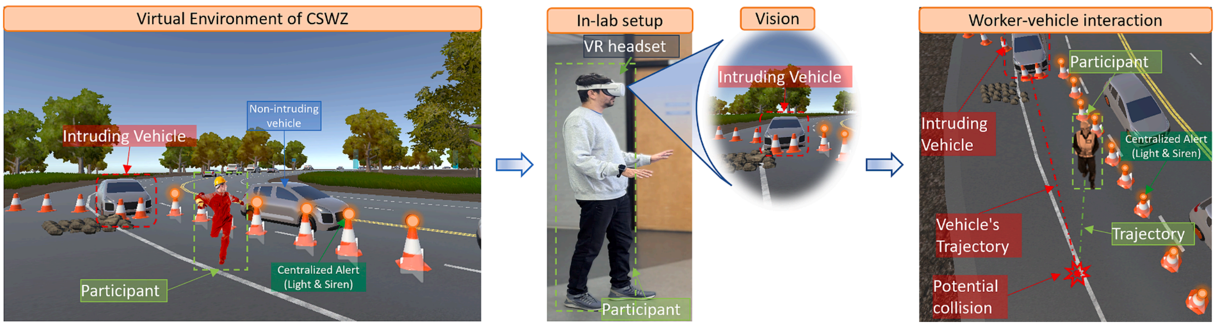
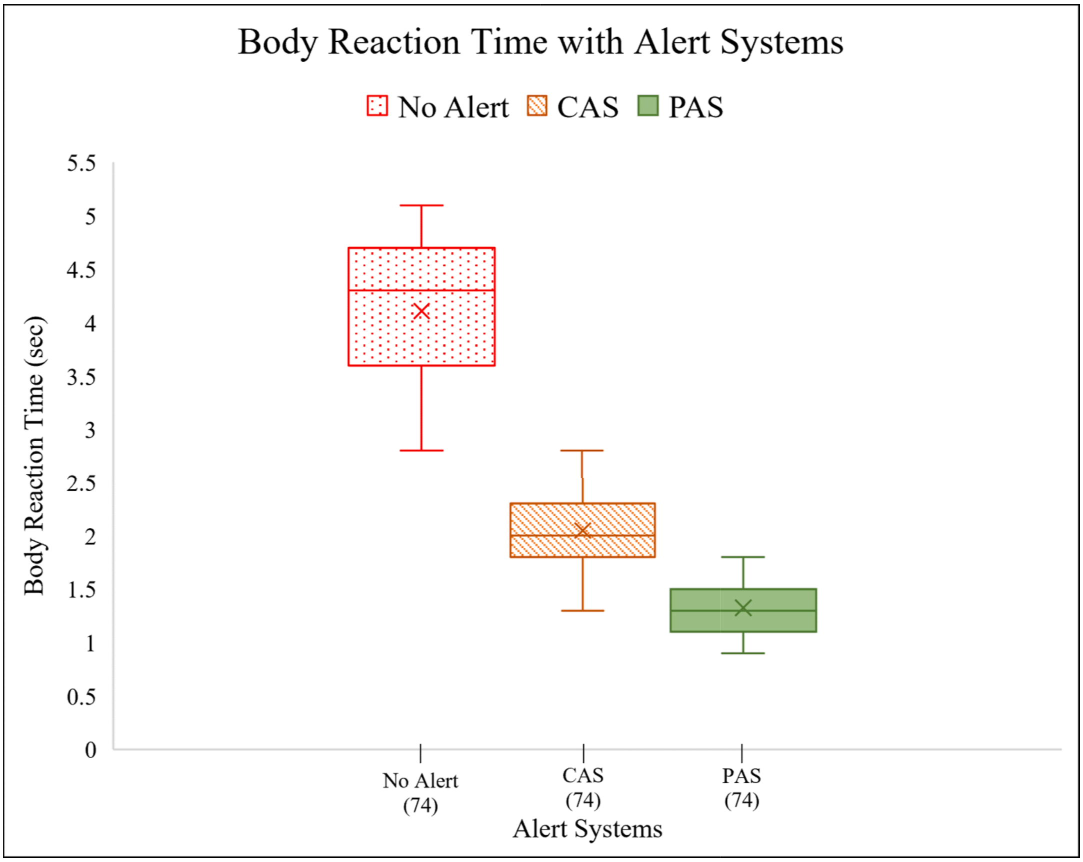


Fig. 5. Experimental setup and VR visualization overview for a participant in the laboratory setting.



The values in the parenthesis represent the number of observations

Fig. 6. Comparison of Median Body Reaction Time for Different Alert Systems.

two systems. This improved performance can be attributed to the PAS's provision of personalized warnings to workers regarding intruding vehicles. By receiving individualized alerts, workers are more cognizant of their surroundings, enabling them to react promptly to potential hazards. In contrast, the CAS employs a centralized siren, which introduces a delay in participants' body reaction time as they first perceive the auditory cues before visually identifying the intruding vehicle. The observed differences in median reaction times emphasize the importance of alert systems in mitigating risks and improving worker safety by reducing response times and facilitating timely evasive actions. The findings are closely aligned with those from field testing. For example, Thapa & Mishra (2021) reported an average reaction time of 5 s, while this study VR environment recorded 4.2 s, attributing the slight difference to the VR setting itself. Further, the findings in this paper align with Yang & Roofigari-Esfahan (2023), where vibro-tactile signals improved reaction times by 46 %; our results showed a similar 45 % improvement with CAS and a 55 % reduction with the PAS. The findings presented in this paper suggest a 45 % reduction in body reaction times because of CAS and about a 55 % reduction in PAS. Additionally, Sabeti et al. (2024), reported similar advancements in AR and VR settings, noting improvements in reaction times after initial warnings, which align with the trends observed in VR experiments conducted in this study.

