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Connected Simulation for Work Zone Safety Applications

Vahid Balali

CSUTC California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

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16. Abstract

Every year, over 60,000 work zone crashes are reported in the United States (FHWA 2016). Such work zone crashes have resulted in over 4,400 fatal and 200,000 non-fatal injuries in the last 5 years (FHWA 2016, BLS 2014). Apart from the physical and emotional trauma, the annual cost of these injuries exceeds $4 million-representing significant wasted resources. To improve work zone safety, this research developed a system architecture for unveiling high-risk behavioral patterns among highway workers, equipment operators, and drivers within dynamic highway work zones. This research implemented the use of a connected virtual environment, which is an immersive hyper-realistic and virtual environment where multiple agents (e.g. workers, drivers, and equipment handlers) control independent simulators but experience an interactive and shared experience. For this project, the team conducted an in-depth analysis of accident investigation, simulated accident scenarios, and tested diverse interventions to prevent high-risk behavior. Overall, the research improved understanding of behavioral patterns that lead to injuries and fatalities of highway workers in order to better protect them in high-risk work environments. As part of making transportation smarter, this project contributes to smart behavioral safety analysis.

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Executive Summary

Every year, over 60,000 work zone crashes are reported in the United States (FHWA 2016). Such work zone crashes have resulted in over 4,400 fatal and 200,000 non-fatal injuries in the last five years (FHWA 2016, BLS 2014). Apart from the physical and emotional trauma, the annual cost of these injuries exceeds $4 million, representing significant wasted resources.

To improve work zone safety, significant research efforts and safety management practices have been developed in the last decades. However, unacceptable injury rates continue to be a common phenomenon across the U.S. Given the predicted increase in the number of work zones to address the nation's aging infrastructure, work zone safety is of significant importance and will remain important in the coming years.

Because improvements in work zone safety have not been detected in recent years, it is important that novel research be conducted that can possibly yield breakthrough results and safety innovations. To that end, this research aims to (1) unveil high-risk behavioral and environmental precursors that lead to accidents and injuries in work zones, (2) identify effective interventions to reduce high-risk behavioral patterns in work zones, and (3) use proven training methods to train drivers, highway workers, and equipment operators on safe work zone practices for injury prevention.

A connected virtual environment where multiple operators experience a unified virtual experience is developed and tested to efficiently and safely conduct this study. Specifically, in the simulation, relevant operators including drivers, highway workers, and equipment operators operate separate simulator units but are connected through a unified virtual experience. Unlike traditional virtual driving simulators, the connected environment shall be capable of capturing interactions amongst the operators to model a more realistic active work zone. Such an environment shall be capable of capturing the dynamic nature of work zones where individual operators may make decisions and adopt behaviors of their choice. On the other hand, like traditional simulators, the connected virtual environment is also able to simulate standardized scenarios to capture the behavioral patterns of specific operators under controlled conditions. It is expected that such a connected virtual environment will enable an understanding of more complex behavioral patterns within work zones and provide a testbed to study a phenomenon that remains unexamined in previous efforts.

The research effort is conducted in three sequential phases. The first phase focuses on conducting an in-depth analysis of previous work zone injury reports identifying common causes of work zone crashes and injuries. Factors of interest include human errors, work zone design characteristics, environmental conditions, road alignment, vehicle types, lighting conditions, crash location, types of traffic channelizers, inattention, distraction, speed, risk-taking behavior, and other factors.

Following the identification of the causes of work zone crashes and injuries from the first phase, the second phase focuses on setting up the connected virtual environment to model the causal factors identified. Relevant scenarios that are of interest based on the input from the expert panel are also simulated. The virtual environment is capable of simulating the causal factors, conditions, and interactions among the operators. In addition, technology-driven innovations to capture behavior and provide warning signs to drivers are evaluated through experimental efforts. The tested technology will include:

- Vision-based activity recognition sensors to capture the reaction of workers, drivers, and other operators in work zones;
- Eye-tracking technology to capture attention allocation (i.e., what stimuli receive visual attention) for each of the operators; and
- Computer-vision-based asset recognition to provide visual and auditory warnings to drivers (e.g., in-vehicle warning) before entry into work zones.

After the connected virtual environment is developed, several research hypotheses were developed and tested based on findings from the first phase.

