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Improved intrusion accident management using haptic signals in roadway work zone

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ABSTRACT

Introduction: Roadway work zones are known for hazard vulnerability, with many injuries and fatalities each year, due mostly to intrusions. Despite several available measures to improve safety, existing mechanisms are unreliable for workers to perceive alerts, due to the harsh working environment, with loud noise and limited vision. This research attempts to overcome hazard perception difficulties by introducing a new communication mechanism for intrusion hazard perception. *Method:* The presented communication mechanism is based on past tactile sensing research, and is enhanced by signal profile and message modeling investigations. Experimental field trials were conducted for mechanism evaluation with a goal of improved situational awareness through tactile sensing. *Results:* The trial results show that users perceive warning messages well, even when their vision and hearing are limited, and that the signalized messages perceived could augment users' understanding of a potential hazard, allowing immediate precautionary actions. *Practical Applications*: The application of haptic signals in vulnerable work zones has the potential to improve upon limitations in innate sensing (e.g., vision and hearing), thus presenting an opportunity to better protect workers from potential accidents.

1. Introduction

Temporary road construction sites are characterized by confined workspaces, with construction workers working in close proximity to construction equipment and moving traffic. Due to these conditions, workers are highly vulnerable to safety hazards, causing minor to severe injuries and fatalities. Road site accident statistics in the United States show that there were 1,844 worker fatalities from 2003 to 2017, which is an average of 123 fatalities per year (CDC, 2019). Given the high priority of worker safety (Wu et al., 2015), various conventional measures are applied at temporary road construction sites to prevent potential accidents. Such measures include the use of traffic cones/barrels and flaggers, along with enforced low speeds in work zones. Further, the work zones are laid out in such a way that there is a safety buffer along the longitudinal and lateral sides of the actual work zone from the moving traffic to protect workers (Manual on Uniform Traffic Control Devices for Streets and Highways, 2012). However, worker fatality statistics highlight the concern for road-site construction safety and the inadequacy of the measures in practice.

Several studies (Bryden et al., 2000; Hourdos, 2012; Schneider, 2014; Ukkusuri et al., 2016) have identified that conventional safety measures implemented in road-site work zones are ineffective in preventing intrusions from distracted, drunk, or drowsy drivers. Besides, distracted drivers have a higher tendency to neglect traffic signals and other warning signals used in work zones (Hourdos, 2012). Statistics show that 10% of fatal accidents and 15% of injury accidents in 2015 resulted from distracted drivers (National Center for Statistics and Analysis, 2017). Moreover, the intrusion of outside vehicles into temporary work zones is a serious safety issue, accounting for a large number of fatalities at road construction sites (Sant, 2009; Schneider, 2014). Of the reported road-site construction fatalities, a large proportion results from intruding vehicles (Bryden & Andrew, 1999), with the severity of such intrusion accidents depending on different factors, such as the work zone location, work duration, worker activity (Wong et al., 2011), and time of day (Al-Bdairi, 2020; Arditi et al., 2007; Wong et al., 2011).

Conventional safety measures are inadequate to prevent accidents caused by intruding vehicles, and researchers found it beneficial to investigate technologies that can alert drivers to take precautionary measures. Accordingly, different studies have proposed the use of rumble strips (Anderson et al., 2016; Hourdos, 2012; Miles et al., 2006; Noyce & Elango, 2004; Yang et al.,

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2016), modified rumble strips (Hossen et al., 2019), and portable plastic rumble strips (Wang et al., 2013) to alert drivers. Similarly, researchers (Anderson et al., 2016; Hourdos, 2012) have proposed other measures, such as using graphic-aided changeable message signs, truck-mounted warning systems, police enforcement, and variable speed limits.

Further, Anderson et al. (2016) proposed other measures to reduce intrusion risks at temporary work zones, such as: (a) identifying the most likely work zone intrusion points before commissioning the construction activities and using crash attenuators in the case of high risk; (b) implementing traffic control plans that follow the relevant guidelines to strictly address potential risks; (c) using intrusion alarms; (d) minimizing the duration of work directly adjacent to moving traffic, and using spotters to watch traffic during such work, or using impact-resistant protective barriers.

Similarly, El-Rayes et al. (2014) identified that it is effective to use spotters instead of flaggers to enhance worker safety at temporary road construction sites during work zone operations with moving traffic; however, it is necessary to ensure that the flaggers/spotters are at a safe distance from the traffic. The researchers also suggested the use of a radar trailer to warn approaching drivers of their speed, as one of the top four measures to enhance work zone safety.

Other researchers have attempted to detect drowsy drivers (Jacobé de Naurois et al., 2019; Soares et al., 2020), as well as distracted drivers (Eraqi et al., 2019; Tran et al., 2018). Most of these measures to prevent potential intrusions are focused on alerting drivers. However, intentional actions of drivers to enter work zones (e.g., entering the closed lanes to get to exit ramps, intersections, or driveways, as well as ignoring the instructions of flaggers at work zones) are also responsible for intrusion accidents (Ullman et al., 2011). Further, Ullman et al. (2016) found that there may be no differences in drivers' behaviors when passing through a work zone with or without flashing warning lights with audio-based alarms.

The findings suggest that alerting drivers alone is insufficient, and it is equally important to alert workers at risk from potential intrusions, which requires additional measures. Accordingly, construction and transportation researchers have invested a significant amount of time into studies to ensure workers' safety from intrusion accidents at temporary roadway construction sites.

