A Connected Work Zone Hazard Detection System for Highway Construction Work Zones

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ABSTRACT

Roadway construction workers have to work in close proximity to construction equipment as well as high-speed traffic, exposing them to an elevated risk of collisions. This research aims to develop an innovative holistic solution to reduce the risk of collisions at roadway work zones. To this end, a connected hazard detection and prevention system is developed to detect potential unsafe proximities in highway work zones and provide warning and instructions of imminent threats. This connected system collects real-time information from all the actors inside and outside of the work zone and communicates it with a cloud server. A hazard detection algorithm is developed to identify potential proximity hazards between workers and connected/automated vehicles (CAV) and/or construction equipment. Detected imminent threats are communicated to in-danger workers and/or drivers.

The trajectories and safety status of each actor is visualized on Virginia Connected Corridors (VCC) Monitor, a custom web-based situational awareness tool, in real-time. To assure the accuracy of hazard detection, the algorithm accommodates various parameters including variant threat zones for workers-on-foot, vehicles, and equipment, the direction of movement, workers' distance to the work zone border, shape of road, etc. The designed system is developed and evaluated through various experiments on the Virginia's Smart Roads located at Virginia Tech.

Data regarding activities of workers-on-foot was collected during experiments and was used and classified for activity recognition using supervised machine learning methods. A demonstration was held to evaluate the usability of the developed system, and the results proved the efficacy of the algorithm in successfully detecting potential collisions and provide prompt warnings and instructions.

The developed holistic system elevates safety of highway construction and maintenance workers at work sites. It also helps managers and inspectors to keep track of the real-time safety status of their work zone actors as well as the accidents occurrences. As such, with the connected work zone hazard detection system, the safety level and productivity of the workers is expected to be greatly enhanced.

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GENERAL AUDIENCE ABSTRACT

In order to reduce the risk of collisions for roadway construction workers, this research aims to develop an innovative holistic solution at roadway work zones. In this research, a connected hazard detection and prevention system is developed to detect potential collision hazards in highway work zones and generate warning and instructions of imminent threats.

This system collects real-time information from all the workers, construction equipment and connected/automated vehicles (CAV) of the work. A hazard detection algorithm is developed to identify potential proximity hazards between them as well as to recognize the activities of workers. The trajectories and safety status of each worker, equipment or vehicle is visualized on Virginia Connected Corridors (VCC) Monitor, a custom web-based tool, in real-time.

A demonstration was held to evaluate the developed system, and the results proved the efficacy of the algorithm in successfully detecting potential collisions and provide prompt warnings and instructions. The developed holistic system helps managers and inspectors to keep track of the real-time safety status of their work zone worker, equipment and vehicles as well as the accidents occurrences. As such, with the connected work zone hazard detection system, the safety level and productivity of the workers is expected to be greatly enhanced.

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Chapter 1

Introduction

1.1 Introduction

With the rapid development of infrastructure, construction and maintenance of highways have is inevitable. Highway construction safety has been a public concern due to their high rate of injury and fatality caused by proximity to high-speed traffic. A connected hazard detection and prediction system is introduced in this research to address the safety issue at highway construction work zone. The chapter provides the research background and the gap in the current researches. In research background, current researches relative to highway construction safety and available hazard prevention methods are discussed. In this chapter, literature review is summarized in the following three aspects: highway construction safety situation, work zone intrusion alarm technology (outside work zone crash detection), and inside work zone crash detection. Based on the literature review, this chapter further discusses the current research gap and points out a novel solution, a holistic connected work zone, to fill the gap.

The results of the literature review reveal that no comprehensive solution exists to combine strategies for inside and outside work zones. The research goal, to develop a holistic hazard detection system for highway work zone, scope and outline of this research are then elaborated.

1.2 Literature Review

1.2.1 Current Highway Construction Safety Situation

Construction safety has always been a great concern in the industry. According to Occupational Safety and Health Administration (OSHA), the fatal injury rate of the construction industry is higher than the national average for all industries(OSHA 2005). It is even more of a concern for highway construction workers since they have to work in close proximity to high-speed traffic. From 2003 to 2015, 1571 deaths related to highway construction work were reported according to the Center for Disease Control and Prevention(NIOSH 2017). The Federal Highway Administration (FHWA) reported that a Highway work zone fatality occurs every 8.7 hours, and an injury associated with highway construction work zones occurs every 9 minutes (Nnaji et al. 2018). From 2003 to 2015, 68 percent of work-related deaths in highway work zones were highway maintenance workers, heavy and tractor-trailer drivers, construction laborers, construction equipment operators and supervisors(NIOSH 2017). It can be concluded that highway workers are in high risk and safety concerns should be carefully evaluated.

Since highway construction and maintenance workers experience dangerous work environments, the National Institute for Occupational Safety and Health (NIOSH) published a safety instruction to specifically addressing highway construction workers. *Building Safer Highway Work Zones: Measures to Prevent Worker Injuries from Vehicles and Equipment* was launched in 2001(Pratt et al. 2001). The suggested injury prevention measures can be categorized into three parts: work zone layout, traffic control, and other management measures.

The measures of work zone layout include making changes to work zone layout such as increase taper length for night work and control the illumination of the work zone. Traffic control measures use devices, personal protective equipment or management methods to interference passing traffic in order to ensure the safety of the work zone. The traffic control measures mentioned in the instruction include use of temporary traffic control devices, flaggers, developing internal traffic control plans, speed enforcement, high-visibility appeal for workers.

In the safety instruction of NIOSH, the other management measures are not included in the previous two parts. And these measures are mostly related to communication, safety training, data keeping, and etc. The measures include:

- Accountability and coordination at the work site
- Equipment operation and maintenance
- Safe equipment operation around workers-on-foot
- Training and certification
- Changes in the contracting process
- Laboratory and field research needs
- Data and record keeping

However, despite these efforts to document safety-related issues and relative control strategies for highway work zone crashes, the control measures are proven to be not efficient enough. As presented in Table 1, from 2007 to 2017, fatal work zone crash rate decreased at the beginning but raised later, resulting in 2007 and 2017 sharing approximately same number of crashes(National Work Zone Safety Information Clearinghouse 2017).

Table 1. Work zone fatal crashes and fatalities(National Work Zone Safety Information Clearinghouse 2017), crash data shown are from the 50 states, the District of Columbia, and Puerto Rico.

Year	Work Zone		Truck-Involved Work Zone		Pedestrian-Involved Work Zone		Work Zone Worker
	Fatal Crashes	Fatalities	Fatal Crashes	Fatalities	Fatal Crashes	Fatalities	Fatalities
2007	732	830	177	233	112	111	106
2008	662	716	172	191	123	122	101
2009	589	680	131	158	99	98	116
2010	521	586	117	135	73	75	106
2011	533	590	145	178	100	99	122
2012	557	619	132	152	98	98	133
2013	536	593	151	171	100	103	105
2014	608	670	183	212	104	103	119
2015	654	712	175	195	107	107	130
2016	687	781	186	233	113	112	143
2017	710	799	216	265	129	126	132

The same fatal crash trend was also observed for truck-involved and pedestrian-involved work zone crashes (National Work Zone Safety Information Clearinghouse 2017). In fact, the work zone crash statistics in the past 10 years are not proving the efficacy of available safety measures, and accordingly there is an urgent need for improving safety measures at highway work zones.

In 2003, NIOSH published another document titled "*Work-Related Roadway Crashes: Challenges and Opportunities for Prevention"* that further provides a comprehensive view of work-related roadway crashes(Pratt 2003). It revealed that fatigue, age and cellphone use are main reasons for potential truck and/or vehicle crashes. Especially, drivers' fatigue during a long drive while in traffic can trigger driver's attention and result in ignoring the work signs before they enter the work zone. Therefore, only make changes to work zone or construction workers are not enough, measures for passing vehicles also should be considered. More effective measures should be provided to both the work zone and the passing traffic.

As a result, many organizations and researchers investigated better methods or improved current methods in order to protect highway construction and maintenance workers. Many of the available methods for improving highway safety focus on integrating emerging technologies to reduce safety risks at highway work zones. These methods focus primary in two areas: collisions from outside the work zone (Figure 1.a) or collisions from inside the work zone (Figure 1.b) as described in the following sections.

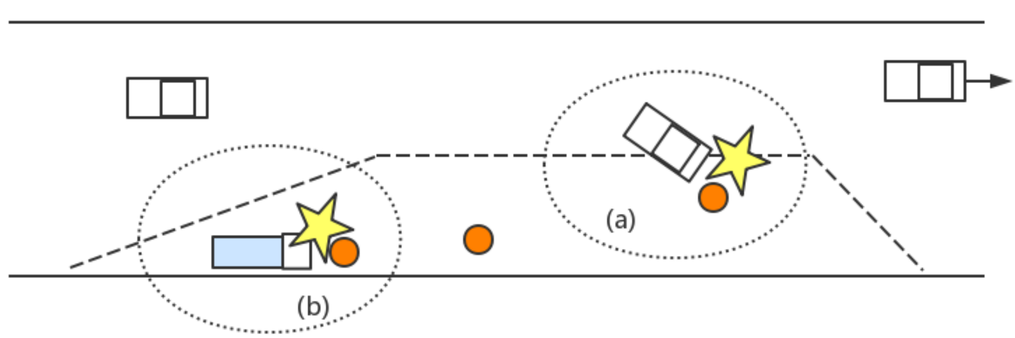


Figure 1. Outside vs Inside collisions of work zone; (a) Collisions from outside the work zone; (b) Collisions from inside the work zone

1.2.2 Work Zone Intrusion Alarm Technology

Previous studies have indicated that even though essential safety training has been put in place to improve construction workers' safety awareness, the unsafe behaviors of construction workers in addition to their lack of situation awareness remains a major cause of many accidents at highway work zones (Guo et al. 2017). One of the most important issues that need to be addressed in order to improve highway construction safety is to increase workers' situation awareness through warning them about dangerous situations. This can improve workers' safety awareness and consequently prevent the potential collisions before they occur. It is recommended to warn workers about how their unsafe behavior can influence their exposure to safety hazards. Such warnings should be made in advance to give workers enough time to react before an accident occurs.

Work Zone Intrusion Alarm Technology (WZIAT) was invented in an effort to solve this problem. The technology aims to detect imminent threat from passing traffic and integrates proximity detection and an alarm system to send audible alerts to workers, taking into account the reaction time needed for workers to act on the received warnings (Nnaji et al. 2018). WZIAT was first introduced in 1995 by a study that focused on evaluating the Strategic Highway Research Program (SHRP) for work zone safety devices (Agent and Hibbs 1996). Previous intrusion alarm technologies include infrared intrusion alarm, microwave intrusion alarm, watchdog perimeter work zone intrusion alarm, etc.(Gambatese et al. 2017). However, due to its high cost, persistent false alarm, difficulty to deploy and several other reasons, those methods have already been decommissioned in the market.

The currently available WZIAT intrusion alert technologies include SonoBlaster®, Intellicone®, Worker Alert System and IntelliStrobe® (Gambatese et al. 2017). SonoBlaster® and Intellicone® are two common WZIAT devices available in the market. The SonoBlaster® device is placed on traffic cones and can be activated when the traffic cone is tilted as a result of an intrusion (Transpo Industries 2017). Intellicone® is another type of WZIAT device that consists of motion sensors, lamps, and portable site alarms. The motion sensors construct a wireless network. When an unplanned motorist entry is detected into the work zone, or a vehicle intrude the work zone, it will be detected by motion sensors and the alarm system will be triggered. A portable site warning device will then produce an audio-visual alarm to warn workers of potential danger (Nnaji et al. 2018)

(a) *(b)*

Figure 2. WZIAT devices; (a) SonoBlaster®(Transpo Industries 2017); (b) Intellicone® (Solutions)

Traffic Guard Worker Alert System (WAS) (Nnaji et al. 2018) is another great example of the WZIAT. The WAS is a pneumatic-based alarm system consisting of an audio-vibratory personal safety device (PSD), pneumatic tubes and other devices. When an unplanned vehicle intrudes into the work zone, pneumatic tubes are compressed and simultaneously activate the PSD attached to worker's belt that would subsequently release an alarm to alert workers of the dangerous situation (Nnaji et al. 2018).

Figure 3. Traffic Guard Worker Alert System(Optics 2017)

Figure 4. IntelliStrobe® (IntelliStrobe)

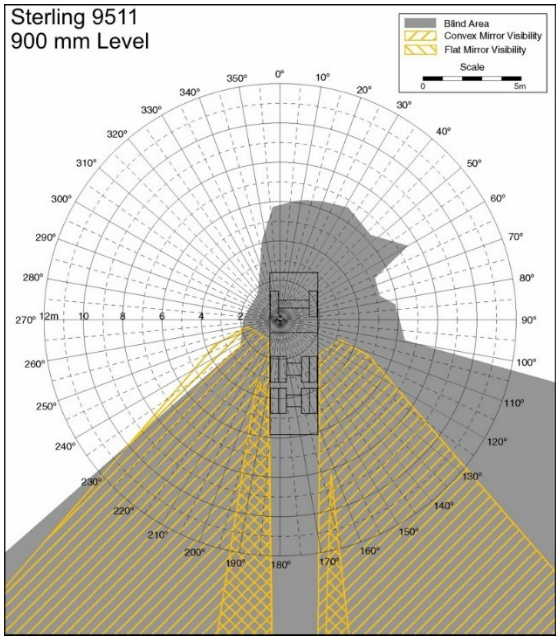
IntelliStrobe® is an automatic flagger which can replace human flagger and be remotely controlled by workers. It also uses pressured trigger pneumatic tube alarm system but only has an audio alarm. The alarm will be activated when a vehicle ignores the stop sign and press the pneumatic tube on its way to the work zone (Gambatese et al. 2017).