The analysis of average body reaction time reveals important insights regarding the effectiveness of different alert systems in work zones. When participants engage in construction activities as main workers (simulating task-focused attention by counting boulders), the average body reaction times are 1.44 s for PAS, 2.20 s for CAS, and 4.20 s for the no-alert system (see Table 3). These reaction times are notably longer than in scenarios where participants act as assisting co-workers (stationed near another worker engaged in clearing

Table 3
Average body reaction time for different alert systems based on different situations.

Type of Alert System	Average body reaction time (in secs)			
	Based on the level of involvement		Based on gender	
	Main worker	Assisting co-worker	Male	Female
Personalized Alert System (PAS)	1.44	1.21	1.30	1.41
Centralized Alert System (CAS)	2.20	1.89	2.01	2.18
No Alert	4.30	3.91	4.01	4.31

a hole). This difference can be attributed to the undivided attention participants can dedicate to potential hazards when they are not engaged in any specific tasks. Additionally, to compare the mean reaction times across different alert and activity types, a two-way ANOVA is performed to assess the statistical impact. Different alert systems and construction activities showed that the effect of alert type on reaction time is significant ($p < 0.001$), suggesting that the alert system (No Alert, CAS, PAS) has a significant impact on reaction times. Also, the main effect of construction activities on reaction time is also significant ($p < 0.001$). This observation indicates that involvement in construction activities has a more pronounced negative impact on reaction times in the absence of an alert system. Consequently, workers engaged in construction activities become more vulnerable to hazards.

When considering the gender aspect, male participants exhibited average body reaction times of 1.30 secs for PAS, 2.01 secs for CAS, and 4.01 secs for the no alert system. In comparison, female participants had average body reaction times of 1.41 s for PAS, 2.18 s for CAS, and 4.31 s for the no alert system. The two-way ANOVA comparing reaction times across different alert types and genders revealed significant effects for both factors. The main effect of alert type on reaction time is highly significant ($p < 0.001$), indicating a strong impact on participant responses. Gender also shows a statistically significant effect on reaction time ($p = 0.021$), though its impact is relatively minor compared to alert type. These findings suggest that males generally displayed faster reaction times across all alert systems, with the PAS system consistently yielding the shortest response times for both genders. Overall, the PAS system consistently demonstrated superior effectiveness in facilitating faster reactions compared to CAS and without an alert system.

5.2. Assessing safety outcomes using choice modelling framework

The analysis of safety outcomes observed during the VR evacuation tasks employed the framework of random utility theory. Three aggregate-level outcomes are considered for each VR evacuation task: 1) occurrence of a critical event, where the intruding vehicle breached the participant's safety envelope at any point in time, i.e., the distance between the centroids of the participant and car is observed to be less than 2.9 m at any point of time during the VR evacuation task, 2) absence of a critical event (non-critical) but the participant is unable to cross the shoulder when the vehicle had its closest encounter, and 3) successful crossing of the shoulder and reaching the safe region to avoid intrusion.

The utility associated with each outcome is modeled as a function of various attributes of the VR evacuation task and participant characteristics. The attributes included the intruding speed of the vehicle, the presence of different alert systems (represented as dummy codes), the participant's level of involvement as a main worker (represented as a dummy code), the average escape speed within the first second of initiating evasive behavior, and gender (represented as a dummy code). Detailed definitions and calculations for each attribute are presented in Table 4. We present the utility functions of different outcomes for individual p in Eq. (9)-(11). Importantly, the utility for a non-critical event ($V_{NonCritical_p}$) is considered as the baseline. This indicates that the coefficients of other outcomes should be interpreted relative to this baseline. This approach allows for a comparison of the relative utility or value of different outcomes.

$$V_{Critical_p} = \text{Const}_{\text{critical}} + \beta_{Veh\_speed_{critical}}(\text{Veh\_speed}) + \beta_{Escape\_Speed_{critical}}(\text{Escape\_speed}) + \beta_{PAS_{critical}}(\text{PAS}) + \beta_{CAS_{critical}}(\text{CAS}) + \beta_{Mainworker_{critical}}(\text{Main\_worker}) + \beta_{Female_{critical}}(\text{Female}) \quad (9)$$

$$V_{NonCritical_p} = 0 \quad (10)$$

$$V_{Safe_p} = \text{Const}_{\text{safe}} + \beta_{Veh\_speed_{safe}}(\text{Veh\_speed}) + \beta_{Escape\_Speed_{safe}}(\text{Escape\_speed}) + \beta_{PAS_{safe}}(\text{PAS}) + \beta_{CAS_{safe}}(\text{CAS}) + \beta_{Mainworker_{safe}}(\text{Main\_worker}) + \beta_{Female_{safe}}(\text{Female}) \quad (11)$$

Based on the analysis of the discrete choice models, the coefficients for the utility functions are estimated to understand the impact of various attributes on worker safety in the work zone. The results related to significant attributes (p-value < 0.05) are presented in Table 5, and no significant interactions are observed. The event specific constant (ESC) in the model represents the influence of different outcomes on utility, holding all other factors constant. The positive and significant ESC for a critical event, compared to a non-critical event, indicates a higher likelihood of a person being involved in an intrusion hazard during simulated intrusions. Conversely, reaching a safe region had a negative and significant ESC. The speed of the intruding vehicle showed a positive association with the

Table 4
Attributes considered in the utility functions for different safety outcomes.