2. Literature on intrusion prevention studies

The continuous effort from researchers has resulted in several commercially available early warning systems, built to warn construction workers of potential intrusion accidents at temporary road construction sites and prevent work zone mishaps. One is the Intellicone Smart Closure System, developed by Highway Resource Solutions (HRS, 2019). This system is comprised of portable alarms that can be installed on traffic cones at work zones to alert workers of vehicle intrusions inside the work zones. A similar type of system, called SonoBlaster, was developed by Transpo Industries (Transpo Industries, 2018). SonoBlaster is an impact activated work zone intrusion alarm, which alerts workers, as well as drivers, with an audible alarm. The alarm devices can be easily mounted on traffic cones or barricades, and alarms are activated upon impact from intruding vehicles.

The traffic guard workers alert system is another commercially available system, developed by Astro Optics (2018), which consists of a trip hose sensor to detect vehicle intrusion. Further, this system has a portable alarm device and a personal safety device to alert workers through audio and light signals. When vehicles pass through the trip hose sensor, the alarm device produces audible and visual signals, and the personal safety device also transmits vibration and audible alerts to workers. Given the commercial availability of these warning systems, a few studies (Awolusi & Marks, 2019; Nnaji et al., 2018) have developed guidelines to assist stakeholders in proper technology selection, depending on the nature of the construction work. For example, Awolusi and Marks (2019) recommended using the traffic guard workers alert system in mobile work zone projects due to its portability. Further, stakeholders can benefit from detailed information available on different technologies from the field evaluation conducted by Nnaji et al. (2020) to select a suitable system.

Besides the commercially available intrusion prevention systems, researchers have conducted several studies to develop intrusion-accident detection and warning mechanisms. For example, Martin et al. (2016) developed an intrusion alarm system based on an ultrasonic beam installed on traffic cones placed at the tapered road sections in temporary work zones. A wireless network available within the work zone connects the vehicle detection system with a programmable watch, used by workers and the site manager as a wearable warning device. Upon detecting vehicles within a pre-defined distance from the work zone along the system's line of sight, warning signals are sent to all wearable warning devices to alert the workers and the site manager. Similarly, Theiss et al. (2017, 2018) conducted a detailed performance analysis of an intrusion-hazard detection and warning system, which detects a potential intrusion by analyzing the speed, location, and possible trajectory of an approaching vehicle. Upon identifying potential intrusion scenarios, flashing-light warnings and an audio-based alarm are activated to warn the workers, as well as the driver. The warning system consists of an additional worker body alarm, which produces vibratory and audio-based warnings when the worker's position falls within the trajectory of an approaching vehicle.

3. Research gap

Temporary roadway work zones have confined workspaces with an adverse environmental nature (e.g., loud noises from construction equipment, traveling vehicles, workers, and their interactions), which limit a human's innate sensing. As such, workers have limited sight and hearing, so they are often unable to hear/see audio/visual-based warning signals. Studies (Fyhrie, 2016; Wang et al., 2013) support this claim through extensive testing that showed audio/visual-based alerts often fail to alert workers. If workers fail to recognize the signals, and are thus unable to take actions for safety, it is equivalent to safety system failure. Therefore, the warning mechanism plays a vital role in protecting workers from potential intrusions, and it is essential to ensure that workers can perceive the warning signals well.

Despite the potential of these systems (Astro Optics, 2018; HRS, 2019; Martin et al., 2016; Theiss et al., 2017, 2018; Transpo Industries, 2018) in preventing potential intrusion hazards, they are mainly focused on detecting intrusions, and little attention has been given to workers' perceptions of the alerts. Most of the systems use audio and/or visual warnings that may not be well perceived by workers in temporary work zones. As such, it is necessary to improve warning mechanisms to overcome the limitation of workers' perception capabilities. The vibratory alerts used by the personal safety device included with the traffic guard workers alert system (Astro Optics, 2018), and the system by Theiss et al. (2017, 2018) overcome this limitation; however, these vibratory alerts are limited to only warning workers, without providing any additional information about the potential hazard. Thus, despite receiving these vibratory alerts, workers are still unable to perceive the exact hazard scenario until they gather the required information from their surroundings. Given that time is a critical factor for hazard prevention, such warning mechanisms may not allow for timely preemptive actions from workers. As a way to overcome these limitations, warning signals with specific intrusion hazard information would improve workers' perception capabilities, while simultaneously helping them be vigilant against potential hazards, and eventually enhance worker safety.

To overcome the limited sensing capabilities of workers to perceive their surroundings in a construction environment, Cho and Park (2018) proposed a vibration-based embedded sensory system that provides an artificial sensing capability, which can be used to improve worker safety awareness. This study formed a basis for developing a tactile-based language that can be used to transmit informational haptic signals. A follow-up study configured the sensory system as a wearable system to be used around the workers' waists to communicate haptic signals on workers' backs (Sakhakarmi & Park, 2019). In contrast to the vibratory alerts used in other intrusion prevention systems (Astro Optics, 2018; Theiss et al., 2017, 2018), the tactile-based wearable system offers flexibility, with customization for different messages. Therefore, this study focuses on adapting the system to enhance the intrusion warning mechanisms, with specialized haptic signals to alert workers. These haptic signals will consist of specific information to reflect the specific intrusion scenario for better worker perception. As such, it will allow workers to make well-informed decisions related to potential intrusions, and thereby prevent potential injuries or fatalities.