In recent years, WZIAT devices have been tested by the Department of Transportation (DOT) in different states. According to reports, different states respond differently to use of WZIAT; e.g. Oregon DOT considered intrusion alert technologies to have the potential to improve worker safety(Gambatese et al. 2017) while New Jersey DOT doubted the reliability and desirability and benefits of SonoBlaster® (Krupa and Systematics 2010).

However, as mentioned earlier, the current research on WZIAT devices only focuses on vehicles intruding the work zone from outside the work zone and the construction processes inside the work zone are largely ignored. In other words, WZIAT devices only trigger an alarm when a vehicle intrudes the work zone, and could not detect collisions inside the work zone, i.e. between workers and construction equipment.

1.2.3 Crash Detection Inside Work Zone

Construction and maintenance workers in the highway are not only exposed to hazardous situations from outside the work zone (i.e. passing traffic), but also frequently encounter safety concerns inside the work zone. Since collision risk within the work zone cannot be ignored, a number of researchers have focused on reducing risk of collision between construction equipment and workers-on-foot in work zones. The heavy construction equipment frequently used in the construction work zone include trucks, forklifts, skid steer loaders, compactors, bulldozers, scrapers etc. Construction equipment are often involved in visibility-related injuries and are deemed dangerous to workers-on-foot (Hinze and Teizer 2011). Researchers have examined 659 visibility-related fatality cases, among which 594 cases involved equipment or vehicles(Hinze and Teizer 2011). They also found that equipment moving in reverse direction impose a much higher accident occurrence rate compared to equipment is moving forward or is stationary (operating but not traveling)(Hinze and Teizer 2011). NIOSH provides construction equipment visibility diagrams online based on contractor and construction equipment company(NIOSH 2017).



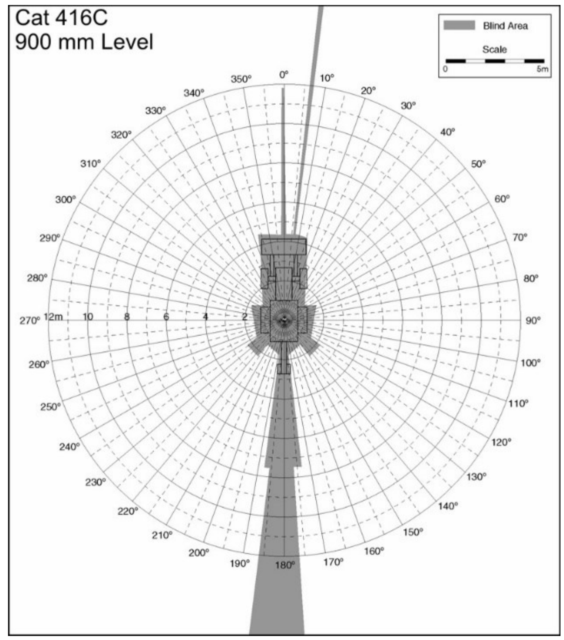
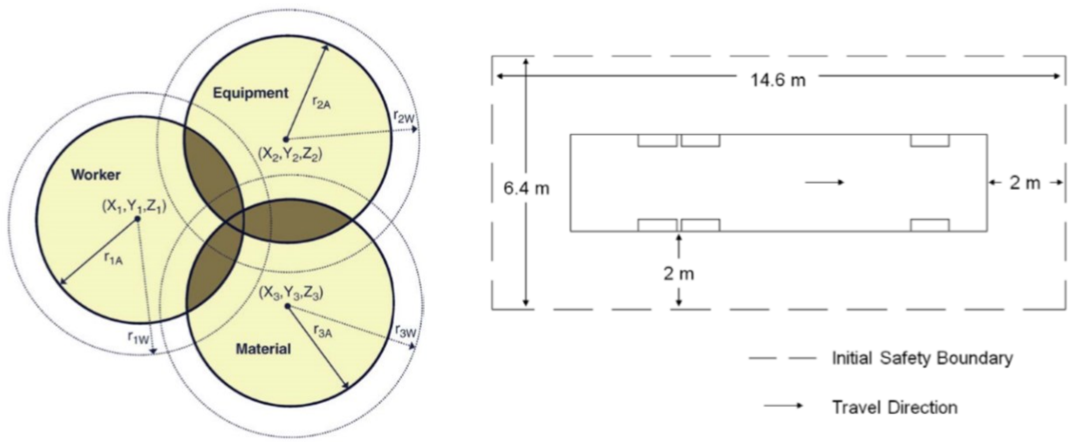


Figure 5. Construction equipment blind spot diagram by NIOSH (a) Sterling 9511 Dump Truck, 900 mm level; (b) Caterpillar 416C Backhoe Loader, 900 mm level

These diagrams present a larger blind spot at the back of the equipment compared to the front in most of the cases. It can be concluded that heavy equipment in the work zones can cause serious accidents when moving in a reverse direction.

Pro-active safety technology is developed to provide warnings to construction workers and equipment operators in real-time(Marks and Teizer 2012). Location sensing is an essential part of the presented solutions. Several sensing technologies are widely applied with the aim to improve safety of construction workers, including global positioning system (GPS) (Oloufa et al. 2003; Wang and Razavi 2015), radio-frequency identification (RFID), radio frequency (Fullerton et al. 2009; Teizer et al. 2010; Park et al. 2015), radar (Ruff 2006), Ultra-WideBand (UWB) (Cheng et al. 2011; Hwang 2012), Bluetooth (Park et al. 2015), etc. Because blind spot can be varied depending on equipment model, various blind spot configurations and measurements are also investigated for heavy equipment in some researches. These studies aim to create potential hazardous zones(called threat zones herein) for workers around equipment, e.g. considering blind spots for obstacle as permanent hazard zones and 3D blind spots for equipment (Teizer et al. 2010; Ray and Teizer 2013; Teizer and Cheng 2015).

Various algorithms are presented for designing threat zones in order to provide warnings to workers in a reasonable way. Threat zones designed by different researchers varies. Teizer et al. proposed a 3-dimensional threat zones with warning radius and alert radius(Teizer et al. 2010). Awolusi et al. considers another way to define threat zone, an initial threat boundary of equipment is a 2-meter distance extended from equipment footprint, the hazardous zone design depending on the specific function of equipment as shown in Figure 6 (Awolusi et al. 2015). Wang and Razavi also defined threat zone with warning distance and alert distance which is similar to Teizer et al. In their method, the difference between warning distance and alert distance is determined by key factors such as reaction distance of worker-on-foot, reaction distance of equipment and braking distance of equipment (Wang and Razavi 2015). The threat zones configurations need to consider inherent danger of construction equipment as well as potential hazard due to its motions.



(a) *(b)*

Figure 6. Hazardous zone design of (a) Teizer et al. 2010 and (b) Awolusi et al. 2015

While various vehicle crash detection systems have been developed in previous researches (Sharma et al. 2016, Yee and Lau 2018), real-time pre-crash detection and prevention remains a need to improve traffic safety at highway work zones. However, the hazard prevention methods mentioned above either focus on accidents from outside the work zone or from inside the work zone. A holistic work zone safety approach requires taking all work zone actors, i.e. workers, equipment and passing traffic, into account. In sum, such a holistic approach is missing in the literature.

1.2.4 The Research Gap

Based on the literature review, the available hazard detection methods focus either on preventing collisions from passing vehicles (i.e. threats from outside of the work zone), or potential hazard from construction equipment or construction material (i.e. threats from inside of the work zone). There remains a research gap that no holistic connected work zone system exists that takes into account all involved actors from inside as well as outside of the work zone. The current hazard detection methods only concern hazards from either inside or outside of the work zone.

As such, there is a pressing need for a holistic and comprehensive connected work zone system that takes into account the collisions involving all actors in potential crashes from both inside and outside of the work zone. The holistic work zone system should detect all the hazards and alert the respective actors regardless of their locations.

1.2.5 Connected and Automated Vehicles (CAVs)

In the literature pertinent to transportation, the focus is on vehicles conditions, where relative position and driving context are used to detect a potential crash and provide a warning to drivers (Liu et al. 2016).

Automotive technology develops rapidly in recent decades. With the emergence of connected and automated vehicles (CAVs), scholars started to consider how to combine it with work zone safety. Connected and automated vehicles are vehicles that can use communication technologies to communicate with the driver, other cars on the road (vehicle-to-vehicle [V2V]), roadside infrastructure (vehicle-to-infrastructure [V2I]), and the “Cloud” [V2C] (CAAT 2018).

The integration of communication technology enables vehicles to not be considered as individual actor on the road but as an integral part of a system. With the feature of communication, scholars tried to make a connection with CAVs and work zone safety. Safety performance impacts of CAVs in a work zone setting is evaluated, the result shows that in a low traffic flow rates, work zone safety performance can be improved by V2V/V2I communication(Abdulsattar et al. 2018).

Scholars also investigated the effect that using CAVs on traffic safety in a network with work zones (Genders and Razavi 2015). The nation’s first connected work zone on I-75 was conducted by the Michigan Department of Transportation (MDOT) and 3M (Lombardo 2017). 3M provided orange barrels with 2D barcode inside. The infrared devices in CAV can read the barcode and communicate the information with both the vehicle and the driver (Lombardo 2017).

With the emergence of location sensing technologies and CAV, the information can be collected from all work zone actors including vehicles, equipment and workers-on-foot and utilized to ensure the safety of the work zone. This research aims at addressing this gap by designing a comprehensive connected work zone system to help enhance the safety level of the highway work zone. Compared to normal vehicles, the communication feature of CAV is a key to address the research gap and it expands the scope of the connected work zone system.

1.3 Objectives

This research's overarching goal is to develop a comprehensive deployable connected work zone hazard detection system to prevent potential unsafe situations in highway workzones, taking into account all involved actors. It addresses the current research gap and enhance the safety level of highway work zone.

The research is separated into 4 subtasks: data collection, hazard detection algorithm design, database development and activity recognition. To finish the subtasks, 6 subobjectives are identified as presented in Figure 7. To this end, the objectives of this research are as follows:

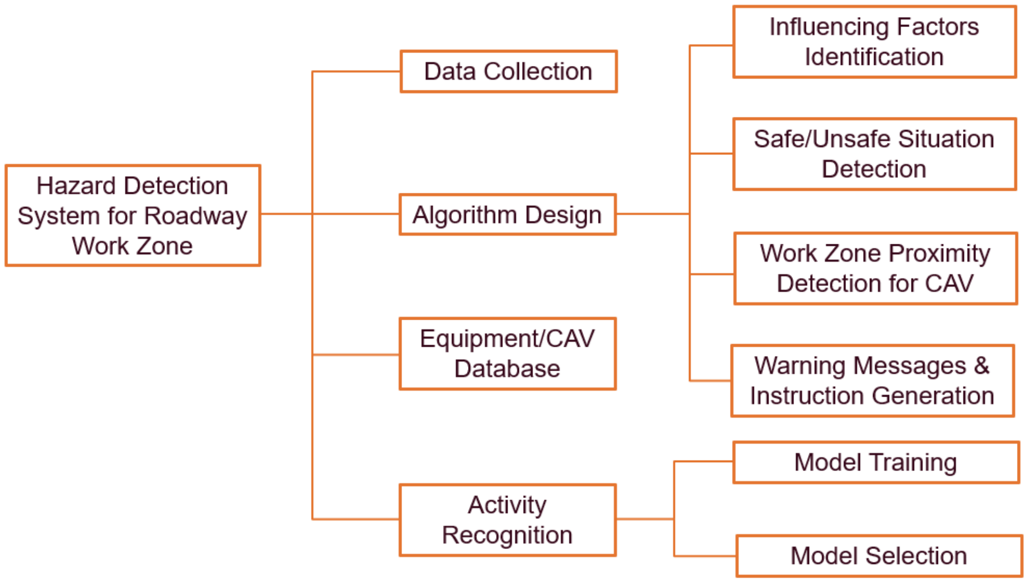


Figure 7. Research framework and objectives

- Investigate influencing factors in safe/unsafe situations
- Identify safe/unsafe situations
- Work zone proximity detection for CAV
- Investigate warning messages and insturctions generation
- Activity recognition model training
- Activity recognition model selection

The first subobjective is to investigate influencing factors in safe/unsafe situations. This aims to investigate what factors can affect the safety level of workers-on-foot, construction equipment and CAVs, such as shape of road, relative location to the work zone border. Once the influencing factors are identified by the hazard detection system, extra protection can be generated to secure the endangered actors. Investigating the influencing factors helps the system be adaptable to real work zone environment.