Attributes	Definition
Outcomes of a VR evacuation task	1) Critical Event (vehicle intruded the safety envelope) 2) Non-Critical Event (considered as baseline) 3) Crossing the shoulder and reaching the safe region
Veh_speed	Speed of intruding vehicle in m/s
NoAlert	1: if no alert system in the work zone and 0 otherwise
CAS	1: if CAS is in the work zone and 0 otherwise
PAS	1: if PAS is in the work zone and 0 otherwise
Main_worker	1: if a participant is the main worker during the VR experiment and 0 otherwise
Escape_speed	Average speed (in m/s) of a participant during the initial one second of the evasive behavior
Female	1: if a participant is female and 0 otherwise

Table 5
Results of discrete choice model to assess different safety outcomes.

Attributes	Event	Coefficient	t-stats	p-value
Event specific constant (ESC)	*Critical*	1.08	2.11	0.0331
	Safe	−14.60	4.04	0.0001
Veh_speed	*Critical*	0.29	4.73	0.0001
	Safe	−0.24	−2.81	0.0049
Escape_speed	*Critical*	−4.56	−2.96	0.0031
	Safe	16.02	4.40	<0.0001
CAS	*Critical*	−4.28	−5.75	<0.0001
	Safe	2.08	2.13	0.0330
PAS	*Critical*	−6.35	−6.17	<0.0001
	Safe	2.31	2.35	0.0190
Main_worker	*Critical*	1.67	2.78	0.0054
	Safe	−14.29	−3.73	0.0002
Female	*Critical*	2.35	4.25	<0.0001
	Safe	−2.46	−2.77	0.0057
Model Goodness of Fit				
Adjusted ρ^2	0.54			
Log-L (Model)	−105.556			
Log-L (Constant)	−243.737			
No. of observations	222			

likelihood of a critical event occurring and a negative association with reaching a safe region, relative to non-critical events. Notably, the rate of increase in the likelihood of a critical event is higher compared to the rate of decrease in the likelihood of reaching a safe region as the speed of the intruding vehicle increases. Significantly, the analysis of evasive behavior, specifically measured by the average escape speed, revealed a negative correlation with the likelihood of a critical event occurring and a positive correlation with achieving a safer outcome compared to the baseline. These findings indicate that an increase in escape speed corresponds to reducing the likelihood of hazards associated with critical events.

The inclusion of alert systems, specifically the CAS and PAS, exhibited a negative correlation with the likelihood of critical events