4. Research objective and scope

Despite the availability of several systems for detecting work zone intrusions, the modes of communicating such intrusions to workers are inefficient and thus require further study. Without a proper warning and perception mechanism, existing technologies for workers safety in temporary work zones may not be effective when workers have limited sensing capabilities. As such, this study aims to improve workers' intrusion hazard sensing capabilities by equipping them with an artificial haptic-based sensing system that utilizes the sense of touch for hazard communication/perception. Such a haptic mode of warning is not impacted by vision or hearing limitations, thereby offering the potential to overcome problems with hazard awareness, in which workers' innate sensing abilities are compromised. Particularly, the objective of this study is to investigate the applicability of a haptic warning mechanism in improving the communication and perception of intrusion hazards, and demonstrate that the proposed approach can communicate intrusion-related information to the users by using pre-defined signal formula through field trials.

For improved communication and perception of intrusion hazards, this study will specifically use the prototype wearable system (Sakhakarmi & Park, 2019) and create enhanced message-encoded signal profiles to alert workers of specific intrusion scenarios. Therefore, the warning mechanism is composed of different vibration profiles to represent different intrusion scenarios. The message will include specific intrusion details to warn workers of potential hazard scenarios based on intrusion location and worker locations. With these details, the signal profiles are modeled to effectively communicate such information to workers. The message embedded within the tactile signals enables workers to understand the potential situation and promptly take preventive actions. Therefore, this study is an important step towards developing a comprehensive intrusion hazard management system for roadway work zones.

It should be noted that this study primarily focuses on communicating perceivable intrusion information rather than detecting hazards simply because there are many hazard detection systems available by the industry and research; thus, it is presumed that the intrusion hazards are pre-detected and necessary information, such as intrusion point location and worker locations, are available for the communication system. The authors believe that this is a reasonable assumption from existing hazard and intrusion detection systems, and this haptic warning mechanism can be easily integrated with effective existing systems.

5. Research methodology

Intrusion hazard prevention involves the detection of potential vehicle intrusions into work zones, successfully warning workers of detected intrusions, and allowing for preventive actions by workers. Thus, an intrusion hazard prevention system must consist of two independent systems: (1) an intrusion detection system to detect potential intrusions; and (2) an intrusion warning system that warns workers to take preventive actions. In order to enhance workers' perceptions of intrusion hazards on temporary roadway construction sites, this study focuses on seamlessly alerting workers of detected intrusions, and investigates the warning mechanism of the intrusion prevention system. As a vehicle intrusion is detected by an intrusion detection system, which this research considers as known information, the information is transmitted to the communication server, and the workers are promptly warned to take preventive actions. The authors used a prototype, tactile-based wearable system for intrusion communication to workers through informational haptic signals. This wearable system consists of 10 cylindrical vibration motors embedded on a waist belt in a 4-2-4 arrangement, as proven effective in past research (Sakhakarmi & Park, 2019) to communicate different information depending on the intended use with respect to perception time and message construction. Fig. 1 shows the configuration of 10 motors arranged in three rows with four, two, and four motors on the first, second, and third rows, respectively.

Fig. 2 outlines the methodology adopted in this study. Initially, the authors determine different warning signal parameters to create informational haptic signals, indicating potential vehicle intrusions into work zones. Then such parameters are integrated with the haptic-based wearable system (Fig. 1) to generate informative and perceivable haptic signals. Finally, field trials are conducted to evaluate the performance of the haptic signals to communicate intrusion-related information. The following sections discuss these steps in detail.

5.1. Warning signal parameters

For developing informative warning signals, it is crucial to determine the warning signal parameters that reflect potential vehicle intrusions into work zones (i.e., specific information to represent specific intrusion scenarios). For instance, Fig. 3 shows an

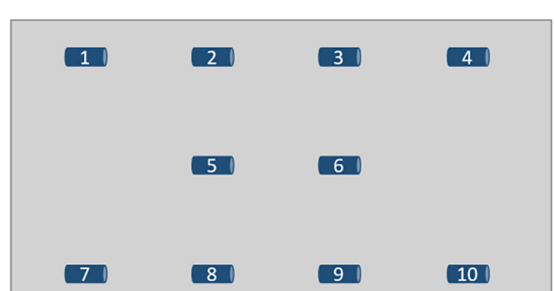


Fig. 1. Vibration motor arrangement on the prototype system.

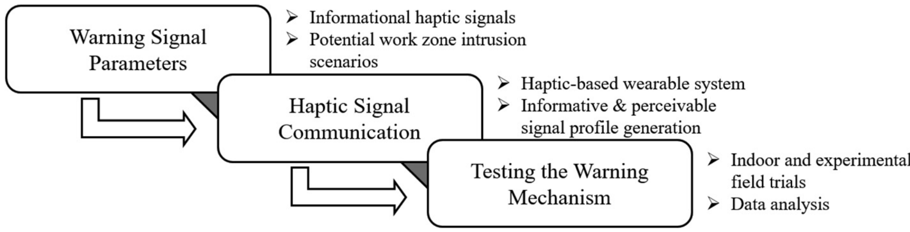


Fig. 2. Methodology.