The second subobjective is one of the core objectives, to identify safe/unsafe situations, and detect imminent threats. As a hazard detection system, it needs to clearly know in what situations the worker-on-foot/equipment/CAV are in real imminent danger. Then the system needs to take action based on the judgements of potential hazards.

The third subobjective is to provide proximity detection for CAV. It aims to provide warnings to the work zone that passing vehicle is approaching. It also provide messages to the CAV that a work zone is ahead. The purpose of the proximity detection is to provide timely information to workers and vehicle driver and increase their awartness.

The fourth subobjectvie follows the first three objectives. After the hazard or proximity detection, the system needs to provide messages and instructions to worker-on-foot/equipment operator/vehicle drivers to notify them about the potential collisions and help them avoid the accidents. The transmission of instructions to the workers/operators/drivers will be investigated in future research.

The fifth subobjectvie is select an activity recognition model to classify common construction activites of workers-on-foot. It aims to predict the activity of workers based on received location data, and accordingly predict their activity-related movement.

Generally, the objective of this research is to create a comprehensive deployable connected work zone hazard detection system to detect unsafe proximity between workers-on-foot and construction equipment and/or passing traffic before potential accidents actually occur. The proposed system is expected to help improve safety at highway work zones by prompt detection of potential imminent threats between work zone actors and accordingly avoiding imminent collision accidents in advance. The developed system is expected to be conveniently used to assist project managers and inspectors to monitor the work zone safety condition and project progress in real-time.

1.4 Research Scope

To achieve the objectives stated in the previous section, the algorithm embedded in the hazard detection system needs to detect unsafe proximity of workers-on-foot to construction equipment and/or passing traffic before potential accidents occur.

Based on literature review, the research adopted previous design to generate threat zones for worker-on-foot, construction equipment and CAV. The conditions and interactions of the threat zones determine the safe/unsafe status of the worker-on-foot/equipment/CAV and the messages/instructions generation is followed by the safe/unsafe status judgement. The system detects the interactions of the threat zones and automatically generate the status messages and instructions to the corresponding worker-on-foot/equipment/CAV. And all the statuses and messages are uploaded to the server. The trajectories and status information can be visualized on the server.

The influencing factors identification focus on workers-on-foot. The conditions of the factors are used to adjust the threat zones of workers-on-foot or construction equipment. The adjusted threat zone differs from other threat zones and it influences the judgement of safe/unsafe status. Therefore, for the actor with higher risk level, the threat zone will be larger and threat warning will be provided earlier.

In the research, data is collected during experiments and activities of workers are recorded. The data is analyzed to train machine learning models. The model with highest classification accuracy was selected to use as activity recognition model in the research. The trained model will be embedded into the hazard detection system in future research.

1.5 Summary

In this chapter, the literature review related to the current approaches towards improving highway construction safety situation was presented. The chapter also points out the research gap which is lacking a comprehensive hazard detection system to ensure safety considering all invloved actors both inside and outside of the work zone. An advanced hazard detection system is introduced to fill the current research gap and research objectives and scope is elaborated. Based on the research scope. Various tasks accomplished to achieve the research objectives are elaborated and discussed in the following chapters.

Chapter 2

Methodology

2.1 Introduction

The objectives of this research, as stated in the previous chapter, are achieved through four inter-related steps, each accomplished through various tasks as demonstrated in Figure 6. These steps include data collection, algorithm design, equipment/CAV database development, and activity recognition. In this chapter the research steps and the tasks relative to each step are elaborated in detail.

First, the data collection scenarios are discussed. The sensors used, work zone layout configuration, the data type collected, communication configuration, the equipment and CAV, and other related information are explained.

The design of the hazard detection algorithm is discussed next. The algorithm is designed to detect potential hazardous proximities between work zone actors and prevent them by sending prompt notification to the involved actors. To this end, first threat zones are defined for all work zone actors and are utilized to detect potential collisions and provide warning messages and instructions to corresponding actors. Influencing factors of safe/unsafe situations are identified and 100-m proximity warning for approaching CAV is also included in the algorithm. They can provide extra protection and alertness for the actors. The developed database containing information pertinent to equipment/CAV to feed the required information needed for the hazard detection algorithm is then discussed. The activity recognition methods and needed factors are discussed in the chapter.

This chapter also discusses the development of hazard detection algorithm. It reveals how to realize the algorithm design and combine the threat zone designs, influencing factors, developed database into one hazard detection system. Lastly, a summary of the methodology is provided.

2.2 Data Collection

In this research, real-time locational data collected from work zone actors is used to detect potential unsafe proximities and provide warnings and instructions to in-danger actors. Therefore, the accuracy and consistency of data need to be taken into account when choosing the technology used for sensing and data collection.

Based on review of literature and available off-the shelf sensors, Ultra-WideBand (UWB) sensors were selected to be used to collect real time location data from cones, workers-on-foot and construction equipment. UWB is selected because of its known precise location tracking (Fang et al. 2016). UWB devices from Decawave® are used. The sensors were programmed as two categories, anchors and tags. As work zone layout shown in Figure 8, three anchors construct a triangle located in the work zone and are responsible for collecting locational information from tags and transmitting the collected data to the server. Tags are hand held by workers-on-foot or mounted on construction equipment and cones to identify work zone boundaries.

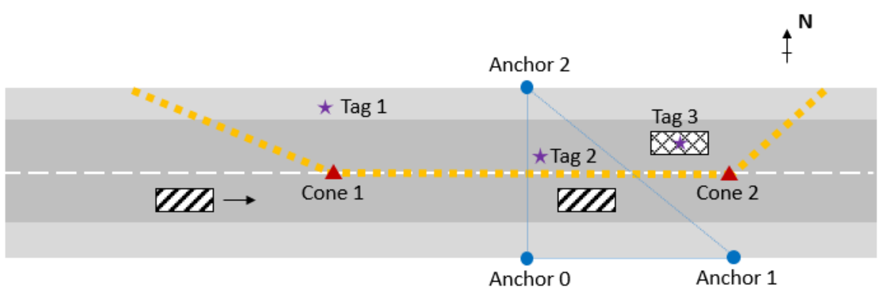


Figure 8. Highway work zone experiment layout

Data from tags and connected vehicle are collected during the data collection. The data from tags include tag number, timestamp, latitude, longitude, X and Y in Universal Transverse Mercator (UTM) coordinate system. Data from CAV include vehicle number, timestamp, latitude, longitude, degree, speed, vehicle length, and width. The collected data is sent to Virginia Connected Corridors (VCC) Monitor, a custom web-based situational awareness tool and is visualized in real-time. Data set is recorded and used later in the algorithm in CSV format.

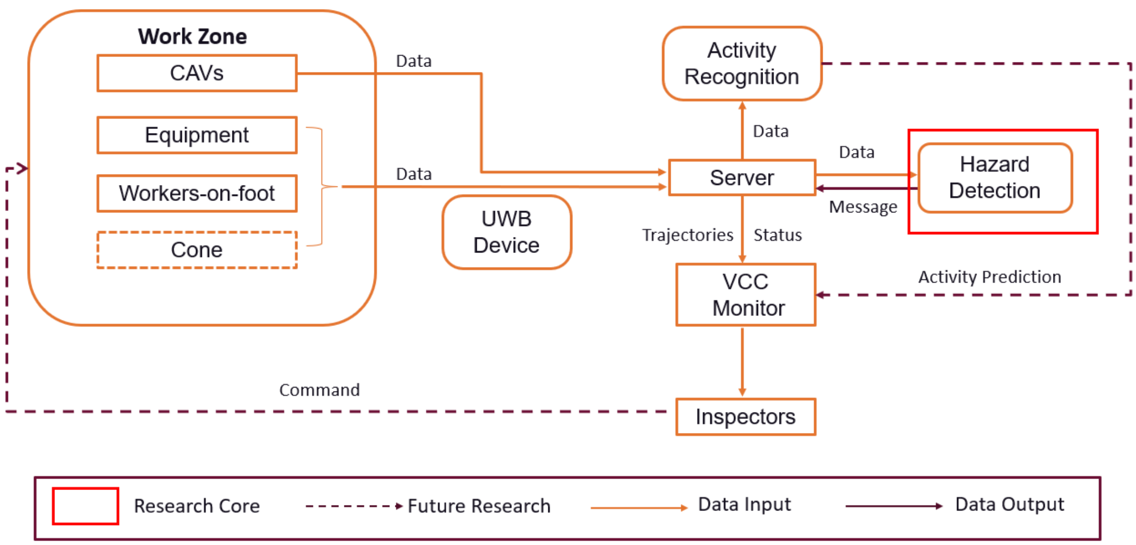


Figure 9. Communication configuration of the hazard detection system

4 formal experiments were held on the Virginia Smart Roads at Virginia Tech Transportation Institute (VTTI). Two were in the straight road section and two were in the curve section. One CAV and three construction equipment were used in experiments (see Figures 10 and 11). The equipment included truck, mule, and mower. 4 students, faculty and staff participated as workers-on-foot. The activities the participants performed were walking, guiding (moving backward), rolling, jackhammering and random activity. The details of the activities are introduced in the activity recognition section later in this chapter.

Figure 10. Truck used in experiments

(a)

(b)

Figure 11. Construction equipment in experiments: (a) Mower used in experiments;(b) Mule used in experiments

Each data set of tags was recorded in the server. The moving directions of workers-on-foots and construction equipment were also recorded manually. A total of 49 movement patterns were simulated and categorized, including three samples of jackhammering, 16 walking, 10 rolling (hand-held equipment which required regular moving), 14 (moving backward) and 6 random movements. The stored locational data and recorded moving directions are used to train the activity recognition model and test the hazard detection algorithm in following sections.

2.3 General Hazard Detection Design

2.3.1 Threat Identification

To identify potential hazardous proximities, it is necessary to determine the safety status of actors. In this research, a threat zone is defined to provide an area around actors in which the proximity can be dangerous. If threat zones overlap, it indicates that the trajectories of actors interfere with each other and there is possible to collide in the near future. Since highway work zones have a higher collision risk than other types of construction sites, a more detailed threat zone is designed here for each actor, i.e. workers, construction equipment and vehicles, for hazard identification.

Threat zone introduced in this research consists of two zones: alert area and warning area. Alert and warning zones introduced by (Wang and Razavi 2015) for equipment are considered here for all actors (i.e., workers, equipment or CAVs). The alert area in this research is an inherently unsafe area around the actor. It is a fixed area that if invaded, the actor can be harmed due to extreme proximity. A warning area is the area whose danger level is lower than the alert area but still involves potential risk, and thus is considered hazardous. The warning area is defined by prediction of the actor's location in the near future depending on speed and current movement pattern/direction. As such, the warning zone helps to predict potential hazards and prevent them before they get to the alert zone (where a crash is imminent).

The potential hazard detection depends on whether the threat zones overlap. As described above, a warning zone or a threat zone is a prediction of an actor's future movement. Therefore, the overlapping threat zones indicate that potential collisions exist in actors' future route.

In this research, threat zones for actors are calculated in real-time. Unsafe proximities are detected when the threat zones overlap. As a result, all involved subjects are identified in the unsafe status by the system.

2.3.2 Workers-on-foot

The determinations of actors' threat zones are important for detecting potential hazards as it impacts the accuracy and efficiency of the algorithm. Therefore, the design of warning zone and alert zone is an essential part of the algorithm.

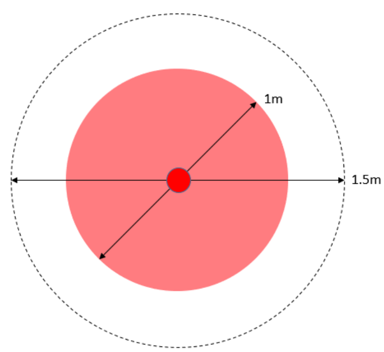


Figure 12. Warning zone (white) and alert zone (red) for workers-on-foot

In this research, for workers-on-foot, one meter and 1.5 meters are used as diameters of the primary alert zone(red area) and the warning zone (white area) from previous researches, respectively (Dagan and Isaac 2015, Roofigari Esfahan et al. 2015) as shown in Figure 11. The worker-on-foot locates in the center of the circle (the red point in Figure 11). One-meter diameter for alert zone is adopted based on minimum required distance between workers with different work operations when considering varied working and training experience (Dagan and Isaac 2015). The alert zone shown in Figure 12 as the red area. 1.5 meters for warning zone is calculated by multiplying the mean of actual comfortable gait speed of men at 30s and 40s and the average reaction time (Roofigari Esfahan et al. 2015). The warning zone is shown in Figure 12 as the white area with a dash boundary. For workers-on-foot, whenever they are moving or staying still, the warning zone and alert zone remains the same. The impacts on warning zone design from other factors are discussed.