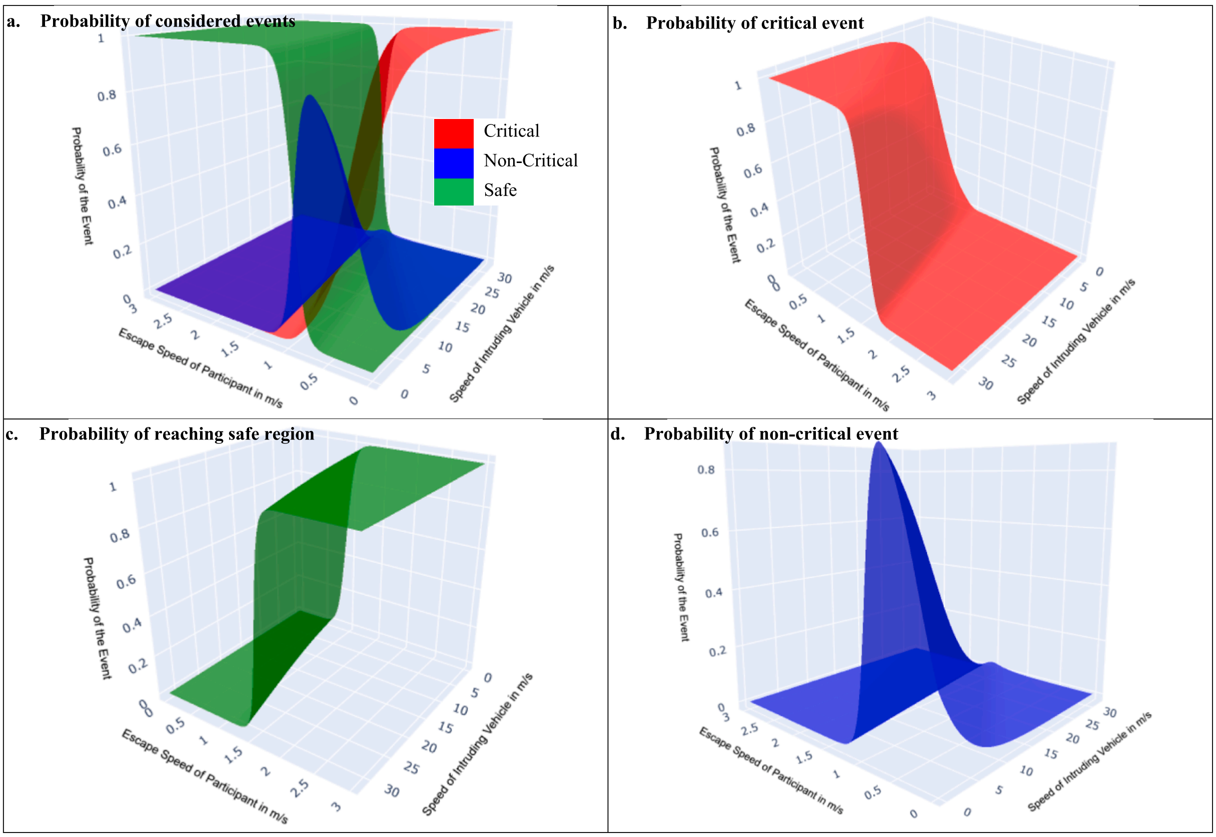


Fig. 7. (a-d) Variation in probability in the observed events for vehicle's intruding and participants' escape speed.

occurring. Notably, the rate of reduction in the likelihood is more pronounced for PAS, suggesting its potential effectiveness in decreasing reaction time and enabling prompt evasive actions. Consequently, the presence of PAS can potentially enhance hazard escape plans by facilitating early response strategies. The model further indicated that a higher level of involvement in construction activities is associated with a decreased likelihood of avoiding vehicle intrusion-related hazards. This emphasizes the significance of employing technological assistance in work zones, considering the substantial engagement of workers in construction tasks, which renders them more susceptible to potential risks arising from traffic-related incidents. Lastly, the findings showed that females are more likely to be involved in critical events than males, which may be attributed to other physical factors that require further investigation. The model results demonstrate the realistic situational behavior of workers, which aligns with what we would expect to observe in real-life scenarios when workers encounter vehicle intrusion hazards.

The elasticity analysis explores the effectiveness of the alert system in influencing safety-related outcomes from the VR experiments. The results reveal that while both systems effectively enhance safety, PAS is notably superior. This effectiveness is attributed to PAS's ability to initiate early reactions, approximately 0.7 s sooner than CAS, which crucially channels escape behaviors, enhancing the likelihood of reaching safety.

The overall findings from the model indicate that in the absence of any alert system, the safety outcome in the work zone predominantly depends on two key factors: the speed of the intruding vehicle and the escape speed of the participant. To better understand the joint sensitivity of these attributes on the safety outcome, we present 3D probability graphs for critical events, non-critical events, and reaching the safe region (refer to Fig. 7 **(a)-(d)**).

Analyzing the probability graph (Fig. 7**b**), we can infer that when the participant has a low escape speed (< 0.5 m/s), there is a high likelihood of encountering critical events, even if the speed of the intruding vehicle is relatively low. This highlights the critical role of initiating evasive action to enhance participant safety. Similarly, at high escape speeds, the impact of the intruding vehicle's speed on the likelihood of reaching the safe region becomes minimal (Fig. 7**c**). However, it is important to note that at moderate participant escape speeds (between 1.3 m/s to 1.8 m/s), the speed of the intruding vehicle can significantly influence the probability of encountering critical events. This suggests that at moderate escape speeds, a high-speed intruding vehicle can increase the likelihood of critical encounters, whereas a low-speed intruding vehicle offers a better chance of avoidance and not encountering a critical event (Fig. 7**c**). This finding underscores the importance of alert systems that can trigger early evasive actions, particularly in work zones on high-speed roadways, such as freeways, where vehicles are more likely to intrude at higher speeds.

5.3. Behavioral and kinematic changes

Evasive behavior refers to actions taken by individuals to avoid potential danger, specifically in the context of this research, when