After various iterations and trials with drivers and highway workers, the results of the hypothesis and the behavioral patterns were recorded. Based on the findings, conditions and behavioral patterns that are likely to cause work zone accidents or injuries were identified. Using these results, training will be provided to highway workers and drivers to reduce risky behavior and improve safety within highway work zones. Specifically, personalized training individualized in accordance with the performance and behavior of each operator will be provided, and the efficacy of the intervention will be tested using experimental studies across many settings.

1. Introduction

One of the main reasons for traffic congestion is maintenance activities occurring along the roadways. Road maintenance activities, such as pavement replacement or adding lanes, occur in road segments commonly referred to as “work zones.” According to the Federal Highway Administration (FHWA), the top three causes of non-recurring delays are incidents (25% of congestion), adverse weather conditions (15% of congestion), and work zones (10% of congestion) (“FHWA Operations - Reducing Non-Recurring Congestion,” n.d.). In order to mitigate the effect of work zones on traffic conditions, an appropriate traffic management plan with an accurate traffic estimation model is required. This could help drivers with their route choice and also inform transportation agencies’ resource allocation.

Previous studies have investigated the effect of work zones’ features on traffic conditions and road capacity. The features could be categorized into different groups, such as work zone configuration, roadway conditions, work activity characteristics, and environmental conditions. The simplicity of implementation, few data required, and no need for specialized software are some of the reasons that many practitioners prefer analytical approaches. However, their inability to capture higher-order relationships between work zone capacity and features is one of their drawbacks. In order to address the disadvantages of prior methods and also increase the precision of traffic estimation models, a novel and automated approach is required. Machine learning is one possible way of finding traffic patterns and evaluating the effect of work zones on traffic. Machine learning algorithms, such as decision tree, ensemble learning, Support Vector Machine (SVM), and Artificial Neural Network (ANN), have been widely used for traffic prediction. This study introduces a deep neural network model that could estimate the traffic flow within state work zones with better accuracy compared to the existing models.

Departments of transportation (DOTs) continuously collect and record data regarding road maintenance projects implemented across the state. These project records and data extracted from traffic sensors provide researchers with an opportunity to investigate the effects of work zones on traffic characteristics. However, due to the lack of resources in many areas and the high cost of traffic sensors, this study develops a neural network model to estimate the work zone traffic volume in areas without any traffic sensors.

2. Background Study

Due to work zones' proximity to high-speed traffic, highway construction safety has always been a great concern. Every year, over 60,000 work zone crashes are reported in the United States (FHWA 2021). Such work zone crashes have resulted in over 4,400 fatal and 200,000 non-fatal injuries in the last five years (Bureau of Labor Statistics 2014). Further, 1,571 deaths related to highway construction work were reported from 2003 to 2015 (Center for Disease and Control 2016). The Federal Highway Administration (FHWA) reported that a work zone fatality occurs every 8.7 hours, and an injury associated with highway construction work zones occurs every 9 minutes. Apart from the physical and psychological trauma involved, the annual cost of these injuries exceeds $4 million, representing significant wasted resources.

Workers and equipment at worksites are often in motion and can come into proximity to each other (Teizer et al. 2010a). As a result, in recent years, several studies have aimed to improve safety conditions for highway construction workers, many of which have focused on integrating innovative technologies to reduce safety risks at highway work zones. For example, Work Zone Intrusion Alarm Technology (WZIAT) was first introduced in 1995 to evaluate the Strategic Highway Research Program (SHRP) work zone safety devices (Agent and Hibbs 1996). Several WZIAT products are currently available on the market (Nnaji et al. 2018). However, WZIAT products are generally used to detect intrusions from traffic outside the work zone, ignoring collisions with equipment operating within the work zone.

To improve work zone safety, significant research efforts and safety management practices have been developed in recent decades. Many researchers have focused on reducing the risks of a collision between construction equipment and workers on foot in work zones. Location sensing is an essential part of the presented solutions. Several sensing technologies are widely applied, including Global Positioning System (GPS) (Oloufa, Ikeda, and Oda 2003), Radio-Frequency IDentification (RFID), Radio Frequency (Teizer et al. 2010a; Fullerton, Allread, and Teizer 2009), radar (Ruff 2006), and Ultra Wide Band (UWB) (Cheng et al. 2011; Hwang 2012). Blind spot measurements of heavy equipment are used in another approach to create threat zones for equipment (Teizer et al. 2010b; Teizer and Cheng 2015; Ray and Teizer 2013).