2.3.3 Connected and Automated Vehicle (CAV)

When it comes to vehicles and equipment, dynamic threat zones are designed taking into account their movements and directions. The threat zones design for CAV and equipment adapted from the hazardous zone design of Teizer in 2015(Teizer and Cheng 2015). Comparing to workers-on-foot, warning zone for the vehicle is changing dynamically with its velocity, driver reaction time, friction coefficient, steer angle. The warning zone itself presents a prediction of CAV's future movement. Thus, when the vehicle is still, the warning zone is theoretically not existing. In this case, the threat zone only consists of an alert zone since the alert zone is always fixed. However, in reality, since the vehicle is in high-speed traffic, the staying still situation cannot hold in most of the cases. Key

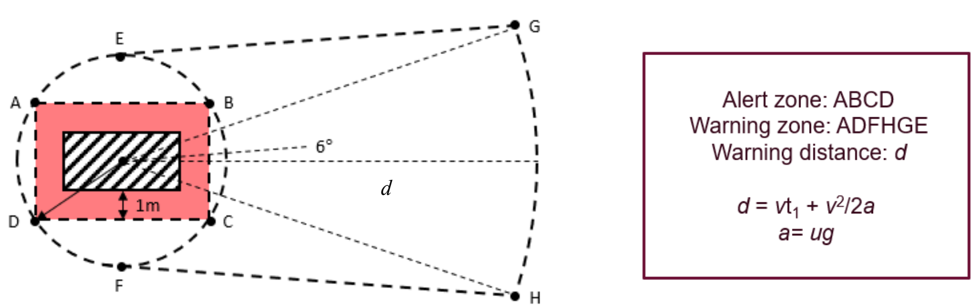


Figure 13. Warning zone (white) and alert zone (red) for CAVs

parameters for threat zone include velocity, width, and length of equipment or vehicle, 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 expanded by 1 meter in all directions (see Figure 13). To determine the warning area, a circle that crosses all four vertexes of the alert area is created and extended as presented in Figure 13. Subsequently, the threat distance is determined by computing stopping distance of the vehicle/equipment, considering the speed of vehicle, the time required for driver's reaction (2.0 second is used as a common driver reaction time (Copradar 2017)) as well as the deceleration time once the driver reacted (0.8 is used as a typical value of friction coefficient of dry road in this research(Chen 2017)). Considering a single lane change, a 6-degree steering angle is adopted to calculate the expanded warning area (Zhao et al. 2014).

2.3.4 Construction Equipment

As described in the previous section, the method of calculating the threat zone for equipment is similar to CAV as presented in Figure 14. Heavy equipment such as dump trucks could frequently get involved in fatalities resulting from poor visibility (Hinze and Teizer 2011). Therefore, the alert area is designed to be larger than one for CAV and the shape of the warning zone is designed to be different according to the moving direction of equipment. Since this research mainly considers the highway work zone as a single-lane work zone layout, the flexibility of equipment is limited. While steering angle is not necessarily considered for equipment, the moving direction can be two-way. Both moving forward and backward are common operations of construction equipment in highway work zones. In this case, same as CAVs, warning zone is only applied along the moving direction to reduce false alarm rate.

When moving forward, the steering angle is 0-degree thus upper bound line and bottom bound line of warning zone are parallel as presented in Figure 14(a). Extra warning zone area when moving backward is taken into account. While moving backward, the field-of-view is limited, thus a wider warning area is considered (see Figure 14 (b)) to account for limited visibility. It is assumed that the 6-degree steering angle is also effective to create a larger warning zone for equipment.

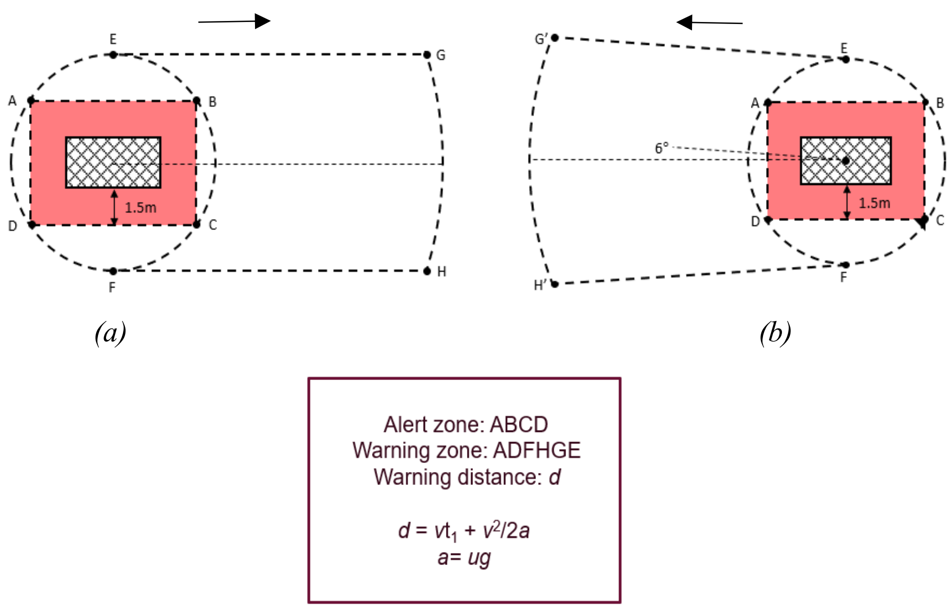


Figure 14. Warning zone (white) and alert zone (red) for construction equipment in two moving directions;(a) moving forward; (b) moving backward

The type of equipment and its activity in the work is another factor for determining the threat zones. However, it would require a detailed analysis of each equipment which is out of the scope of this research. In the future, the factors will be discussed.

2.4 Influencing Factors for Hazard Detection Algorithm

2.4.1 Distance to Border

The general hazard detection design introduced above is suitable for all workers-on-foot, equipment, and CAVs. However, the environment in the work zone is complicated and the general design does not cover all situations. The safety level between two individual workers may differ for typical factors, such as road condition, movement of workers-on-foot, weather, glare, etc. In this research, these factors are influencing factors which means they can increase the collision risk of the workers. Therefore, under the influence of these factors, the warning zone can be dynamic in order to provide extra protection for workers.

The distance to the work zone border is taken into account in the warning zone 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 the extra warning zone area is considered to increase the safety level as presented in Figure 15.

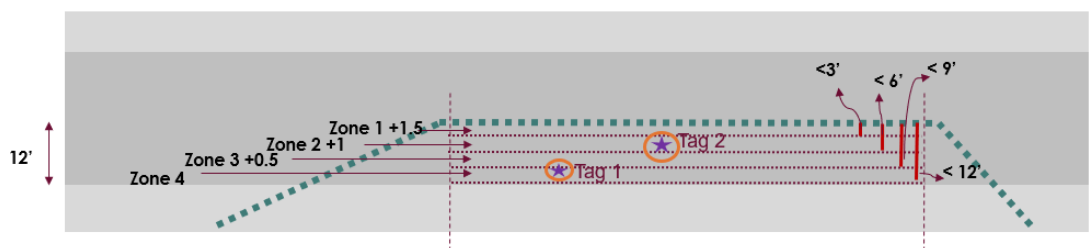


Figure 15. Single-lane work zone partitions and corresponding extra warning zones

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, warning zone with a diameter of 1.5 meters as basic diameter is determined for workers positioned at 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 subzone (Figure 15). When the worker moves to the zone 1 (closest zone), the warning zone diameter is 3 meters. As such, the warning zone for tag 2 is larger than the one for tag 1.

For example, as shown in Figure 15, tag 1 and tag 2 are represented as two individual workers. Tag 1 locates in zone 4 while tag 2 is in zone 2. Warning zone is drawn as an orange circle around the tags.

With due consideration to extra warning zone area, worker approaching the work zone border receive higher-level protection compared to worker located in the farther from the border. Therefore, when workers-on-foot approach the high-speed traffic, they are still well secured and can receive hazard warning earlier, reducing the chance of potential collisions.

2.4.2 Curve/Straight Roadway

Vehicles are subject to centrifugal movement when traveling on a curve at a high speed, potentially leading to serious rollover accidents (Wang et al. 2011). This fact indicates that curve sections of roads are more dangerous than straight sections. As a result, curve sections require larger warning areas for workers-on-foot to ensure their safety. Curve/straight road condition of the work zone is also considered as influencing factor in this research.

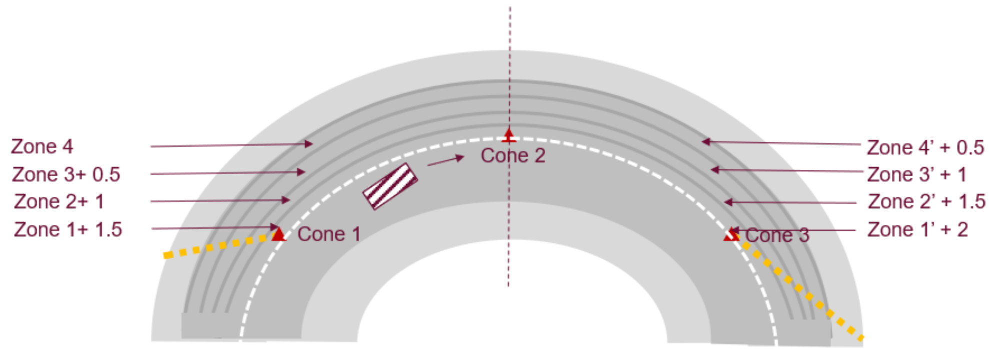


Figure 17. Curve road condition and corresponding extra warning zones

For the curve section, due to the higher risk caused by centrifugal movement of vehicles, the area to the right of the cone 2 (as shown in Figure 16, the 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 (center of the curve) to compensate for the higher risk as shown in Figure 16. Before passing cone 2, the profile of warning area for zone 4 to zone 1 in the curve section is the same as that in the straight section. As shown in Figure 16, after the adjustment, the diameter of warning area in zone 4 is 2 meters, and 2.5 meters for zone 3, 3 meters for zone 2 and 3.5 meters for zone 1.

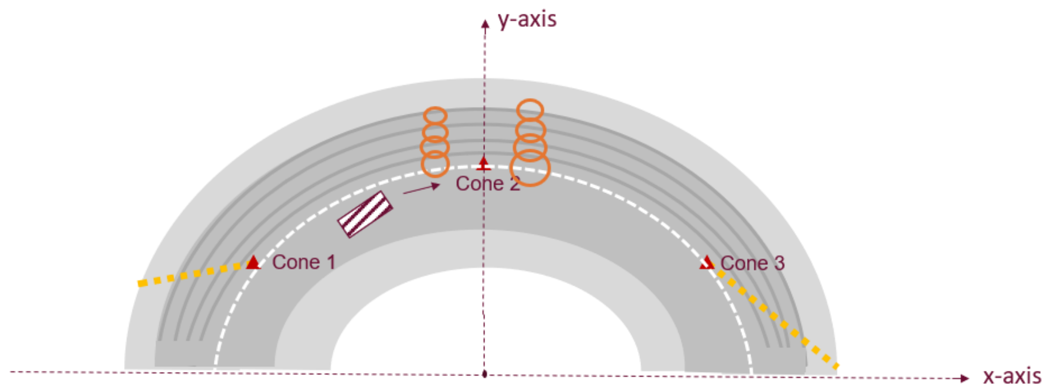


Figure 16. Dynamic extra zones under x and y axis

Figure 17 summarizes the use of influencing factors in the determination of threat zones. The orange circles represent individual workers that are located in different distances from the work zone border. The closer the workers to the x-axis (the border), the larger the orange circles or warning zone areas are presented. Furthermore, warning zones for workers on the right of the y-axis are larger than the ones on the left of the y-axis (before and after cone 2).

In this section, factors of distance to the border and curve/straight road condition are discussed. The moving direction of equipment is another influencing factor introduced as explained when defining the warning zone of construction equipment. The listed factors have an impact on the safety of workers-on-foot, but they are not enough to cover all situations for the highway work zone.

2.5 Real-Time Proximity Detection and Visualization

The detected proximity status of work zone actors is visualized on the VCC monitor in real time. The visualization helps in providing pre-warning for workers and equipment inside the work zone, indicating unsafe situations. As presented in Figure 18, markers with typical colors represent specific status. Blue represents safe status; orange present proximity and red mean hazard and warning.