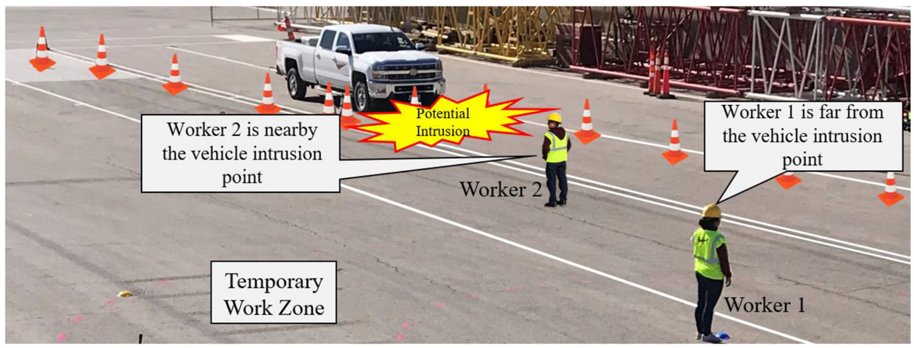


Fig. 3. Work zone intrusion scenario.

example of a potential intrusion-prone work zone with two workers. Based on the location of intrusion point and worker locations, the vehicle intrusion has different impacts on the two workers. For instance, worker 2 is nearby the path followed by the intruding vehicle; however, there is a significant margin of safety between the intrusion path and worker 1. Similarly, the intrusion point is far behind worker 1 and is nearby worker 2, making the situation riskier for worker 2 due to closer proximity to the intrusion point. This scenario indicates that worker 2 is comparatively at higher risk than worker 1. Further, worker 1 is facing towards the incoming vehicle while worker 2 is facing away from it. Considering this situation, worker 1 can visually perceive the situation and take preventive action while worker 2 cannot. As such, a general intrusion warning is inadequate for workers to perceive the situation. Thus, to overcome this, it is required that workers are warned with additional details to intuitively perceive the scenario and take preventive action.

Based on the above discussion, the potential risk of any intrusion is related to two factors: (a) the vehicle break-in point; and (b) the worker location from the intruding vehicle (e.g., along the line of intrusion or how close the worker is to the intrusion point). These two sets of information can be used to define an intrusion scenario to workers. Knowing the vehicle break-in location helps workers to locate the potential intrusion point. To simplify the communication of intrusion location, the authors divided the work zone stretch into different zones along the direction of moving vehicles. Fig. 4 illustrates such a virtual scenario with four zones to locate potential intrusion location within the work zone. Depending on the site layout, the zone size and label may change.

However, it is not practical to communicate workers' location, as such communication would require them to infer their intrusion risk level depending on the vehicle break-in location, preventing them from reacting instantly. As discussed, the closer the vehicle break-in location to the worker's position, the higher the risk level for the worker and vice-versa; that is, the risk level is a function of the worker's location and the vehicle break-in location (specifically the longitudinal and transverse distances between these two locations). Thus, the authors incorporated the risk level as a communication parameter to warn workers of potential intrusions. In this study, the authors categorized the risk levels into low, moderate, and high-risk levels, depending on the closeness of the break-in point to the worker's position.

Therefore, the communicated warning signals incorporate the intrusion zone and the risk level information to warn workers, so that they are able to perceive the potential situation, without the need to look around to gather additional information, and take the appropriate actions. The delivery of such informational warning signals in this study is an advantage over existing audio/visual warnings that require workers to use their vision/hearing capabilities before taking preventive actions. However, identifying specific hazard information is not within the scope of this study, but systems for hazard identification are readily available, based on the

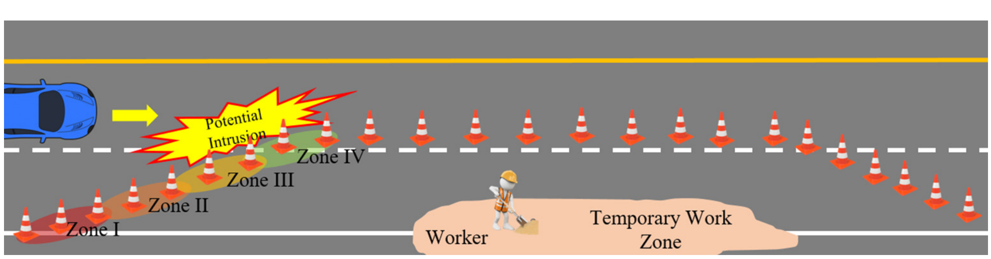


Fig. 4. Virtual scenario illustrating different potential intrusion zones.

literature. Accordingly, the further steps in this study are designed based on the assumption that hazard information is readily available from existing intrusion detection systems and/or other proximity sensing systems. Thus, for our purposes, the vehicle intrusions are manually detected during the experimental field trials to test the haptic warning mechanism.

5.2. Haptic signal communication

This study uses haptic signals to communicate potential intrusion-related hazard information. Therefore, the intended information must be well-transmitted with the haptic signals, so that the signal receivers (i.e., workers) require minimum effort to become aware of the situation and can take safety measures immediately when they receive the signals. Accordingly, the haptic signal communication design is an essential component of this warning mechanism. For this purpose, the researchers took advantage of the different number of motors available on the prototype wearable system (Fig. 1). Different motors on the system were assigned to represent different intrusion zones, such that the vibration of a particular motor would represent specific information. Such motor indexing was done to enable easy information perception through the haptic signals. Once the motors are indexed, different vibration pattern sequences are utilized for communicating intended intrusion information.