While vehicle crash detection systems have been developed in previous research (Sharma, Reddy, and Karthik 2016; Yee and Lau 2018), real-time pre-crash detection and prevention remain an important topic related to traffic safety at highway work zones. The focus of previous research in the transportation domain has been on vehicle conditions where relative position and driving context are used to detect a potential crash and provide a warning to drivers (Watta, Zhang, and Murphey 2020). However, a holistic work zone safety approach must take all work zone actors—workers, equipment operators, and passing traffic—into account.

Unacceptable injury rates continue to be a common phenomenon across the U.S. (Moghaddam et al. 2020, 2021). Given the predicted increase in the number of work zones to address California's aging infrastructure needs, work zone safety remains very important. In order to improve work zone safety, it is necessary to conduct research that can possibly yield breakthrough results and safety innovations. In recent years, the study of human behavior within a simulator environment has been a popular method among safety scientists and road designers. The simulator environment provides a means for researchers to study the impact of work zones without exposing the participants and other users of the road to potentially unsafe situations. Studying driver behavior in a controlled environment also offers better experimental control than field studies.

3. Data Collection and Setup

The objective of this research is to design and develop a system architecture of a hyper-realistic and connected virtual environment that will serve as a testbed for research efforts focusing on work zone safety applications. This research aims to:

- Unveil high-risk behavioral and environmental precursors that lead to accidents and injuries in work zones;

- Design a system architecture of a connected virtual environment; and

- Design high-risk driving simulator scenarios for the verification which is the of future direction of the developed system architecture.

An in-depth analysis of accident investigation reports in work zones is conducted to identify common causes of work zone injuries. Then, the most frequently observed accident scenarios are simulated within a virtual environment where the behaviors of independent participants are captured and analyzed. Based on the observed characteristics, a system architecture of diverse interventions including engineering controls (e.g., safer work zone designs, and traffic control systems) and administrative methods (e.g., planning, training, and the use of protective equipment) is proposed and designed for future evaluation of its effectiveness in preventing high-risk behavior. The proposed framework is developed and implemented in this research and allows the exploratory study to serve as a proof of concept to simulate work zone characteristics to evaluate work zone behavior, test intervention effectiveness, and provide a safe and realistic environment for effective training.

To efficiently and safely conduct this research, a system architecture of a connected virtual environment, where multiple agents experience a unified virtual experience, is designed and developed. In this framework specifically, relevant operators including drivers, highway workers, and equipment operators operate separate simulators but are connected through a unified virtual environment. The proposed connected environment can capture the interactions amongst the operators to model a more realistic active work zone compared to traditional virtual driving simulators. The designed environment shall be capable of capturing the dynamic nature of the work zone where individual operators may make decisions and adopt behaviors of their choice. On the other hand, like traditional simulators, the connected virtual environment is able to simulate standardized scenarios to capture the behavioral patterns of specific operators under controlled conditions. It is expected that such a connected virtual environment will enable an understanding of more complex behavioral patterns within work zones and provide a testbed to study an area that has remained unexamined in previous efforts.

The research effort will be conducted in three sequential phases as follows:

1. The first phase focuses on conducting an in-depth analysis of previous work zone injury reports identifying common causes of work zone crashes and injuries. Factors of interest include human errors, work zone design characteristics, environmental conditions, road alignment, vehicle types, lighting conditions, crash location, types of traffic channelizers, inattention, distraction, speed, risk-taking behavior, and so on. The findings are supplemented with a thorough review of previous research and insights from an expert panel of Caltrans professionals.

2. Following the identification of the causes of work zone crashes and injuries from the first phase, the second phase focuses on designing and developing the connected virtual environment architecture for modeling scenarios based on the causal factors identified. Relevant scenarios that are of interest based on the input from the expert panel are defined. The system architecture of the proposed virtual environment includes the capability of simulating the causal factors, conditions, and interactions among the operators. In addition, technology-driven innovations to capture behavior are evaluated (e.g., vision-based activity recognition sensors, eye-tracking technology, and computer-vision-based roadway asset recognition). The expert panel also advises the research team and provides input throughout the research process to ensure the relevance of the research to real-world work zone safety challenges. This phase of the project leads to the first connected virtual environment for work zone safety applications.