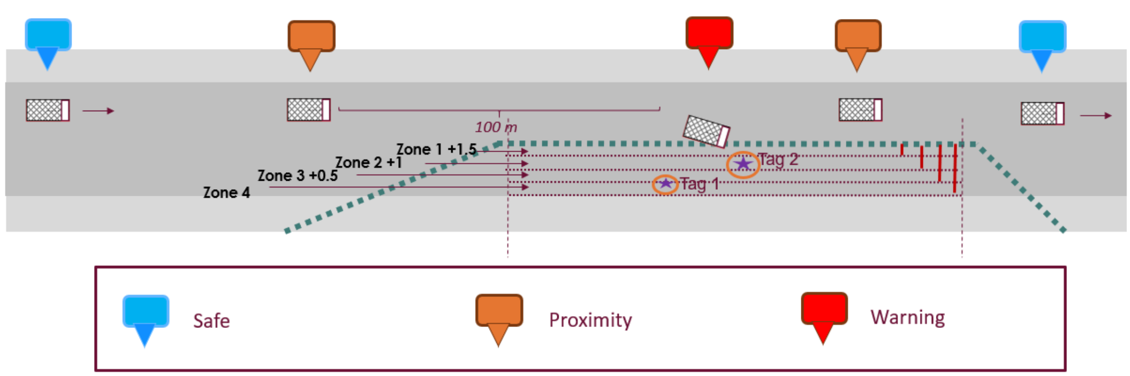


Figure 18. Proximity detection and visualization

The proximity detection is introduced with data visualization on VCC Monitor in this section. As presented in Figure 18, the passing vehicle moves from left to the right and drives pass the work zone. At the beginning on the left, the vehicle is far from the work zone, status is analyzed as safe, so the representing marker is shown as blue on VCC Monitor. When the vehicle is approaching the work zone, and its distance to the first worker (represented as tag 1) inside the work zone is 100 meters as shown in Figure 18, the status of vehicle changes to orange, indicating proximity situation. At this point, the algorithm generates proximity messages to the server and reminds it the vehicle is approaching the work zone (the messages will directly be sent to the workers and operators in future research). When the warning zone of vehicle overlaps with other threat zones of actors, the status of the vehicle and corresponding actors change to red, indicating warning status. In this case, the vehicle has a trend to intrude a worker-on-foot (tag 2) inside the work zone and the marker is turned red on the monitor. In the end, as the vehicle comes back to the normal trajectory or passes the work zone, the color of the status of the vehicle returns to blue indicating safe status.

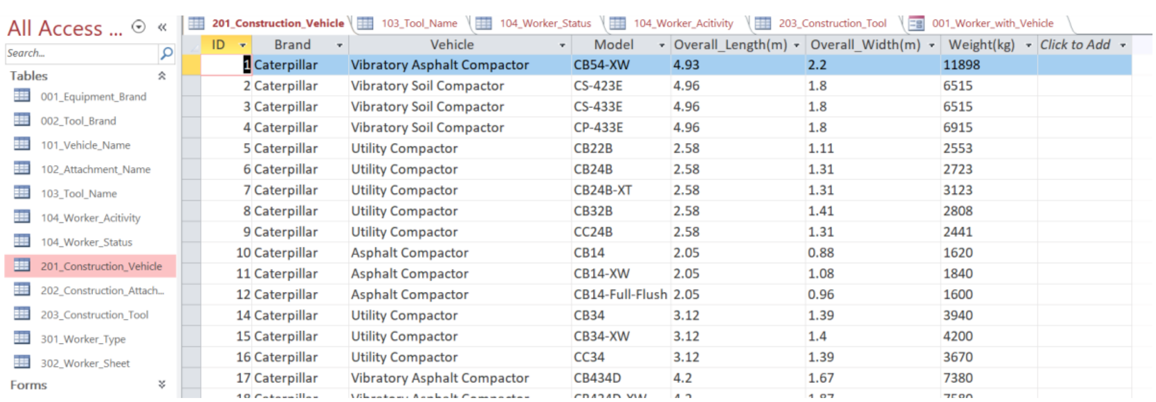
Figure 19. Data visualization on VCC Monitor

100-meters proximity detection is used to notify workers and operators inside the work zone in advance. With the proximity notification, they have enough time to react and avoid the potential hazard such as move back to inner work zone area. With different color markers, managers or inspectors can easily keep track of the trajectories of actors and monitor their safety statuses.

2.6 Equipment/CAV Database Design

As stated in previous sections, the alert zone area is customized for each equipment/CAV (extend the length and width of each side of the equipment/CAV), the information of the equipment/CAV is needed for accurate creating of the threat zone areas. In theory, due to the brand and model, each equipment/CAV has a unique alert zone area and warning zone area.

However, it is infeasible to consider a customized alert zone or warning zone for every model and is out of the scope of this research. To make the process more efficient, two databases containing needed information about equipment/CAV is built in Access and Excel.



ID	Brand	Vehicle	Model	Overall_Length(m)	Overall_Width(m)	Weight(kg)	Click to Add
1	Caterpillar	Vibratory Asphalt Compactor	CB54-XW	4.93	2.2	11898	
2	Caterpillar	Vibratory Soil Compactor	CS-423E	4.96	1.8	6515	
3	Caterpillar	Vibratory Soil Compactor	CS-433E	4.96	1.8	6515	
4	Caterpillar	Vibratory Soil Compactor	CP-433E	4.96	1.8	6915	
5	Caterpillar	Utility Compactor	CB22B	2.58	1.11	2553	
6	Caterpillar	Utility Compactor	CB24B	2.58	1.31	2723	
7	Caterpillar	Utility Compactor	CB24B-XT	2.58	1.31	3123	
8	Caterpillar	Utility Compactor	CB32B	2.58	1.41	2808	
9	Caterpillar	Utility Compactor	CC24B	2.58	1.31	2441	
10	Caterpillar	Asphalt Compactor	CB14	2.05	0.88	1620	
11	Caterpillar	Asphalt Compactor	CB14-XW	2.05	1.08	1840	
12	Caterpillar	Asphalt Compactor	CB14-Full-Flush	2.05	0.96	1600	
14	Caterpillar	Utility Compactor	CB34	3.12	1.39	3940	
15	Caterpillar	Utility Compactor	CB34-XW	3.12	1.4	4200	
16	Caterpillar	Utility Compactor	CC34	3.12	1.39	3670	
17	Caterpillar	Vibratory Asphalt Compactor	CB434D	4.2	1.67	7380	

Figure 20. Construction equipment information of Caterpillar

The first database is built in Access. This database contains information related to workers-on-foot and equipment. For the equipment, as shown in Figure 20, it includes construction equipment brand, model, length, width, and weight information. Basically, the length and width of equipment/CAV are required to create the corresponding alert zone. Weight is also included in the database. Collected models of equipment are mainly from Caterpillar(Caterpillar 2019). Besides equipment, information for common equipment attachments and hand-held tools for workers-on-foot are also collected as in Figure 21. Most of the product information is collected from the Caterpillar official website.

ID	Brand	Contruction_Equipment	Model	Overall_Length(m)	Overall_Width(m)	Weight(
1	Finn	Bark Blower	BB302	4.34	2.01	2656
2	Finn	Bark Blower	BB1208	4.51	2.44	7548
3	Finn	Bark Blower	BB1216	7.01	2.44	11111
9	Simco	Auger	255-PTC			
10	Caterpillar	Auger	A7B	0.24	0.28	
11	Caterpillar	Auger	A14B	0.24	0.27	
12	Caterpillar	Auger	A19B	0.30	0.27	
13	Cifa	Truck Mixer	E8	7.17	2.36	4600
14	Cifa	Truck Mixer	E9	7.66	2.36	4900
18	Caterpillar	Backhoe	BH150	2.78	0.3(bucket)	1023
19	Caterpillar	Backhoe	BH160	2.94	0.3(bucket)	1047
20	Caterpillar	Blade	1893MM Angle Blade	0.75	1.89	313
21	Caterpillar	Blade	BB121 Box Blade	2.06	2.22	907
22	Caterpillar	Blade	14.8 M³ Coal U-Blade		4.90	2420
23	Caterpillar	Blade	3048MM Cushion Dozer Blade		3.05	4273
24	Caterpillar	Blade	2007MM Dozer Blade	1.03	2.01	491
25	Caterpillar	Blade	18.35 M³ Landfill U-Blade		4.27	2567
26	Caterpillar	Blade	16.4 M³ Reclamation U-Blade		4.88	3810
27	Caterpillar	Blade	6.9 M³ Variable Radius Semi-U Blade		4.27	1905
28	Caterpillar	Blade	72.6 M³ Woodchip U-Blade		6.73	7530
29	Caterpillar	Broom	BA118C	1.74	2.64	411
30	Caterpillar	Broom	BP115C	1.84	1.99	526
31	Caterpillar	Broom	BU115	1.49	1.81	430

Figure 21. Construction equipment attachment information table

ID	Worker Activity	Worker Speed(m/s)	Description/Charateristics	Click to Add
18	Dig		use shovel/tool, static, random position	
3	Drill		static, use driller	
4	Drive		use vehicle, see vehicle charateristics	
6	Fill		Pothole filling, static, use shovel	
15	Guide		can be edge or out of work zone, flag, guide truck	
19	Install/Uninstall		install barricades, cones, and markers	
17	Load/Unload		near back of truck, static, small range movement	
27	Measure		measure, mark point, big range	
2	Moving-Tool Handle		slow walking with roller, parallel to road	
21	Mow		similar to trim, only for grass	
16	Paint		1-3 workers, walk slow, with tool, not continous	
25	Pour			
26	Repair		Other movements of fixing structure	
11	Run	>1.79		
20	Saw		1 or 2 workers, with saw, no position specific	
24	Spread			
12	Sweep		slow walking with broom, or picking items	
23	Tamp		use tool (tamper), slow, specific area	
13	Trim		slow walking on shoulder/edge, with trimmer	
22	Turn		change direction	
14	Walk	0.89-1.79		

Figure 22.Common activities of highway construction workers

In the first database, besides the construction equipment, common activities of highway construction workers are collected as presented in Figure 22. It should be noted that in the activity recognition part, all activities are classified into 5 categories to improve efficiency.

Number	Sedan Model	Length	Width	Number	Small SUV	Length	Width	Number	Large SUV & Pick up	Length	Width
1	Citroen C4 Cactus	4.17	1.71	1	Hyundai i30 SW	4.58	1.79	1	BMW X5	4.89	1.94
2	Peugeot 308	4.25	1.8	2	Honda Civic Tourer	4.59	1.77	2	BMW X3	4.7	1.89
3	Hyundai i30 Fastback	4.45	1.8	3	Opel Astra Sports Tourer	4.7	1.81	3	Jeep Wrangler Unlimited	4.75	1.88
4	Audi A3 Sedan	4.46	1.8	4	Kia Stonic	4.14	1.76	4	Hyundai Santa Fe	4.77	1.89
5	Hyundai IONIQ	4.47	1.82	5	Suzuki Vitara	4.17	1.77	5	Subaru Outback	4.82	1.84
6	Mazda 3	4.47	1.95	6	Audi Q2	4.19	1.79	6	Mercedes-Benz G	4.82	1.93
7	Audi A4	4.73	1.84	7	Honda HR-V	4.29	1.77	7	Toyota Land Cruiser 5p	4.84	1.88
8	Volkswagen Passat	4.77	1.83	8	Jeep Compass	4.39	1.82	8	Lexus RX	4.89	1.89
9	Toyota Avensis	4.75	1.81	9	Jeep Renegade	4.25	1.8	9	Porsche Cayenne	4.92	1.98
10	Kia Optima	4.86	1.86	10	Toyota C-HR	4.36	1.8	10	Bentley Bentayga	5.14	2
11	Lexus GS	4.88	1.84	11	BMW X1	4.44	1.82	11	Audi Q8	4.99	2
12	Lexus ES	4.97	1.86	12	Mazda CX-5	4.55	1.84	12	Mitsubishi L200	5.2	1.78
13	Hyundai Veloster	4.22	1.79	13	Lexus NX	4.64	1.85	13	Nissan NP300 Navara	5.33	1.85
14	Porsche 911 Carrera	4.52	1.85	14	Volvo XC60	4.69	1.9	14	Ford Ranger	5.36	1.86
15	Honda Civic 4p	4.65	1.8	15	Mercedes-Benz GLC SUV	4.66	1.89	15	Isuzu D-MAX	5.29	1.86
16	Tesla Model 3	4.69	1.85	16	Toyota RAV4	4.6	1.84	16	Toyota Hilux	5.33	1.85
17	Suzuki Baleno	4	1.74	17	Honda CR-V	4.6	1.85	17	Volkswagen Amarok	5.25	1.95
18	Toyota Auris	4.33	1.76	18	Land-Rover Discovery	4.6	1.92	18	Infiniti QX70	4.86	1.92
19	Tesla Model S	4.98	1.96	19	Mazda CX-5	4.55	1.84	19	Land-Rover Range Rover	5	1.99
20	Audi A8	5.17	1.94	20	Subaru Forester	4.61	1.79	20	Renault Alaskan	5.4	1.85
	Avg	4.5895	1.8305		Avg	4.48	1.821		Avg	5.0275	1.9015

Figure 23. Common vehicle dimension database

As for CAV, the second database was built in Excel. Common models of vehicle are collected, and the length and width information as shown in Figure 23. In this section, vehicles are identified as sedan, small SUV, large SUV or pickup truck. For each category, dimensions of 20 common models are recorded and averages are calculated. The dimensions of vehicles are from automobile dimension website (Automobile dimension).