While indexing the motors, it is important to ensure that the users are able to learn the haptic signals quickly. Based on the warning signal parameters identified to indicate vehicle intrusion, the haptic signals should be able to communicate four intrusion zones. Out of 10 motors arranged in a 4–2-4 pattern, the eight motors on the top and bottom rows were indexed to represent vehicle break-in zones, as shown in Fig. 5. The paired motors 1–2, 3–4, 7–8, and 9–10 were indexed to represent Zone I, Zone II, Zone III, and Zone IV intrusions, respectively. On vibration of those paired motors, the worker will perceive the potential scenario and identify the intrusion zone, as illustrated in Fig. 6.

For indicating the risk level, the location-indexed motors were activated for different counts, corresponding to different risk levels. The motors were activated three times for high-risk levels, meaning that they vibrate three times if the intrusion scenario presents a high worker risk. Similarly, for moderate and low-risk levels, the motors were activated twice or once, respectively. The break-in location is communicated by the paired vibrating motors used, while the vibration pattern identifies the risk level, as shown in Table 1. Accordingly, haptic signal profiles were created for all intrusion scenarios to incorporate four break-in zones at three different risk levels. The two motors on the second row (i.e., motors 5 and 6) were not used in this study. However, these motors may be engaged to incorporate additional information deemed necessary for workers to perceive a situation. Further, it should be noted that the signal communication may be modified depending on the number of intrusion zones and risk levels to meet the work zone requirement.

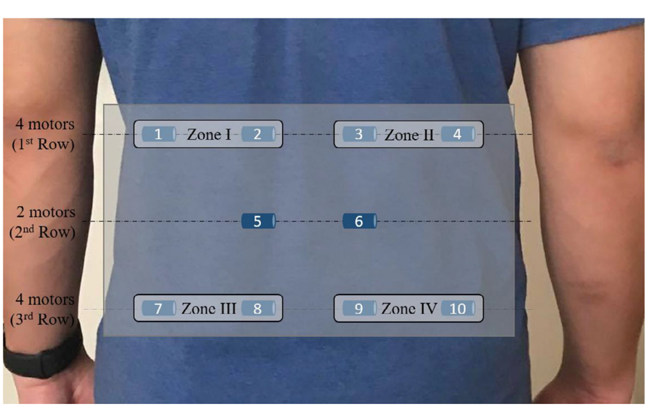


Fig. 5. Vibration motor indexing on the wearable system.

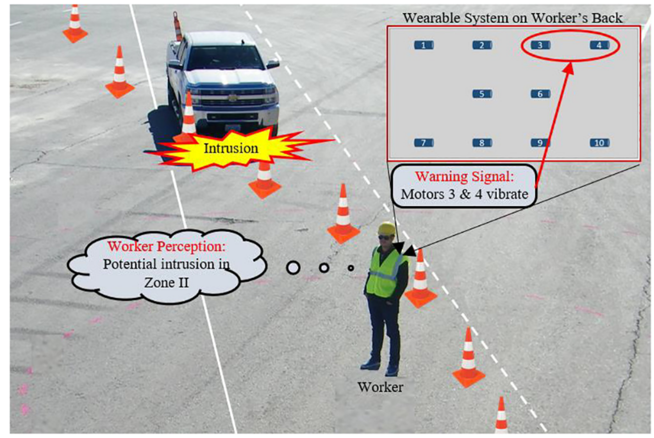


Fig. 6. Warning and perception of vehicle intrusion.

Table 1
Haptic signal profiles for vehicle intrusions.

Vibrating Motors		Haptic Signal Profiles	
Break-in Zones	Assigned Motors	Risk Levels	Vibration Pattern
I	Motors 1 & 2	High (3)	Assigned motors vibrate three times
II	Motors 3 & 4		
III	Motors 7 & 8	Moderate (2)	Assigned motors vibrate two times
IV	Motors 9 & 10	Low (1)	Assigned motors vibrate one time

5.3. Testing the warning mechanism

After determining the haptic signal profiles to communicate different vehicle intrusion scenarios, the research team proceeded with testing the warning mechanism. For evaluating the warning mechanism, the authors selected five test participants, all of whom were able to sense haptic signals on their backs; however, none of the participants were actual construction workers. As the warning mechanism is based on a new vibration-based language, the participants needed to be aware of the wearable system's components and its working mechanism, as well as the different haptic signal profiles created to represent different intrusion scenarios. Thus, all participants were trained in an indoor environment to become familiar with the communication system and recognize haptic signal profiles for different scenarios until they could identify at least 95% of the signals.

After training the participants, the authors used indoor trail sessions to ensure that they were familiar with the haptic signals and capable of recognizing information corresponding to different signals. The indoor trial sessions were conducted for five successive days and did not involve any vehicles. During each session, participants were equipped with the wearable system, and each participant was transmitted 50 haptic signals. Therefore, over the five days of training, 250 signals were transmitted to each participant. For evaluation purposes, the authors recorded the information perceived by the participants for each of the communicated warning signals.

After the indoor trial sessions, a field trial was conducted in partnership with a local general contractor. Fig. 7 shows the field test setup to resemble the intrusion of an outside vehicle into a work zone. The road work zone was marked with traffic cones, and a pick-up truck was deployed as the intruding vehicle. This field test was intended to evaluate the performance of the haptic signal-based warning mechanism to alert workers in an environment where their vision and hearing capabilities were impeded. Thus, to simulate such an environment, the participants were additionally equipped with eye covers and earplugs to obstruct their vision and hearing capabilities. Such a test setup ensured that the participants were completely dependent on the haptic signals to perceive the vehicle intrusion situation and take preventative actions.