3. After the architecture of the connected virtual environment is designed, several research hypotheses are defined based on findings from the first phase for future tests on the developed system in this research. Examples of potential hypotheses are as follows:

    - When a work zone flagger is present and spotted by the driver (captured using an eye tracker), lower driving speeds will be observed throughout the work zone compared to when a flagger is not present.

    - Lower driving speeds will be observed when the channelized roadway is narrower as opposed to when it is wider.

    - Workers allocate more attention to vehicular traffic (captured using an eye tracker) when a discontinuous barrier system is used to ensure their safety as opposed to a continuous barrier system. (An example of a discontinuous barrier system is traffic cones, while an example of a continuous system is a concrete-based barrier.)

    - When temporary traffic channelizing in work zones (i.e., using traffic cones) contradicts the original pavement markings (which remain in the work zone), drivers experience more confusion and driving difficulty.

- Distracted drivers exhibit a lower level of vehicular control and higher levels of lane deviations.

- Higher driver speeds are observed when active construction within work zones is not visible.

4. Analysis

To identify potential hazardous proximities, it is necessary to define a threat zone with reasonable limits for all actors including workers, construction equipment, and vehicles. Since highway work zones have a higher collision risk than other types of construction sites, a more detailed threat zone map needs to be developed for hazard identification. Alert and warning zones for equipment are counted for all actors: i.e., workers, equipment operators, or connected automated vehicles (CAVs). The threat zone introduced in this project consists of two zones: alert area and warning area. The alert area in this research is an inherently unsafe area around the actor. It is a fixed area, and if it is invaded, the actor can be harmed due to extreme proximity. A warning area is the area having a danger level lower than that of the alert area but still involving potential risk, and it is thus considered hazardous. The warning area is defined by the prediction of the actor's location in the near future depending on their speed and current movement pattern. As such, the warning area helps predict potential hazards and prevent them before they reach to the alert zone (where a crash is very likely). For workers on foot, 1 meter and 1.5 meters are used as diameters of the primary alert area (red area) and the warning area (white area), respectively, as shown in Figure 1(a).

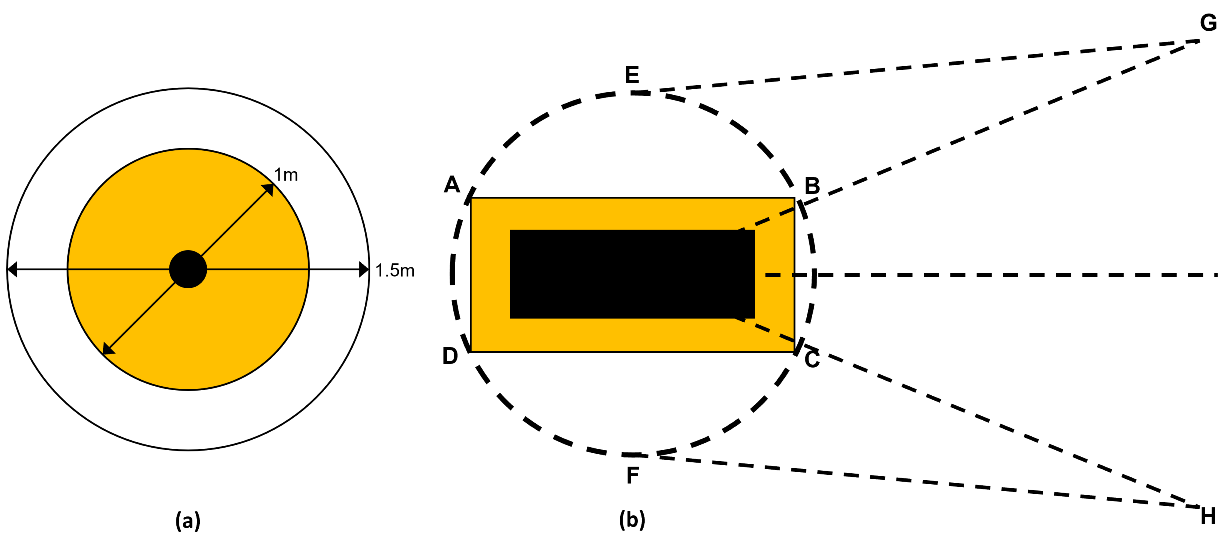

Figure 1. Proposed Threat Zones for (a) Worker on Foot and (b) Passing CAV

They are adopted based on an average minimum required distance between workers with different work operations and each actor's expected stopping distance. The dynamic threat zones of equipment and vehicles are designed by researchers according to their movements and directions. Key parameters for threat zone include velocity, equipment or vehicle dimensions, and friction coefficient of the road surface.