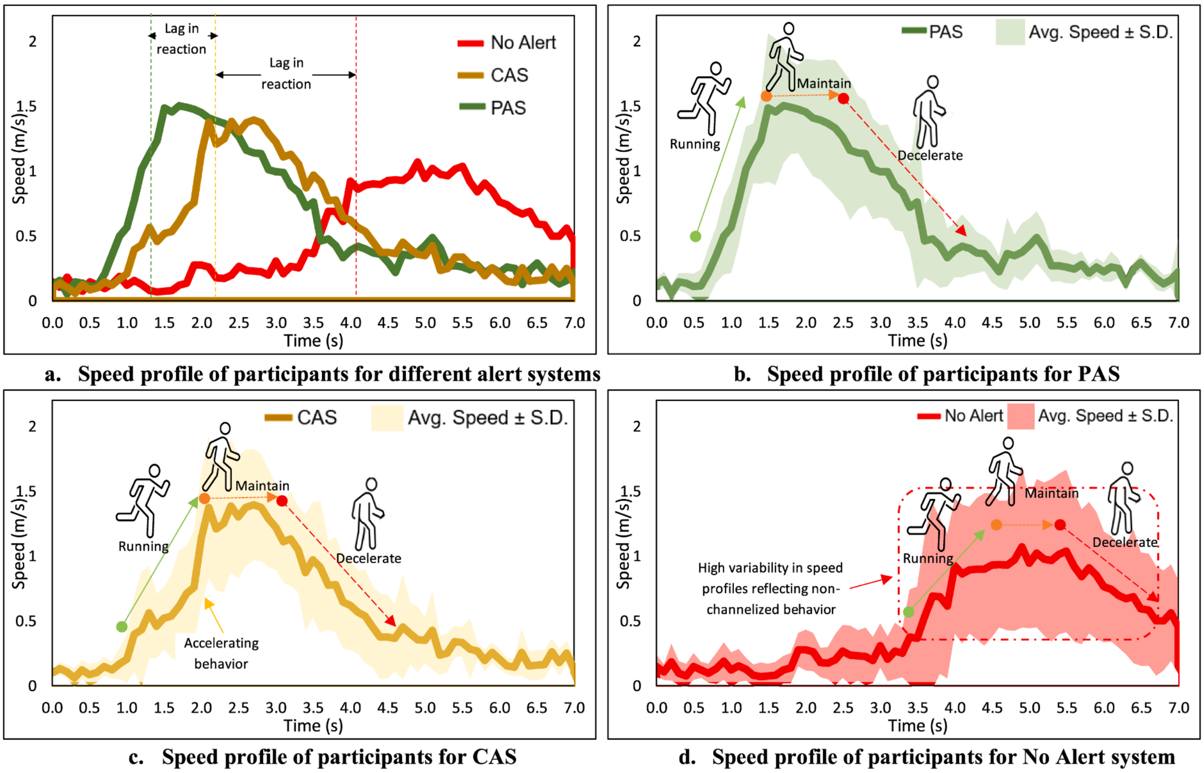


Fig. 8. (a-d) Speed profile of the participants in avoiding an intruded vehicle by application of different alert systems.

facing a vehicle intrusion within a work zone. The effectiveness of evasive behavior can be enhanced through the application of various technologies, which can also be used to evaluate the efficacy of different alert systems. The assessment of evasive behavior in work zone exposed to vehicle intrusion hazards involves a comprehensive analysis of speed profiles over time. By examining the temporal changes in speed, we can evaluate the evasive actions and participant's ability to mitigate the risks associated with vehicle intrusions. The temporal variation of the speed profile provides valuable insights into evasive behavior and the role of alert systems in influencing their behavior. Fig. 8**a** depicts the average speed profile of participants for different alert systems. At the aggregate level, these speed profiles reflect the latency in the body's reaction time to hazards when different alert systems are employed. The results indicate that, on average, participants assisted with the PAS and CAS exhibit reactions that are 2.8 and 2.1 s earlier, respectively, compared to scenarios without any alert system. The evasive behavior to avoid vehicle intrusion hazards, as indicated by the speed profiles, generally follows a three-phase sequential motion: 1) an initial sudden acceleration in response to hazard identification, 2) maintaining speed to avoid the hazards, and 3) deceleration once the workers perceive that the hazard has passed (see Fig. 8**b**, Fig. 8**c, and** Fig. 8**d**).

This three-phase sequential motion is consistently observed across the different alert systems considered in the VR evacuation tasks. However, there is a general delay in the occurrence of this sequential motion, which aligns with the trend of body reaction time. It is initially observed for PAS, followed by CAS and at last for no alert system. The first phase, characterized by the initial sudden acceleration behavior, represents the workers' immediate response. On average, an initial sudden acceleration of 1.3 m/s^2 (between 0.9 and 1.5 secs) is observed in the speed profile when PAS is employed (see Fig. 8**b**). Similarly, for CAS and scenarios without any alert system, the observed initial accelerations are 0.91 m/s^2 (between 1.5 and 2.7 secs) and 0.47 m/s^2 (between 3.5 and 4.8 secs), respectively. A higher initial acceleration suggests a prompt and proactive evasive action, indicating a potentially more effective response to the hazard. The second phase indicates workers' ability to maintain momentum and move away from the intruding vehicle and reduce their exposure to the hazard. A higher average speed during the second phase is observed for PAS (1.43 m/s), followed by CAS (1.31 m/s). Conversely, scenarios without any alert system show lower average speeds during the second phase, mainly due to higher variability in speed (see Fig. 8**d**). The higher speed variability is observed in scenarios without alert systems compared to those with CAS and PAS, suggesting that the application of technological assistance in the form of alert and warning systems helps channelize workers' behavior.

By thoroughly analyzing the temporal variation of the velocity profiles, we gain valuable insights about the predominate phases of the evasive behavior of workers in work zone exposed to vehicle intrusion hazards. This analysis provides a deeper understanding of how technology-assisted systems can enhance workers' responsiveness, maneuverability, and effectiveness in avoiding potential dangers. These findings can inform the development of strategies and interventions aimed at enhancing worker safety in work zone and mitigating the risks associated with vehicle intrusions.