The field trials involved one participant at a time inside the work zone, and the vehicle intrusion was manually measured under significant margins of safety, meaning that the information related to the intrusion was manually set to warn the participant based on the position of the intruding vehicle. However, on actual construction sites, potential intrusions are detected by deploying available intrusion detection systems, and the risk levels are identified based on the location information obtained using other proximity sensors. Then the participants were warned of the intruding vehicle with the haptic signals. Finally, the authors recorded the information on the vehicle break-in zone and the risk level, as perceived by the participants for each warning signal.

6. System evaluation results

In the indoor trial sessions, a total of 1,250 haptic signals were communicated to the participants over the five successive days, and the intrusion information perceived by participants for each signal was recorded. The perceived information was then compared with the actual vehicle break-in zone and risk level associated with the corresponding warning signal to determine each participant's intrusion perception accuracy. Table 2 summarizes the results of the indoor trial sessions for each participant. The results show that the participants were able to correctly identify most of the signals, with approximately 98% average accuracy. Such participant performance in the trial sessions indicates that the haptic signals are easy to learn, and that these signals can effectively transmit specific information.

After the indoor trial sessions, field trials were conducted with all participants. During the field trials, each participant received 200 haptic signals for different intrusion scenarios, with a total of 1,000 signals for five participants, and they were required to identify the communicated information corresponding to each warning signal. Table 3 summarizes the field trial results for all test participants. The results show that two of the five participants were able to identify the transmitted signals 100%, and the minimum accuracy was 95%. Overall, there were 26 incorrect signal identifications out of 1,000, giving an average accuracy of 97.40% for all test participants. Participants correctly identified at least one piece of information, and both vehicle break-in zone and risk level equally contributed to the incorrect signal identifications, at 13 each.

Fig. 8 shows the bar plots for accurate identification of specific information from the communicated haptic signals for each participant, with intrusion zone and risk level reported separately. This plot shows that all participants accurately identified more than 96% of communicated information, with an overall accuracy of 98.70%.

Fig. 9(a) and 9(b) show the assessment of intrusion zone and risk level information, respectively, as identified by all participants. Fig. 9(a) shows that out of 13 incorrectly identified intrusion zones, more than half were Zone I being identified as Zone II. Two of the 13 cases incorrectly identified Zone II as Zone I. Similarly, there were two cases each for Zone IV being incorrectly identified as Zone II and Zone III. In the case of risk level (see Fig. 9(b)), most incorrect identifications were for Risk Level 1 (i.e., low-risk level), being identified as Risk Level 2 (i.e., moderate-risk level). There were two instances each for Risk Level 2 (i.e., moderate-risk level) being incorrectly identified as Risk Level 1 (i.e., low-risk level), and Risk Level 3 (i.e., high-risk level) being identified as Risk Level 2 (i.e., moderate-risk level). Similarly, there was an instance of moderate-risk level being identified as high-risk level. Fig. 10(a), 10(b), and 10(c) show the incorrect identifications by participants P1, P2, and P4, respectively. Based on these figures, participants P1, P2, and P4 had three, four, and six incorrect break-in zone identifications, respectively. Similarly, among the three participants, participant P1 incorrectly identified 7 out of 13 risk levels, and participants P2 and P4 had two and four misperceptions, respectively. The incorrect signal identifications show the participants' tendency to incorrectly identify transmitted lower-level signals as higher-level signals, creating more caution about the potential hazard. Thus, regardless of the correctness of details perceived in these 26 signals (out of 1000), the perceived information could warn the participants of potential intrusion risks.

For statistical evaluation of overall test results (Table 3), along with results for specific information (Fig. 8) for all 1,000 haptic signals, 95% confidence interval values were computed. Table 4 summarizes the overall accuracy, along with the lower and upper limits of the 95% confidence interval for the overall test and specific information. The confidence limit values indicate field test result validity, and the authors can conclude that the haptic signals used in this study are well perceived by the participants. This result suggests that the haptic-based warning mechanism is able to enhance the intrusion hazard perception capabilities of workers. Thus, the

(a) View 1 (b) View 2

Fig. 7. Field trial to transmit potential intrusion information.

Table 2
Indoor trial session results.

Test Participants	No. of Tests	Intrusion Perception Accuracy (%)					Average Accuracy (%)
		Day 1	Day 2	Day 3	Day 4	Day 5	
P1	50	98	98	100	98	100	98.80
P2	50	98	100	100	98	96	98.40
P3	50	98	98	98	100	98	98.40
P4	50	100	96	98	98	96	97.60
P5	50	100	100	98	98	100	99.20

Table 3
Field trial results for vehicle intrusion warnings.