Construction equipment and vehicles share roughly the same alert and warning area configuration, with a few differences. For vehicles, the alert area is assumed to be a rectangle extending 1 meter in all directions. To determine the warning area, a circle that crosses all four vertexes of the alert area is created and extended as presented in Figure 1(b). Subsequently, the threat distance is determined by computing the stopping distance of the vehicle/equipment, considering the time required for the driver's reaction and the deceleration time once the driver has reacted; 0.8 is used as a typical value of friction coefficient in this research. Considering a single lane change, a 6-degree steering angle is adopted to calculate the expanded warning area. Heavy equipment such as dump trucks could frequently get involved in fatalities resulting from poor visibility (Hinze and Teizer 2011). Therefore, the need for extra alert distance when moving backwards is taken into account. While steering angle is not necessarily considered for equipment, the moving direction can be two-way. Construction equipment frequently moves forwards and backwards in highway work zones. In this case, the warning area is only applied along the direction of motion to reduce the false alarm rate by limiting unnecessary side-predicted areas in the near future. While moving backwards, the field of view would decrease, and thus a wider warning area is considered (see Figure 2). After identifying the threat zones for workers on foot, vehicles, and equipment, hazard identification is performed. When two or more threat areas overlap, it is an indicator of potential collisions, depending on the direction of movement. The type of equipment and its activity in the work zone are additional factors that may be used for determining the threat zones. However, this would require a detailed analysis of each piece of equipment, which is out of the scope of this research.