2.7 Hazard Detection Algorithm Development

The threat zones and influencing factors of the hazard detection design are presented in previous sections. They are the elements of the hazard detection design which construct the functions of the system. To realize the individual elements in a feasible and comprehensive detection system, more details related to programming need to be considered such as data recognition and classification, threat zones generation for each actor, unsafe proximity recognition, messages generation, etc. The following sections reveal the combination of the elements and introduce the realization of the algorithm design in MATLAB.

2.7.1 Data Time Flow

In the algorithm, the first step of data processing is to recognize the timestamp of the dataset. In this research, due to the format and content of data from CAV or UWB tags is different. In the beginning, the algorithm identifies the CAV data and UWB tag data based on the tag numbers. Datasets from CAV and UWB are stored separately.

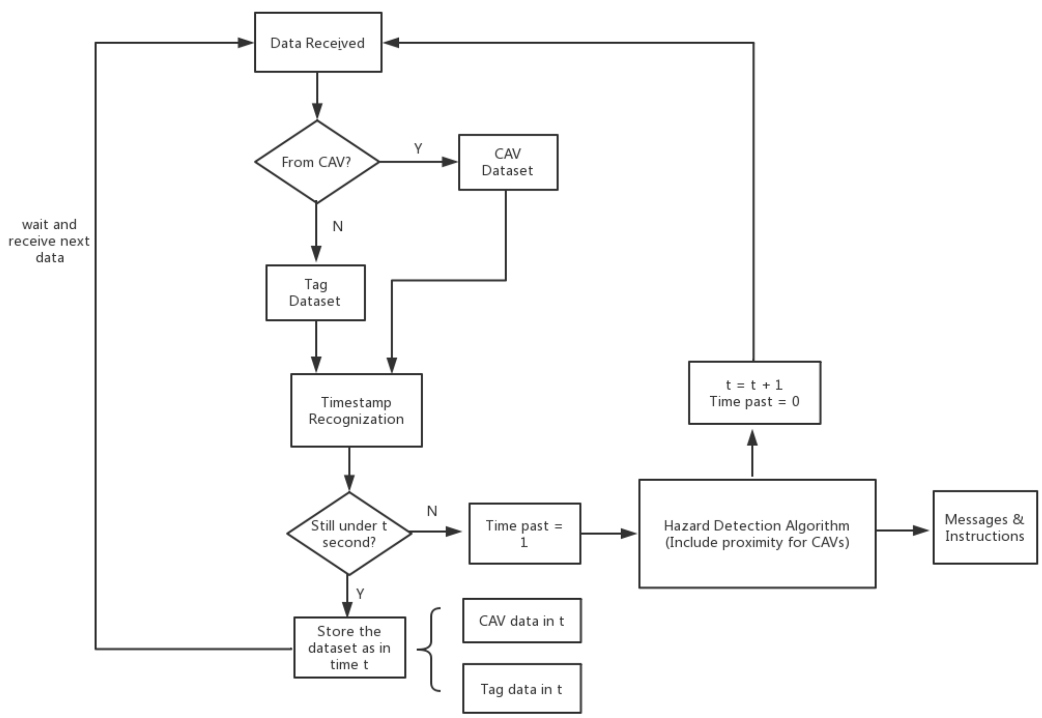


Figure 24. Time flow of the algorithm and data

Then the algorithm extracts and reads the timestamp from the dataset. To be noted, the server sends out one dataset each time, therefore, the algorithm reads the datasets one by one. The identified timestamp is compared with the current time *t* (current time collected from last second, unit is second). Locational data sent from the same second is collected and combined into one dataset for the following analysis. Once the timestamp is identified from the next second *t+1*, the dataset from last second *t* is determined and no new dataset will be added to it (as presented in Figure 24). And the parameter *time past* equals to 1 means the current second is ended.

Then the datasets from CAV and tags are processed by the hazard detection algorithm. The processed locational data in the same second is averaged to ensure accuracy. When finished the processing, *time past* parameter returns to 0 and the current second moves to next second. The data collection part is repeated from second to second.

2.7.2 Data Classification

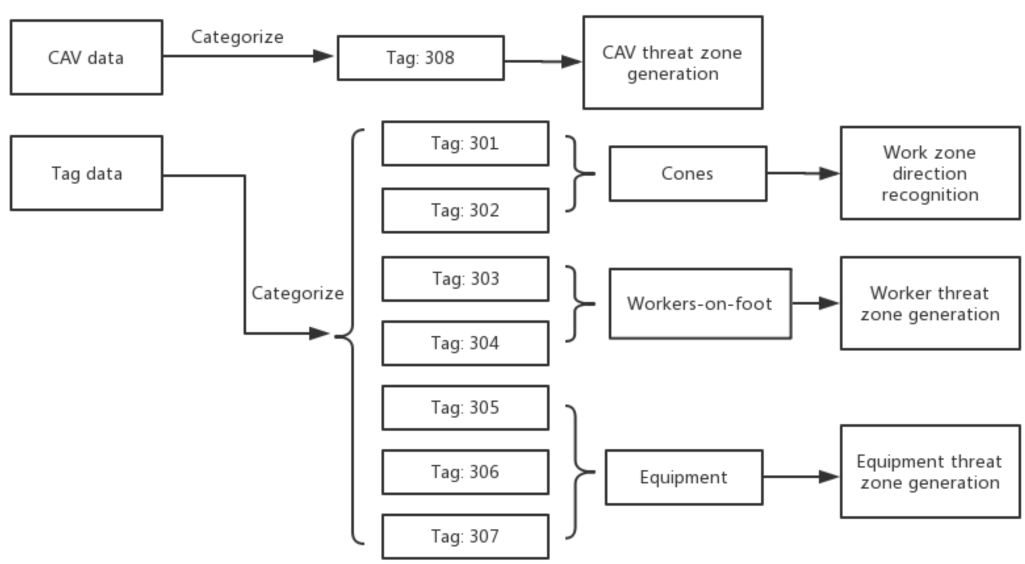


Figure 25. Data classification in the algorithm

Although the CAV datasets are separated from tag datasets, no filter is built in the server to recognize datasets from each tag. Before process the data, it is essential to classify the sources of the datasets. Tag numbers are predefined in the programming, as presented in

Figure 25. 301-302 are presenting cones; 303-304 are presenting workers-on-foot; 305-307 are presenting the equipment. 308 is for the CAV. After filtering the CAV data and tag data introduced above, tag data is categorized into fine classification. Based on the sources of the data, tag dataset and CAV dataset will be transferred to typical threat zone generation functions.

2.7.3 Threat Zones Generation

After the data classification, the classified data is used for generating the work zone border or threat zones based on its source. Data from the cones are used to define the work zone boundaries. And data from other sources is used for threat zone generation.

The algorithm compares the data in the current second and one in the last second to calculate distance, velocity, direction of the actor within one second. As an example, the algorithm for equipment is presented in Figure 26. With the construction equipment dimension information from the databases, the algorithm can automatically generate alert zones for the equipment. Then the algorithm expands the alert zone area to generate a warning zone according to the calculated speed and direction.

As a real-time algorithm, it only generates the warning zone and alert zone within the current second. If in the next second, the actor is stationary then no direction, displacement will be calculated. Thus, the algorithm cannot generate the warning zone (since the warning zone is dynamic) and the alert zone with reasonable direction (direction is also calculated based on displacement). To make the threat zone consistent with time, when the current second ends, the alert zone for that second will be stored for one second until the end of the next second.

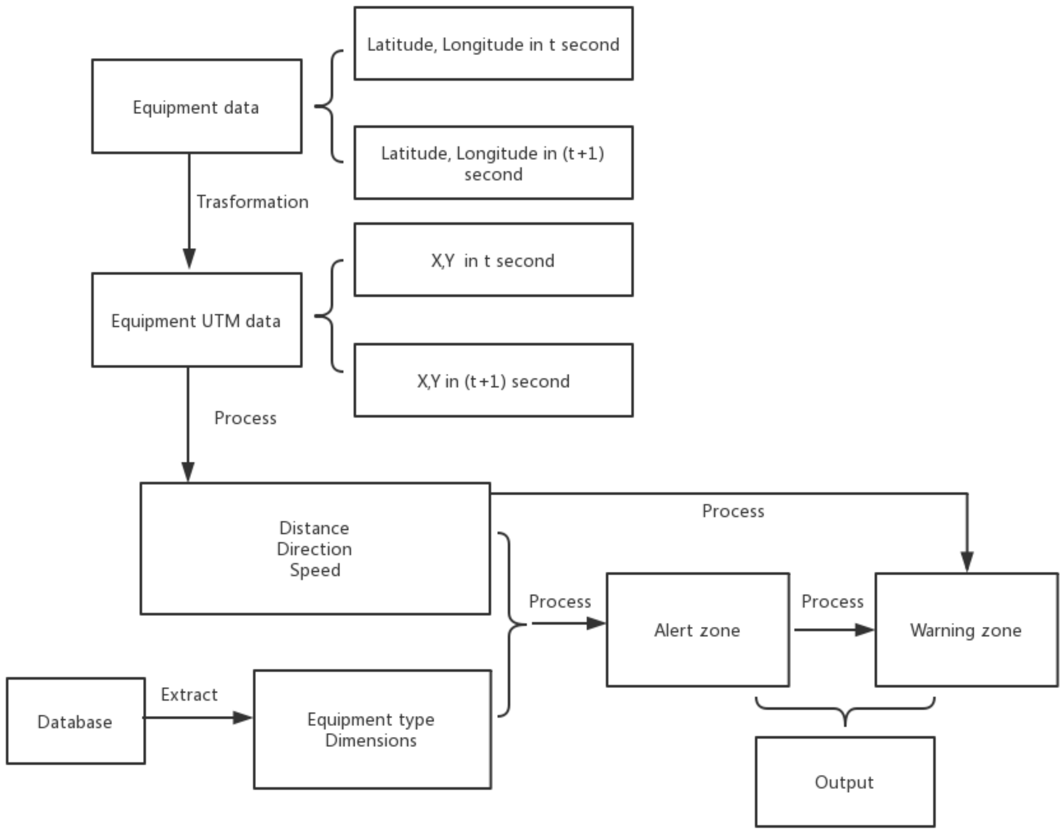


Figure 26. Real-time alert zone and warning zone generation

If the equipment remains stationary, then it will have the alert zone as in the last second. However, since the warning zone is dynamic and it is the prediction of equipment's future movement, no warning zone will be displayed since future movement cannot be predicted by a stationary condition.

Furthermore, the threat zone generation algorithms for workers-on-foot and CAVs have similar logic as the equipment one. They all require locational and other information to provide the warning zones and alert zones. Different from equipment, since the warning zone of workers-on-foot, is predefined and CAVs are in high-speed traffic in most of the cases, their alert zones will not be stored for stationary situations.

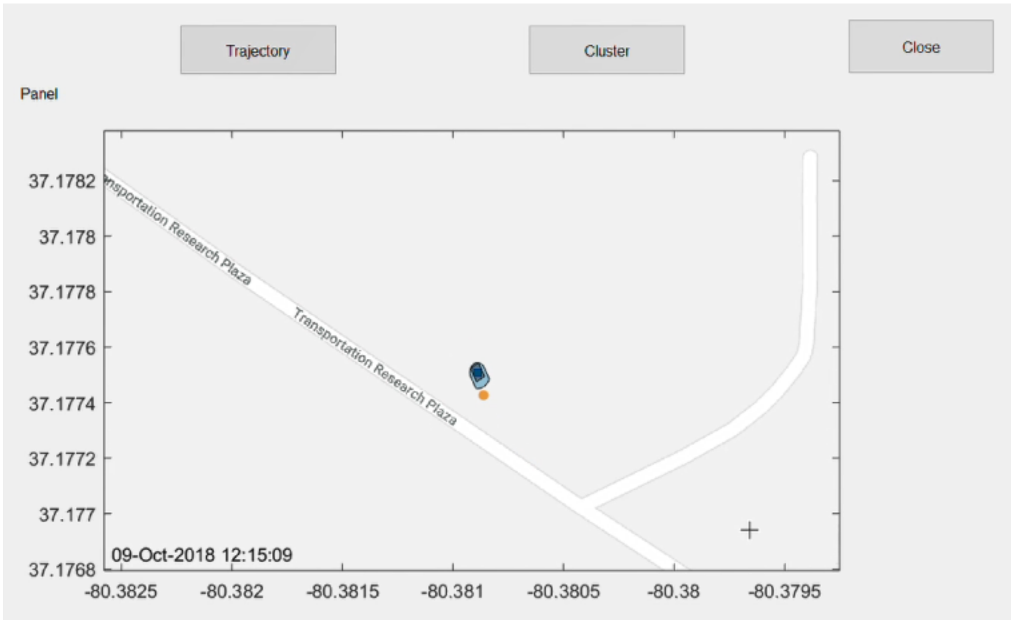


Figure 27. Real-time threat zones for equipment and worker-on-foot in MATLAB GUI

2.7.4 Proximity Development

The work zone proximity warning is only for passing CAV on the highway. It aims to provide proximity information to both the driver and the on-site workers. The proximity part of the algorithm only considers locations of CAV and workers-on-foot.