Participants	No. of Signals Communicated	No. of Inaccurate Identification	Signal Identification Accuracy (%)
P1	200	10	95.00
P2	200	6	97.00
P3	200	0	100.00
P4	200	10	95.00
P5	200	0	100.00
Overall Accuracy			**97.40**

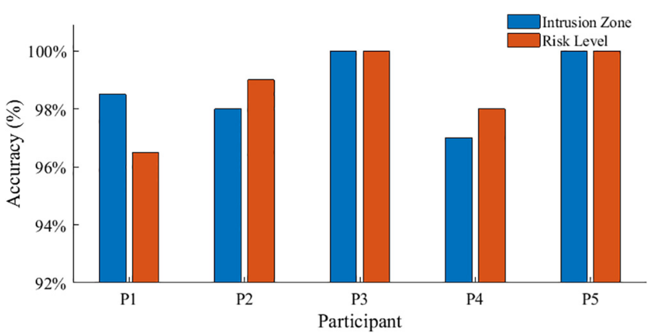


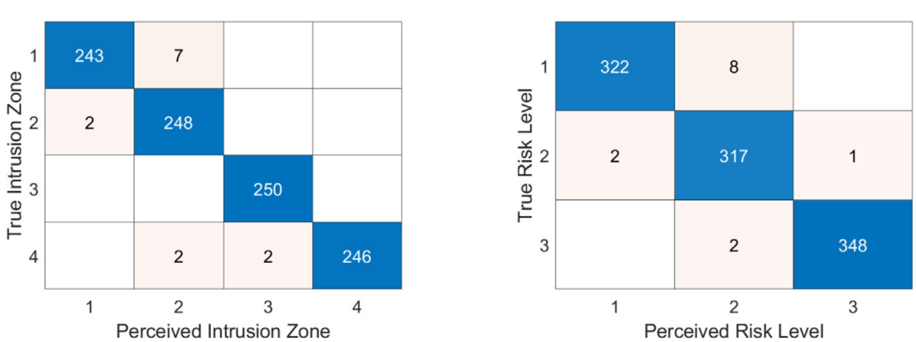
Fig. 8. Participant accuracies for specific information perception.

adoption of this warning mechanism has the potential to protect workers from intrusion hazards.

7. Discussion

This study used a new language based on haptic signals to communicate specific vehicle intrusion information in temporary work zones. The results demonstrate that the haptic signals are suitable to communicate informational signals, and the participants perceived such signals well. It should be noted that past studies have adopted vibration-based warning signals; however, the signals were general (not informative), and despite receiving them, workers had to rely on their vision and hearing to perceive the hazard scenario. However, the haptic-based mechanism in this study is designed to communicate signals containing information associated with the potential risk (e.g., break-in point and risk level), and these signals are communicated in less than a second. Thus, correctly perceiving informative warning signals communicated in a short duration enables workers to instantly take preventive measures and avoid potential fatalities/injuries due to intruding vehicles.

This study specifically categorized four intrusion zones and three risk levels. Accordingly, the haptic signals were composed with vibrations of motors—assigned to communicate specific intrusion zones—for different counts to indicate different risk levels (see Table 1). The categories for intrusion zones and risk levels may be modified to match the work zone requirements, and the haptic signals can be composed accordingly. During the field trials, the participants incorrectly perceived some of the signals (i.e., 26 out of 1000 signals < 3%). However, the participants were able to correctly identify at least one piece of information from the communicated signals, and thus perceive some level of danger even from the incorrectly perceived information as well. Further, the incorrect identifications show a greater tendency towards identifying transmitted lower-level signals incorrectly as higher-level signals, making the participants more cautious of the intrusion situation upon perceiving any hazard. For example, most of the incorrect risk levels were lower-risk level signals being identified as higher-risk levels (i.e., 9 out of 13 risk levels) and most of the incorrect intrusion zones being incorrectly identified as Zones I and II that were located closer to the temporary work zone (i.e., 11 out of 13). Thus, such types of incorrect identifications may have a lower impact on safety considerations. However, they may be prevented by adjusting the intensity/duration/interval of haptic signals to improve the signal distinguishability or increasing the training period for the users. Note that the participants in this study were trained until they could identify at least 95% of the sig-



(a) Intrusion Zone (b) Risk Level

Fig. 9. Incorrect identification of all transmitted signals.