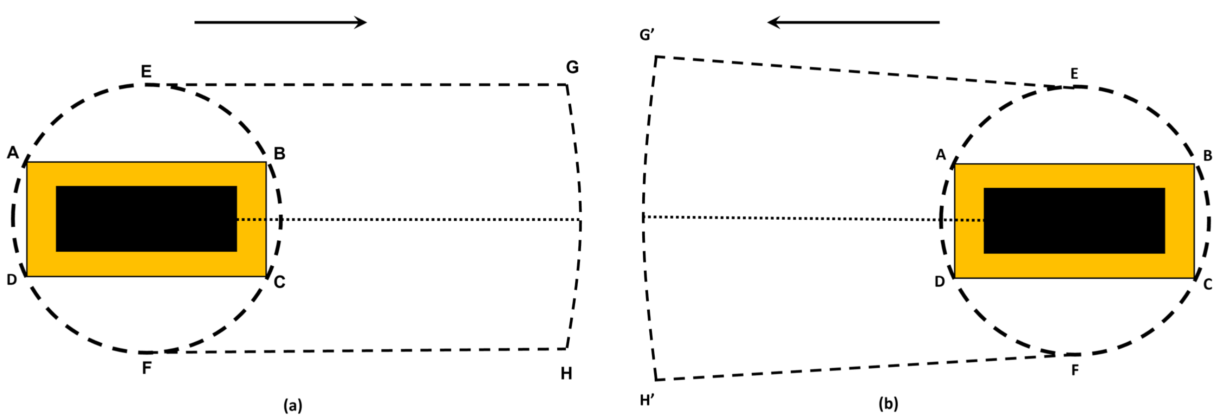

Figure 2. Threat Zones for Equipment Moving (a) Forwards, (b) Backwards

Vehicles are subject to centripetal force when traveling on a curve, especially at high speeds, which may lead to serious rollover accidents. Thus, curved road sections are more dangerous than straight sections. As a result, curved sections require larger warning areas for workers on foot to ensure their safety. The distance to the work zone border is also taken into account in the warning area determination. The closer workers stand to the work zone border, the higher is the risk of being exposed to potential collisions. The distance to the border is partitioned and an extra warning area is considered to increase the safety level. The U.S. Interstate Highway System generally employs a 12-foot standard lane width. In this research, a 3-foot width is used as a unit for partitioning. Hence, four separate zones are created in a single lane. Zones closer to the work zone border require larger warning areas with an assumed increase of 0.5 meters of diameter between two adjacent zones. As such, a warning area with a diameter of 1.5 meters is determined for workers positioned in the farthest zone (zone 4). As the worker approaches the border, the warning area diameter linearly increases by 0.5 meters as the worker moves into each subsequent partitioned area (Figure 3). For the curved section, due to the higher risk caused by centripetal force on vehicles, the area to the right of cone 2 (as shown in Figure 4, when a vehicle is departing the curve) could be more dangerous. As such, 0.5 meters is added to the diameter of warning areas after workers pass cone 2 to compensate for the higher risk as shown in Figure 4. Before passing cone 2, the profile of warning area zone 4 to zone 1 in the curve section is the same as in the straight section. After the adjustment, the diameter of the warning area is 2 meters for zone 4, 2.5 meters for zone 3, 3 meters for zone 2, and 3.5 meters for zone 1.

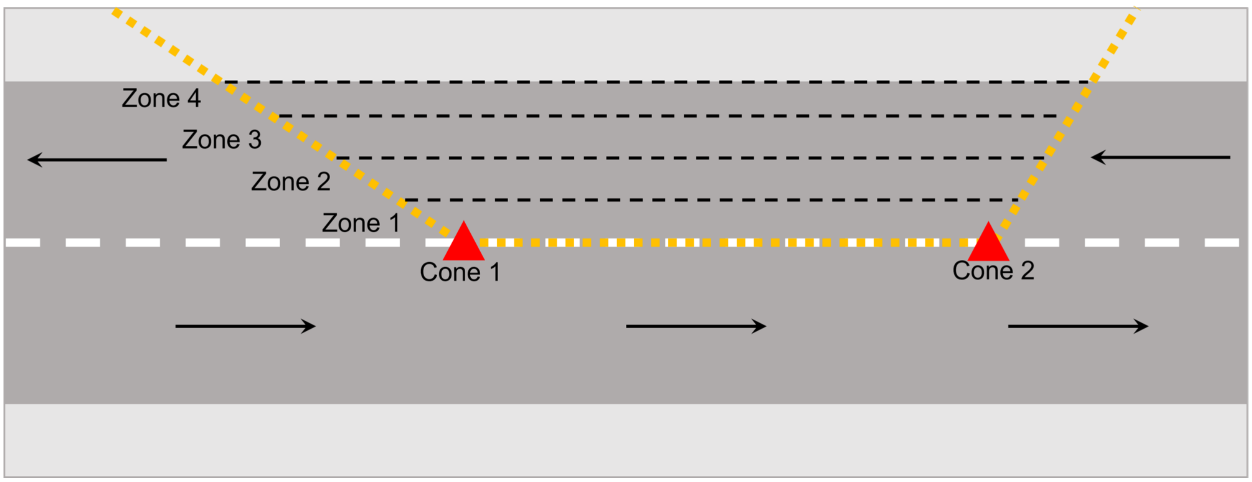

Figure 3. Warning Area for Workers on Foot in the Straight Section from Zone 1 to Zone 4

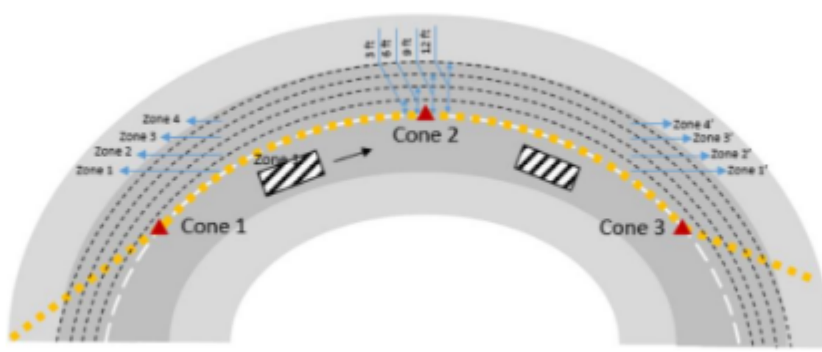

Figure 4. Warning Area for Workers on Foot in the Curved Section

A database is also developed where the dimensions of common highway equipment as well as information regarding general highway construction activities and worker movement patterns relative to different activities are collected and stored. The stored information is utilized in the hazard detection algorithm in Section III.