In this section, firstly, the location of CAV needs to be compared with work zone border location data. Through the distance between CAV and two ends of the work zone (proximity warning only for the straight section at this phase of the research), the algorithm can estimate the relative location of the CAV, such as approaching or passing the work zone. If the algorithm determines the CAV is approaching the work zone, it will move to the next part of the algorithm. Otherwise, if the CAV has already passed the work zone, it will ignore the CAV movement; or if it is inside the work zone road section, the algorithm will only focus on potential collisions detection (because proximity warning is for vehicles which are approaching).

As presented in Figure 28, when the algorithm determines that the vehicle is approaching, it calculates the relative distances between the CAV and each worker-on-foot. The worker who has the shortest relative distance to the CAV will be marked as the first worker inside the work zone. When the relative distance between the first worker and the CAV is less than 100 meters, the algorithm adds the CAV in *proximity* parameter and provides proximity warning to both the vehicle driver and the workers-on-foot inside the work zone. If the distance does not reach 100 meters the algorithm will continue to compare their distances in each second.

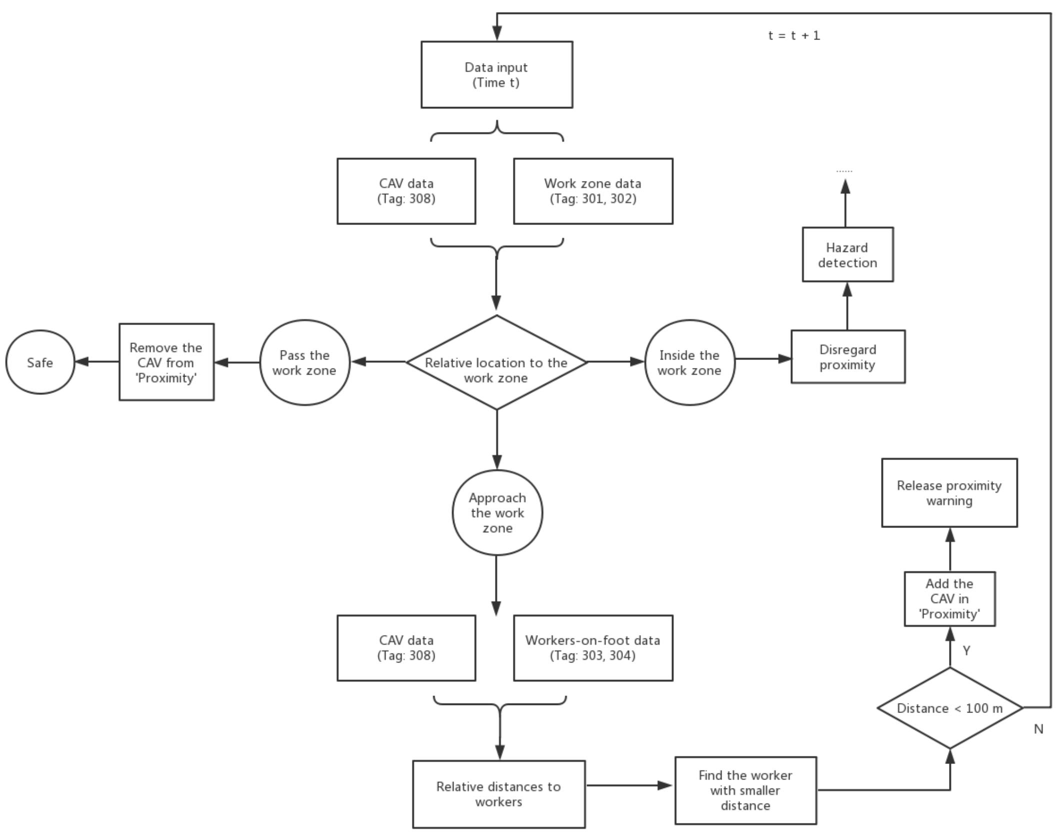


Figure 28. Proximity determination for CAV

2.7.5 Messages and Instructions Generation

In this research, hazard detection is determined by the overlapping threat zones. Once the threat zones overlap, the potential hazard is predicted to happen in the new future due to their trajectories may interfere with each other (as shown in Figure 29). Therefore, once threat zones overlap, the warning messages will be generated as shown in Figure 30.

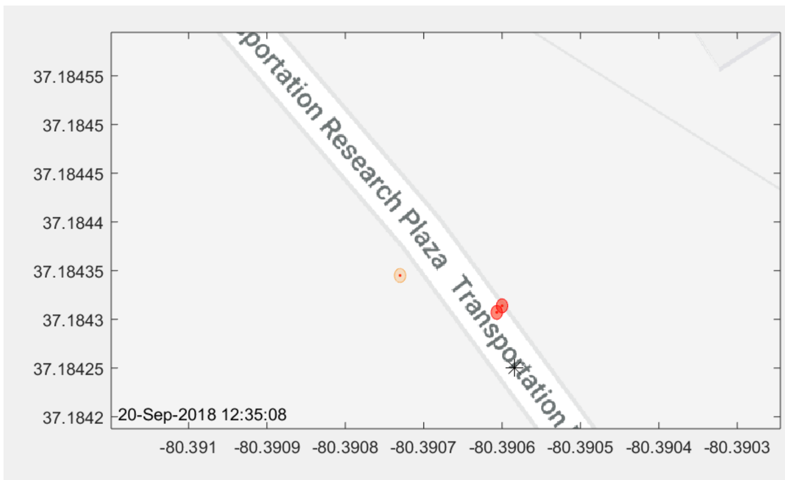


Figure 30. Hazard detection between two workers-on-foot; Workers-on-foot in danger are shown in red

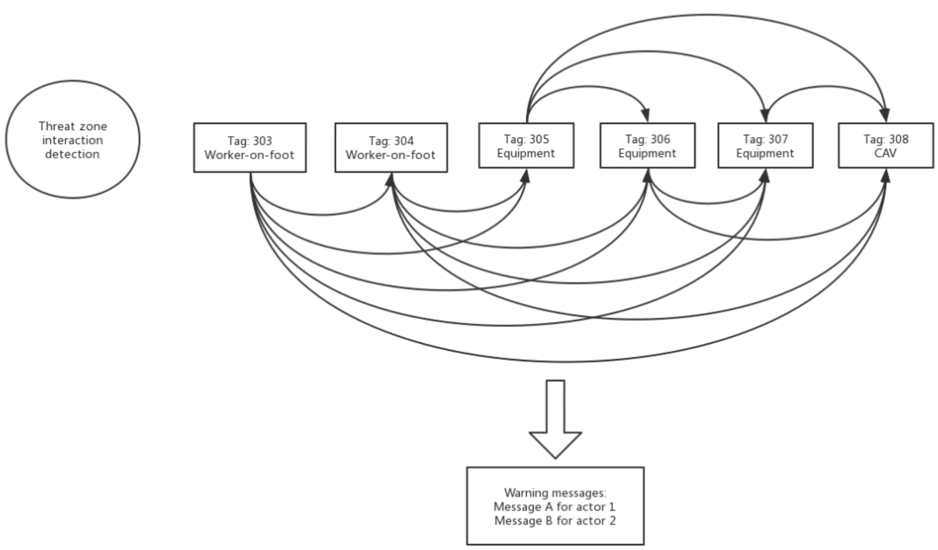


Figure 29. Hazard detection between each actor and message generation

The logic of hazard detection is to find the overlapping situation between every actor. In Figure 30, the algorithm detects the threat zone interaction for each actor, two at a time. Once two actors have a potential collision between, the threat warning messages for both actors will be generated and sent to the server.

For workers-on-foot, the algorithm can provide short instructions to advise them on how to avoid potential collisions. As presented in Figure 31, if a threat is detected and one or both related actors are workers-on-foot, the message generation process will move to the next section. In this section, suitable escaping directions will be analyzed and presented as part of the messages.

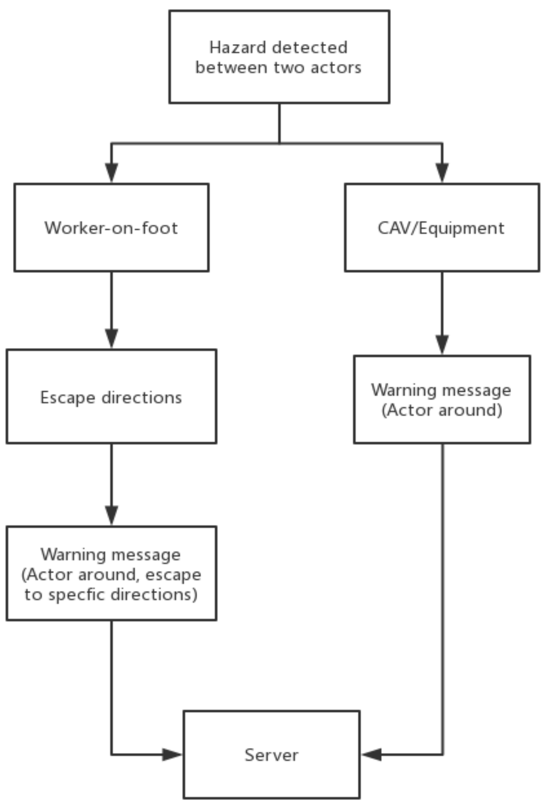


Figure 31. Different message generation processes

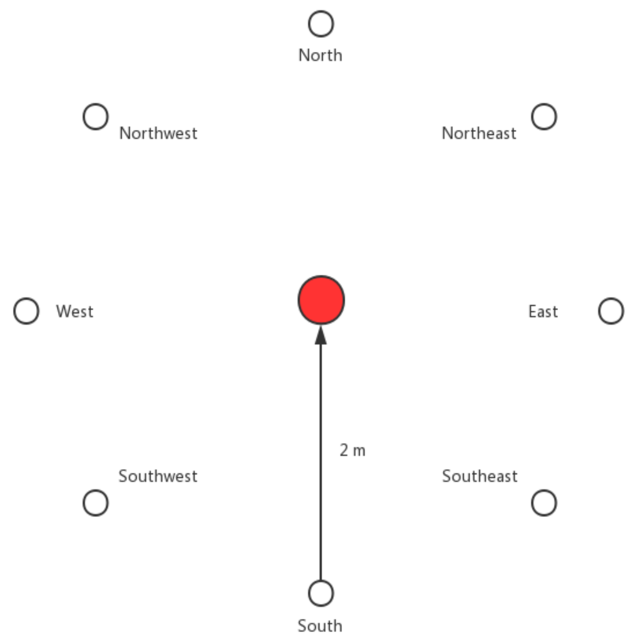


Figure 32. Instruction generation

In the instruction generation process, 8 virtual points are created and located around the worker-on-foot as presented in Figure 32. Each virtual point represents a direction which indicates an escaping route for the worker. The distance between worker-on-foot and each virtual point is 2 meters. This distance is larger than the warning zone radius, but worker-on-foot still can reach the virtual points in a very short time. The algorithm tests each virtual point safety status to see if any of the virtual points locate inside the threat zones of other actors. The virtual points inside the other warning zones are marked as dangerous and filtered by the algorithm. Only virtual points with safe status and their representing directions are returned as instructions. As presented in Figure 33, the warning zone of equipment overlaps with the one of a worker-on-foot, two messages are created for both the driver and worker. The message for the worker-on-foot includes instruction with escaping directions. It advises the worker-on-foot should move to south, southwest, and west direction. The instructions can help workers-on-foot find a feasible route for avoiding the potential hazard.

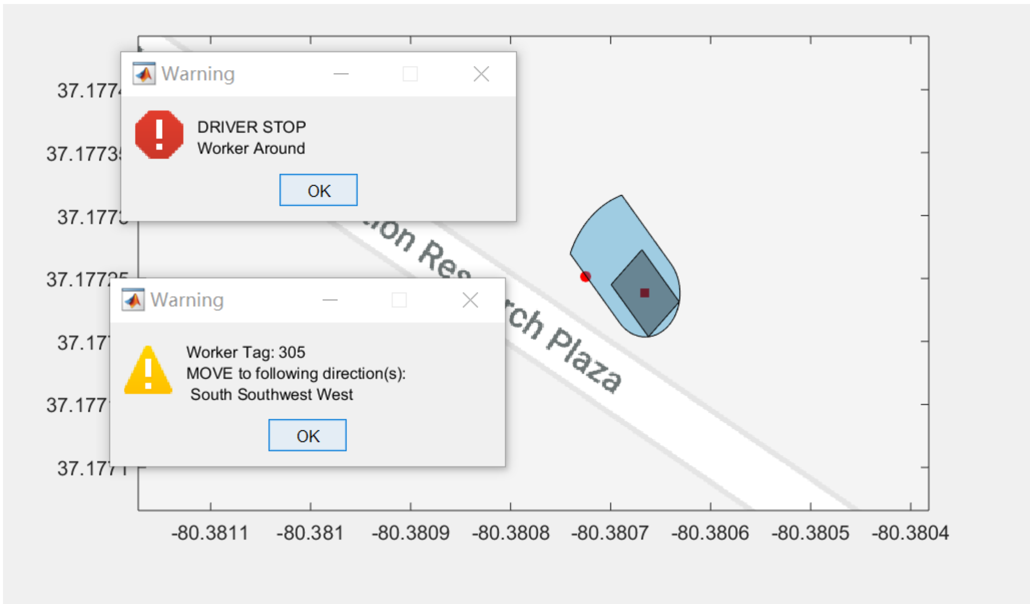


Figure 33. Messages with real-time instruction in MATLAB GUI

Proximity messages generation is similar to the threat messages generation process. When the relative distance between the CAV and the first worker is less than 100 meters, proximity messages will be generated and sent to the server. The proximity messages are only provided when the vehicles are approaching the work zone.