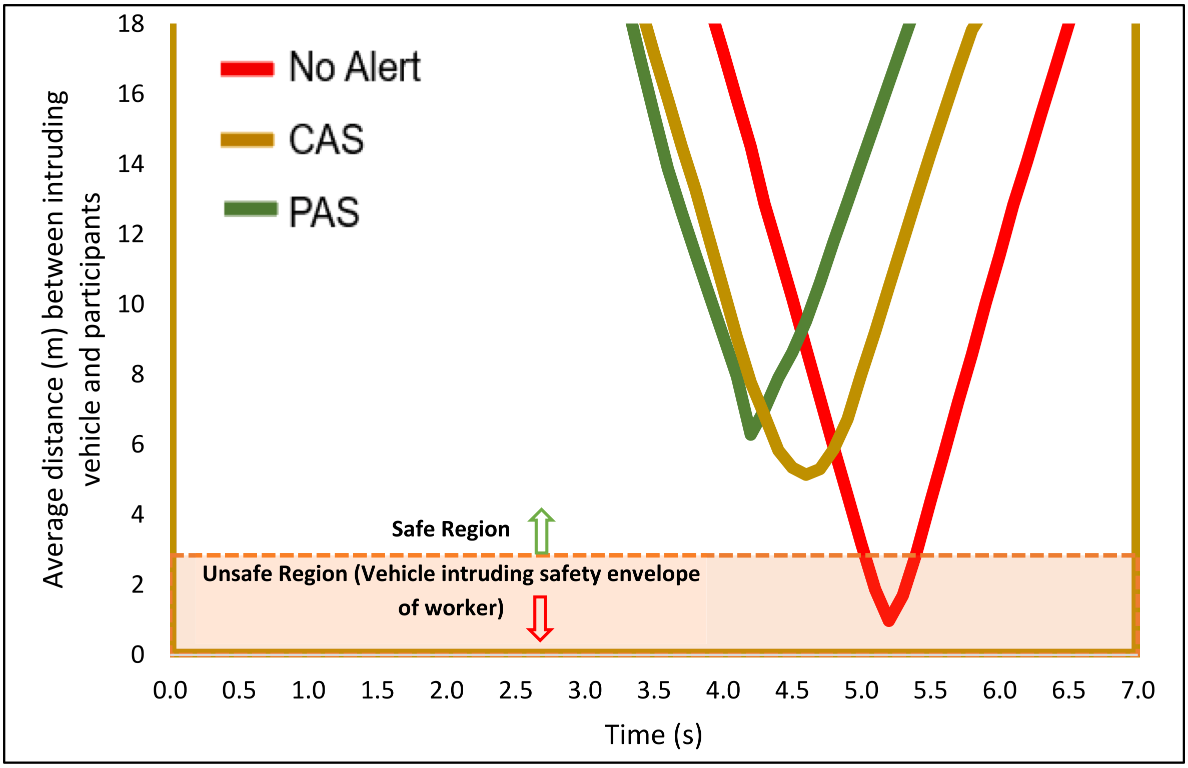


Fig. 9. Temporal variation of the average relative distance between the participants and the vehicle intruding the work zone at 20 m/s.

Further, the assessment of risk to workers in work zones exposed to vehicle intrusions involves analysis of the relative distance between the intruding vehicle and the workers over time. The temporal variation of the relative distance provides crucial information regarding the level of proximity and potential danger faced by the workers under different alert systems deployed in the work zone. Fig. 9 presents the temporal variation of average relative distance for different alert systems for the vehicle intruding at 20 m/s. Here, the average relative distance follows a parabolic pattern, where the lowest point represents the minimum distance recorded between the participant and the intruding vehicle. A smaller minimum distance indicates a higher level of risk and potential for a critical event, where the intruding vehicle poses a direct threat to the workers' safety. It can be observed that the minimum average relative distance is lowest for no alert system compared to PAS and CAS, and there is a marginal difference between the minimum average distance value between PAS and CAS. This reflects that the deployment of alert systems in work zone setup can reduce the proximity-related risk for the workers, as alert systems tend to initiate early responsive and evasive behaviour in case of hazards. Importantly, if we compare the relative distance based on the threshold distance between the participant and the vehicle to define the critical event (refer to section 4.3.1), it can be observed that the average relative distance curve for no alert system tends to fall in the region of critical event, where the distance between the participant and the vehicle is less than 2.9 m. Whereas, the average relative distance curve for PAS and CAS does not fall in the region of critical event.

In addition to the type of alert system, it is important to consider other factors that can influence the average relative distance between the intruding vehicle and the workers. Two significant factors are the intruding vehicle's speed and the level of involvement of the workers. The minimum distance between the intruding vehicle and the worker provides crucial insights into the level of proximity and potential danger faced by the workers. Analysis reveals that the no alert system results in the lowest average relative distance of 1.24 m when workers are exposed to a 20 m/s intruding vehicle while engaged in construction tasks. This indicates a high susceptibility to critical events in a work zone without alert systems, as the minimum average distance remains below the critical threshold of 2.9 m. This suggests that a work zone with no alert system is very much prone to observe a critical event. The findings consistently demonstrate a notable trend: higher intruding vehicle speeds lead to shorter distances between the vehicle and workers, thereby increasing the risk of collisions or hazards. For instance, with no alert system, the number of critical events increased from 11 to 14 as the vehicle intruding speed rose from 13.5 to 20 m/s (refer to Table 6). In contrast, lower vehicle speeds allow for greater distances, affording workers more time to react and mitigate risks effectively. Additionally, the level of worker involvement in tasks correlates with lower relative distances. For example, in the absence of an alert system at a 13.5 m/s intruding speed, the minimum average distance decreased from 2.61 m to 1.69 m, and the number of critical events increased from 9 to 11 when participants are engaged in construction activities. This heightened vulnerability arises because workers actively involved in construction tasks tend to react later to hazards due to divided attention, increasing their susceptibility to vehicle intrusions.