During highway road work processes, workers perform various activities depending on their work assignments. Different activities involve different levels of exposure to potential hazards. Some common activities are selected for analysis in this study and categorized in Table 1.

Table 1. Activity Category and Description

Number	Category	Description
1	Jackhammering	Utilizing hand-held equipment which requires a consistent or inconsistent static position, such as a jackhammer, drill, etc.
2	Walking	Normal walking or running of workers.
3	Rolling	Utilizing hand-held equipment which requires regular moving, such as a small compactor.
4	Guiding	Workers may walk backwards to guide dump trucks or other heavy equipment to adjust their locations.
5	Random	The random movement of workers may include changes of direction and other unpredictable activities.

Speed, static time, type of movement (parallel/perpendicular to traffic, moving in/against traffic direction) are used here as factors for activity recognition. Supervised learning is performed using MATLAB. All models in the Classification Learner application are tested and compared, and the trained model with the highest accuracy is selected for activity classification and prediction. Static time describes the duration of workers on foot staying at a certain position when performing tasks. Direction is another feature for classification, because certain activities may be tied to a typical direction or combination of directions.

5. Conclusion and Future Work

Construction work zones reduce the road lane number and width and also limit traffic speed, resulting in traffic delays and congestions on roadways. Therefore, accurate work zone capacity estimation is required to help transportation agencies in configuring work zones and allocating resources. This study developed a four-layer neural network model to estimate traffic volumes in areas without sensors. The dataset collected in this study included field data and data acquired from open-source datasets. This research promises to help transportation agencies make effective decisions in work zone setting design and project delivery. Although many variables could affect the work zone traffic flow, the study results indicate that the suggested model outperforms the common traffic prediction models.

One limitation of this study is the lack of detailed information about the work zone setup, such as the lane closure dynamics and project implementation timeline. Another limitation is the lack of traffic sensors on rural, low-volume roads. Although many sensors are installed on primary freeways, very few sensors are available on low-volume roads. Future research could focus on adding probe vehicle data to improve the model accuracy further. Another possible approach towards improving results is to use images and videos collected by Mandli. Mandli is a specialized highway data collection company that integrates 3D pavement technology, mobile LiDAR, and geospatial equipment for multiple DOTs throughout the U.S. Using data collected by Mandli and computer vision techniques such as photogrammetry, we can collect more accurate data on the road attributes, such as lane numbers, grades, and shoulder width.

Abbreviations and Acronyms

ANN	Artificial Neural Network
BLS	Bureau of Labor Statistics
CAV	Connected Automated Vehicle
CDC	Center for Disease and Control
DOT	Department of Transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
RFID	Radio Frequency Identification
SHRP	Strategic Highway Research Program
SVM	Support Vector Machine
UWB	Ultra Wide Band
WZIAT	Work Zone Intrusion Alarm Technology

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About the Author

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Vahid Balali, Ph.D., is the principal investigator for this research and an Assistant Professor in the Department of Civil Engineering and Construction Engineering Management at California State University Long Beach. Dr. Balali's research focuses on visual data sensing and analytics, virtual design and construction for civil infrastructure and interoperable system integration, and smart cities in transportation for sustainable decision-making. He also has experience as a visual data analyst, and he developed a video-based construction resource tracking and action recognition tool for activity analysis of operators at Caterpillar. He has the knowledge, technical skills, and experience that are crucial to the successful completion of the proposed work.

Dr. Vahid Balali was a recipient of the 2020 Early Academic Career Excellence Award by California State University Long Beach. He was also selected as one of the Top 40 under 40 by the Consulting-Specifying-Engineer for the year 2017 and the top young professional in California by the Engineering News Record for the year 2016. He received the 2014 second-best poster award from the Construction Research Congress, as well as the 2013 CMAA national capital chapter scholarship award. He is currently an associate member of ASCE and CMAA, a committee member of the ASCE Data Sensing and Analysis and ASCE Visual Information Modeling and Simulation committees, and a friend member of relevant TRB committees. He is also serving as a reviewer of several top-notch journals. He is actively collaborating with industrial partners and is involved in professional and outreach activities.

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