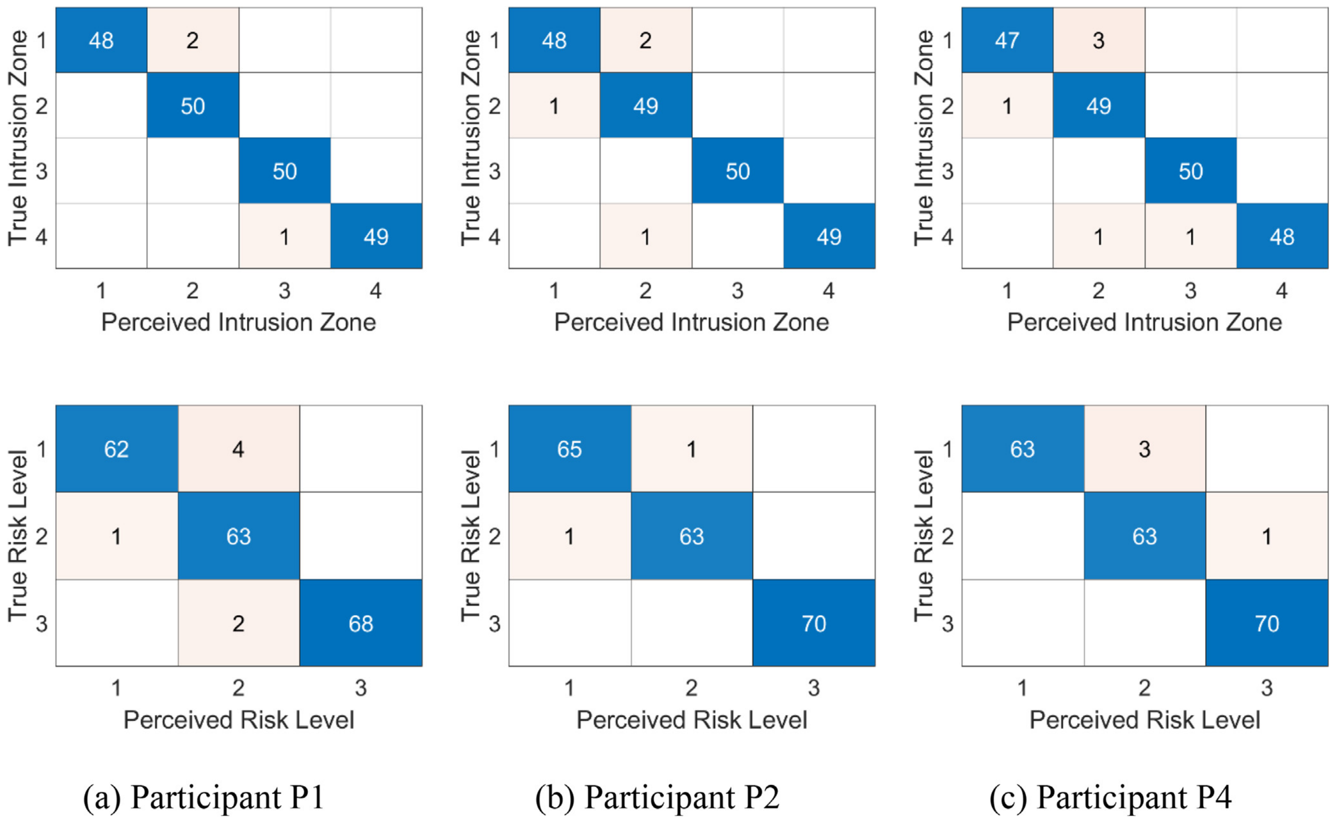


Fig. 10. Incorrect identifications by each participant.

Table 4
95% confidence interval results.

	Accuracy	95 % Confidence Limits	
		Lower Limit	Upper Limit
Overall Test	0.9740	0.9641	0.9839
Intrusion Zone	0.9870	0.9800	0.9940
Risk Level	0.9870	0.9800	0.9940

nals, and their average accuracy was approximately 97% during the field trials.

Further, the test results highlight that the prototype wearable system has an effective communication mechanism that users can easily learn. The warning mechanism is fully capable of communicating intended intrusion information to users in all indoor and field test scenarios conducted in a controlled environment. It should be noted that the warning signal profiles are created by combining haptic signal units that were easily perceivable on the backs based on a past study (Cho & Park, 2018). Accordingly, the intrusion signal perception is not impacted by the workers' movement while they are working or moving around. Therefore, this warning mechanism can be reliably used to alert occupied workers in work zones.

8. Conclusion

The need to work in close proximity with moving vehicles in temporary road construction sites makes such work zones unsafe. Every year, temporary work zones have a large number of fatalities and injuries, mostly resulting from outside vehicle intrusions into the work zones. These reported intrusion accidents demonstrate that conventional safety measures are insufficient to ensure worker safety. Thus, several intrusion detection and warning systems are available; however, workers' perception of audio/visual-based warning signals used in most systems is impacted by limited sensing capabilities in the temporary work zones. As a result, those warning signals are not effective for intrusion hazard safety. Although vibratory warning signals adopted in some intrusion detection systems overcome the limitation of audio/visual warnings, the signals are limited to alerting workers, without specific intrusion-related information. Therefore, workers cannot entirely rely on these warning systems to avoid intrusion accidents.

To address the issue with intrusion warning mechanisms, this study focused on enhancing intrusion hazard management by improving a new information delivery system, rather than detecting intrusions. For this purpose, the authors proposed a haptic-based warning mechanism to transmit informational warnings to workers. The authors created haptic-based intrusion warning signals to represent different intrusion scenarios by incorporating vehicle intrusion zones and workers' risk levels due to the intrusions. Such informative signals 'explain' intrusion scenarios to workers without requiring them to look around to perceive the situation. However, it is necessary to pre-train workers to learn the information provided within different haptic signals before this system can be used to warn them. Accordingly, all participants were trained, and then the authors conducted controlled field trials to demonstrate the effectiveness of the haptic warning signals in communicating intrusion hazards. The trial results demonstrated that informative haptic signals are well communicated with the prototype wearable system. Therefore, work zone safety management systems can be significantly improved by integrating haptic warning mechanisms to communicate potential vehicle intrusions.

It should be noted that the presented work is limited to intrusion warning mechanism research, without fully integrating all aspects of a comprehensive intrusion detection and warning system. Future studies will thus focus on devising such an integrated system by combining an intrusion detection system with the haptic warning system (i.e., two independent systems) to extract and transmit the required information using this haptic mechanism, and will conduct more comprehensive tests. Such an integrated system would ensure informational signal transmission to workers, enabling them to make correct judgments for preventive actions. For this purpose, the detection system should be capable of identifying workers' locations and potential intrusion points, so that the risk levels can be identified for individual workers. As such, the employed detection system may be a combination of technologies, such as proximity sensors to detect worker locations and intrusion points, along with other vision-based approaches, as well as intrusion detection systems to detect vehicle intrusions. On integration with a detection system, the prototype wearable system can be reliably employed on temporary work zones to prevent worker injuries and fatalities resulting from intrusion accidents.

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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