The deployment of a PAS shows a substantial reduction in the number of critical events and an increase in minimum average relative distance compared to the absence of an alert system. For a scenario involving a 20 m/s intruding vehicle speed and workers involved in tasks, the number of critical events decreases from 14 to 5, and the minimum average relative distance increases from 1.24 m to 3.02 m with the implementation of PAS. Similar impacts are observed when comparing the CAS to the no alert system. Notably, the PAS outperforms both the CAS and the no alert system, significantly reducing the number of critical events and minimizing proximity-related risks to workers in the work zone. These findings emphasize the effectiveness of PAS and CAS in mitigating risks associated with intruding vehicles, particularly in scenarios involving high vehicle speeds and worker involvement levels.

6. Discussions

6.1. Comparative discussion with existing studies

The body reaction times observed in this paper are close to what is found in field testing. For example, the average worker reaction time was 5 s, as found in Thapa & Mishra (2021). The body reaction times experienced by workers in this paper is 4.2 s, which is close to the field experiments; the marginal difference can be attributed to the difference between the field experiment and that of the VR environment. The worker's initial reaction time to perceive intrusion was detected by 0.4 to 0.5 s (Awolusi and Marks, 2019), which was also the case in this paper. When vibro-tactile signals are provided to the workers, the body reaction times are improved by 46 %, as reported in the construction work zone setting in a recent study (Yang & Roofigari-Esfahan, 2023). In this paper, our findings suggest

Table 6
Minimum relative distance between the participants and intruding vehicle during VR evacuation tasks.

Alert Systems	Activity of Participant	Minimum of average relative distance (in m) between participants and intruding vehicle and occurrence of critical event		
		13.5 m/s	**20 m/s**	**27 m/s**
No alert	Assisting main worker	2.61 (9)	–	1.93 (12)
	As the main worker	1.69 (11)	1.24 (14)	–
Centralized Alert System (CAS)	Assisting main worker	–	5.24 (5)	3.11 (5)
	As the main worker	4.65 (3)	–	2.19 (10)
Personalized Alert System (PAS)	Assisting main worker	6.58 (2)	6.24 (2)	–
	As the main worker	–	3.02 (4)	2.68 (6)

Value in parentheses indicates the number of critical events observed during the VR evacuation tasks for the corresponding set of attributes.

a 45 % reduction in body reaction times because of CAS and about a 55 % reduction in PAS setting; showing similarity in observation. In the combination of AR and VR settings (Sabeti et al., 2024), when body reaction time was measured, there was improvement between the first and second warning, while the initial body reaction time was similar to the VR experiment conducted in this paper. Additionally, the implementation of PAS successfully prevented the critical event—an intruding vehicle entering the safety envelope of participants—81 % of the time, as highlighted in Table 6. This efficacy is comparable to the 78 % reduction in vehicle collisions reported by Lordianto et al. (2024) when workers received haptic notifications from the Hapti-met system. These findings illustrate that work zone safety and worker response to vehicle intrusions are critical areas of emerging research. The results from various studies indicate that multiple factors—including the speed of the roadway, type of alert, work zone configuration, worker experience, noise levels, and the presence of heavy equipment can influence safety outcomes.

6.2. *Performance of alert systems for work zone safety*

The PAS consistently exhibited effectiveness in facilitating quicker reactions and leading to improved safety outcomes evaluated using choice model. Also, PAS helps achieve higher average speed, followed by CAS, while scenarios without alerts have lower average speeds, with high variability. These higher escape speeds are correlated with a lower likelihood of occurrence of critical events. Importantly, at low escape speed, there is a high likelihood of encountering critical events, even if the speed of the intruding vehicle is relatively low. Similarly, at high escape speeds, the impact of the intruding vehicle's speed on the likelihood of reaching the safe region becomes minimal. The absence of an alert system results in the lowest average of minimum relative distance, increasing susceptibility to critical events in work zones. Implementing a PAS significantly reduces critical events and increases minimum relative distances, surpassing CAS and no alert systems, effectively mitigating risks in the work zone. Also, worker involvement in construction activities is associated with a reduced likelihood of avoiding vehicle intrusion-related hazards, underscoring the importance and need for technology assistance for actively engaged workers. For practical application, work zone controllers and sensors can utilize advanced sensor technologies to enhance vehicle intrusion detection and communication. Radar technology, which uses radio waves, can detect vehicles' distance, speed, and direction, while LiDAR provides precise 3D mapping, offering real-time vehicle tracking even in low-light or adverse weather. High-resolution cameras can capture visual data to monitor potential hazards from multiple angles. Combined with existing work zone intrusion systems (e.g., dynamic signs, warning lights, audible alarms), these sensors can enable a robust alert system. This integration enhances work zone safety by delivering real-time intrusion alerts, enabling workers to take timely evasive actions and reduce accident risks.

7. Conclusions

Work zones are highly dynamic environments with significant exposure to errant vehicle intrusions, making highway construction and maintenance among the most hazardous occupations. Despite this high risk, systematic safety assessments for workers in these settings remain limited. This study addresses the gap by evaluating Connected and Smart Work Zones (CSWZ) as a technology-driven solution to enhance work zone safety by enabling timely worker responses, offering a promising approach to mitigating risks. This paper developed a systematic approach to conceptualize the working of CSWZ from a worker-centric safety perspective using VR. This helps evaluate the impact of different alert modalities—no alert, centralized, and personalized alert systems—on safety outcomes, including reaction time improvement. Additionally, the study examines kinematic behavior by analyzing the temporal variation of evasive speed and relative distance. A proximity-based threshold is used to analyze vehicle intrusion into the safety envelope. The safety outcomes of the VR evacuation tasks are modelled using a discrete choice model, considering various attributes related to the work zone environment, alert technologies, intruding vehicle speed, and evasive actions.

The implementation of the PAS consistently improves response times, decreases the frequency of critical events, and increases the distance between workers and intruding vehicles, outperforming both the CAS and scenarios without any alert systems. The analysis of evasive speed profiles revealed a three-phase sequential motion trend: acceleration, speed maintenance, and deceleration, which is consistently observed for all alert conditions. However, the initialization of this three-phase sequential motion is observed to have a lag for no alert system compared to other considered alert systems. The first phase of workers' response to alerts in the VR simulations is characterized by an initial sudden acceleration. Higher initial accelerations indicate prompt and proactive evasive actions, suggesting a more effective response to hazards. The second phase involves maintaining momentum and moving away from the intruding vehicle. The analysis reveals higher variability in evasive speed for no alert systems than those employing CAS and PAS, which underscores the importance of technological interventions to help channelize workers' behavior. The study offers valuable insights into mitigating risks associated with intruding vehicles, particularly in scenarios involving high vehicle speeds and varying levels of worker involvement.

The findings from this study contribute to the knowledge of CSWZ safety, emphasizing the value of leveraging technology to enhance worker well-being and improve overall work zone safety. The insights derived from these experiments can inform the design and implementation of advanced alert systems, ultimately fostering safer and more efficient work zone environments.

8. Limitations and future scope

While virtual reality (VR) technology offers a controlled environment to monitor human behavior in complex settings, it has drawbacks. One notable limitation is that reaction time and behaviour assessed using VR may differ in real-world scenarios. In this research context, this can be because the participants know that there is no actual physical danger, which can influence their responses. Furthermore, the composition of our sample—comprising primarily students rather than professional road workers—introduces another limitation. This selection was necessitated by the early stage of this research, resource constraints, and the complexities involved in securing necessary ethical approvals. However, these students have some degree of familiarity with similar work environments through VR familiarization tasks and previous internships or field visits. However, the findings showcase similar trends applicable across different participant groups, though we acknowledge that results from road workers with a larger sample size could offer deeper insights. Future studies can aim to include professional road workers to better understand the behavior and responses in technology-aided work zones. The perceptions and reactions of the participants might also differ based on the type and size of the intruding vehicle. Future research can consider investigating the impact of varying vehicle sizes on worker safety and perception in work zones.

To advance the field further, future studies should consider developing and implementing more advanced discrete choice models that better capture the complexity of decision-making processes in hazardous situations. These models could integrate additional variables, including psychological factors, environmental conditions, and more diverse participant characteristics, enhancing the predictive accuracy and relevance of the research findings. This study paves the way for future research in worker safety, focusing on emerging technology-assisted alert systems. Promising avenues include investigating personalized alert systems using wearable and haptic devices for hazard communication and faster reactions. Additionally, calibrating these personalized devices based on working conditions and individual characteristics is an important future direction. Further research can explore strategies for facilitating the adoption of advanced technologies among the workforce, with the development of VR training modules being a potential solution for widespread implementation.

CRediT authorship contribution statement

Gajanand Sharma: Writing – review & editing, Writing – original draft, Data collection, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sabyasachee Mishra:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Symbolic notation

Notation		Definition
$2a$	:	Length of the intruding car
$2b$	:	Width of the intruding car
d_{PC}	:	Distance between the centroids of the vehicle and the safety envelope
r	:	Radius of safety envelope
U_{ps}	:	Utility for individual 'p' and safety outcome 's'
V_{ps}	:	Deterministic component of utility for individual 'p' and safety outcome 's'
β_a	:	Coefficients vector associated to different attributes used for estimating the utility
X_a	:	Attributes vector used for developing model based on random utility theory
P_{ps}	:	Probability of observing outcome 's' by an individual 'p'
$L(\beta_a)$	:	Likelihood for model based on random utility theory
D_{ps}	:	Binary outcome, which is 1, if safety outcome 's' is observed, and 0 otherwise
$\Delta t^{p}_{bodyreaction}$	:	Time difference between the moment the intruding vehicle crosses the controller and the time when the participant reacts

Data availability

The data that has been used is confidential.

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