After all the hazard messages and proximity messages, if the actor comes back to a safe status, the algorithm will send a safety message to indicate their status change. It can help all the actors check their status easily.

Currently, real-time messages can be only sent to the server and the CAV. In the future, additional devices will be designed to provide real-time messages to the workers-on-foot and equipment operators.

2.8 Activity Recognition

2.8.1 Activity Category

During highway road work processes, workers perform various activities depending on work assignments. Different activities are subject to different levels of exposure to potential hazards. In data collection section, activities and movement data were recorded and classified into 5 common categories as presented in Table 2. In this research, a supervised learning method is used for classification.

Table 2. Activity Category and Description

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

A total of 49 movement patterns were identified and categorized, including three samples of jackhammering, 16 walking, 10 rolling (hand-held equipment which required regular moving), 14 guiding(moving backward) and 6 random movements.

2.8.2 Influencing Factors and Calculation

Data sent from the tags, which was used for classification, include the tag number, timestamp, and location. Therefore, activity recognition in this research is a rough classification only based on location data and timestamp for workers-on-foot. The activity pattern is identified from the movement in a time period.

Speed, static time, type of direction (parallel/perpendicular to traffic, moving in/against traffic direction) are used here as quantified factors for activity recognition. Speed is calculated by distance divided by the corresponding time of movement. Static time describes the duration of workers-on-foot staying at a certain position when performing tasks. It is a fraction with static duration time as the numerator and with total activity time as the denominator. The longer the worker stays still, the larger the fraction can be. If the static time parameter equals 1, it means that the worker stays at the same location during the whole activity.

The direction is another factor for classification, because certain activities may be tied to a typical direction or a combination of directions. To categorize directions, parallel/perpendicular to traffic, moving in/against traffic direction situations are considered in this study. The direction of workers-on-foot is a vector and it needs to be combined with the direction of the highway. The categorized directions in this research is a relative direction when comparing to the highway. Furthermore, the direction of the highway should be absolute direction such as north, south, etc.

To calculate the relative directions of workers, absolute direction of the highway needs to be calculated at the beginning. The absolute direction is obtained by the location of cones in this research. Two cones are located at the two ends of a straight work zone, or 3 cones located at the two ends and the center of a curve work zone, can help to construct a/two lines. The line(s) can be used to calculate the difference of degrees between the work zone and the north direction.

After the absolute direction of the highway work zone is identified, relative direction needs to be determined. In this research, trigonometric functions are used to describe the relationship between the direction of workers and roadway.

For the parallel/perpendicular to traffic direction, the sine function is used to quantify the direction value. As calculated as Equation 1 and 2, when no degree difference between absolute moving direction and absolute roadway direction, the value is 0. When moving direction perpendicular to traffic direction, the value would be 1. Therefore, under the sine function, the absolute value closer to 0 means the moving direction tends to be parallel to the traffic direction. Relatively, the result closer to 1 means the moving direction tends to be perpendicular to the traffic direction.

$$\sin 0° = 0$$

Equation 1. Parallel to traffic direction

$$\sin 90° = 1$$

Equation 2. Perpendicular to traffic direction

Similarly, for the in/against traffic direction, the cosine function is used to quantify the direction value. As shown in Equation 3 and 4, in/against traffic direction can be determined by the result of the cosine function. When moving in traffic direction, the equation result would be 1. Therefore, under sine function, the result closer to 1 means the moving direction tends to be in the traffic direction. Similarly, the result closer to -1 means the moving direction tends to be against the traffic direction.

$$\cos 0° = 1$$

Equation 3. Moving in traffic direction

$$\cos 180° = -1$$

Equation 4. Moving against the traffic direction

Supervised learning was performed using MATLAB. All models in Classification Learner application were tested and compared, and the trained model with the highest accuracy is selected for activity classification and prediction.

2.9 Summary

In this chapter, various elements of the threat detection system are presented. The hazard is detected when the threat zones overlaps. The developed hazard detection algorithm designed for workers-on-foot, construction equipment, and CAVs to reduce the risk of collisions. The different influencing factors is then explained. Moreover, the trajectory and status of each worker-on-foot/equipment/CAV is visualized on VCC Monitor.

A database is developed to provide basic information of equipment and CAVs to the algorithm in order to generate accurate threat zones. The database also includes common activities of work zone workers. The collected data from the experiments were categorized and the activity recognition factors are introduced in this chapter.

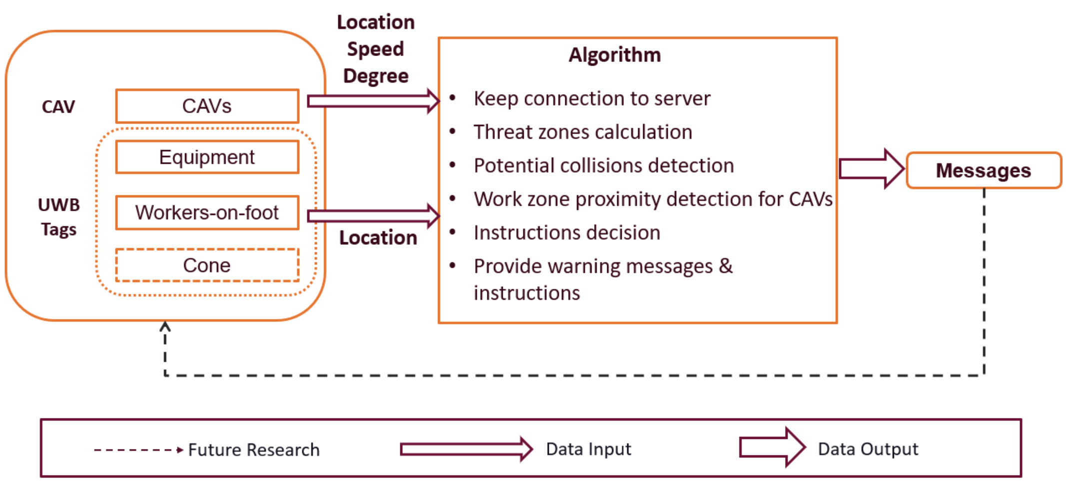


Figure 34. Data flow and algorithm

As presented in Figure 34, this chapter also introduces the data flow and how it goes through the algorithm. Once the data received by the system, the algorithm reads and classifies the data. Based on its source, the algorithm provides different process to the data. Data from specific cones will be analyzed by different functions in the system. Based on the data, speed and direction is calculated and determine the threat zones. Once threat zones overlap, the hazard will be identified by the algorithm. Then the messages and instructions will be generated based on the result of the hazard detection as output.

Chapter 3

Results

3.1 Introduction

In this research, MATLAB was used to realize the hazard detection algorithm and activity recognition as mentioned in previous chapter. The main program and related functions were compiled into a stand-alone application. The application is installed in the cloud server and a demonstration was held to eveluate the outcomes. The demonstration tested the connection between the algorithm and the server. The hazards were detected by the hazard detection system, and the corresponding threat messages and instructions were successfully generated. The inspectors could directly read the messages and instructions through the server.

Activity recognition model is trained by MATLAB classification learner application. To enhance the accuracy, a two-step analysis method is applied. Firstly, the qualitative moving directions are predicted by the model through the quantitive factors. Secondly, the qualitative directions are added as factors to predict the final activity result. Ensemble Bagged Trees model with the highest accuracy 75.5% is selected. However, the results show that the model has confusion in typical activities such as walking and rolling, which share similar moving patterns.

3.2 Activity Recognition

A total of 49 movement patterns were identified and categorized, including three samples of jackhammering, 16 walking, 10 rolling (hand-held equipment which required regular moving), 14 guiding (moving backward) and 6 random movements. Four feature selections for classification were speed, static time, movement direction as parallel/perpendicular to traffic and moving in/against traffic direction. The factors identification and quantification are introduced in the previous chapter.

49 data samples and 5 activity categories are used to train the models of supervised learning. MATLAB classification learner is the training tool. The learner can train typical models at the same time and give corresponding results.

Initially, 65.3% accuracy was the highest achieved from Ensemble Bagged Trees, which was a combined machine learning method that groups weaker learners and outputs a stronger result. In order to improve the accuracy, the training process was split into two steps as shown in Figure 35. The first step is to use the quantified data of the 4 factors to define the direction of movement in terms of parallel/perpendicular and the moving in/against traffic parameters in qualitative data as shown in Table 3.

Table 3. Prediction Categories of First Step Learning

Prediction	Category
Direction	Parallel, Perpendicular, None
Traffic	Facing, In, None

Subsequently, using the detected movement directions with the quantified factors, undergoing activities are recognized in the second step as in Figure 35. Step 2 combines the original information in step 1 and the results of the step 1 models. With the qualitative results of movement directions, the decision making of the supervised model is more efficient. This way, direction information can be double verified, and the accuracy of the

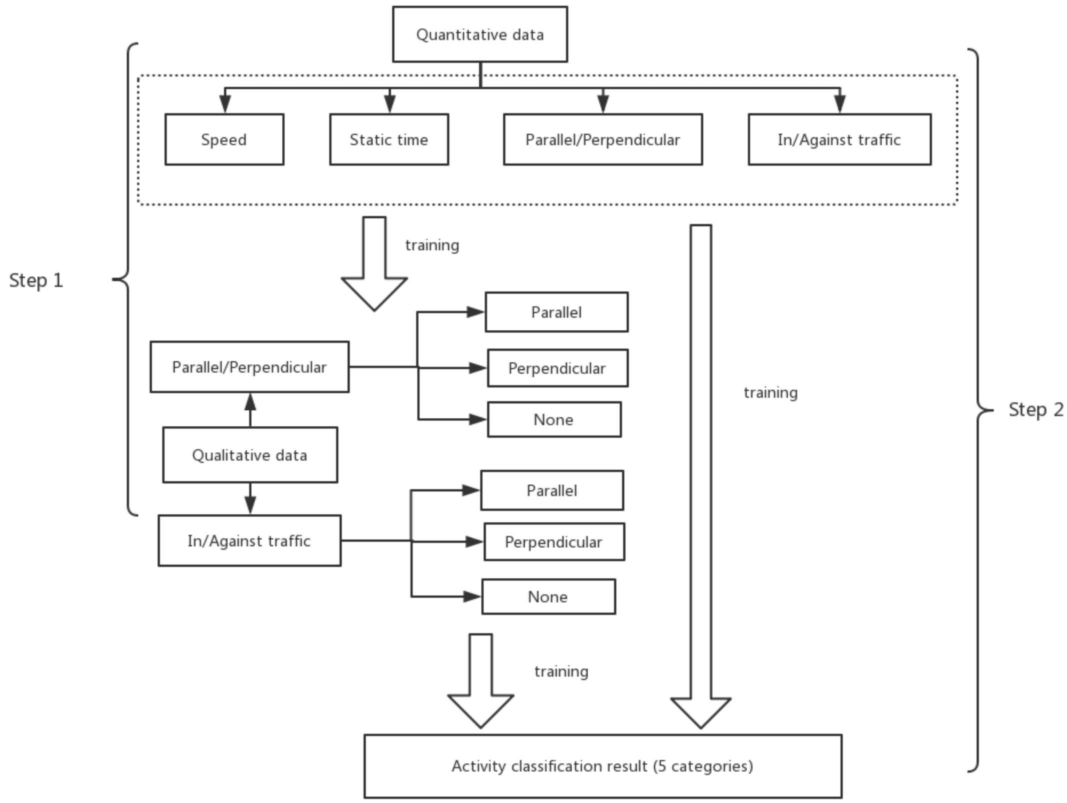


Figure 35. Two-step method for activity recognition

model was significantly improved through this further verification. As a result, the accuracy was enhanced to 75.5% from Ensemble Bagged Trees.

Although the trained model shows an enhanced accuracy, the confusion matrix shown in Figure 36 reveals that some activities are easily confused. Such as walking and guiding, jackhammering and random activity, rolling and walking, etc. Because this research chooses common activities inside the work zone for workers-on-foot, however, activities have similar features are hard to classify. Take a walking and guiding as an example, two activities are basically movements of walking. But guiding is generally representing walking backward at a slow pace. The influencing factor between walking and guiding is the moving direction and speed. However, besides individual factor, walking forward can also at a slow speed.

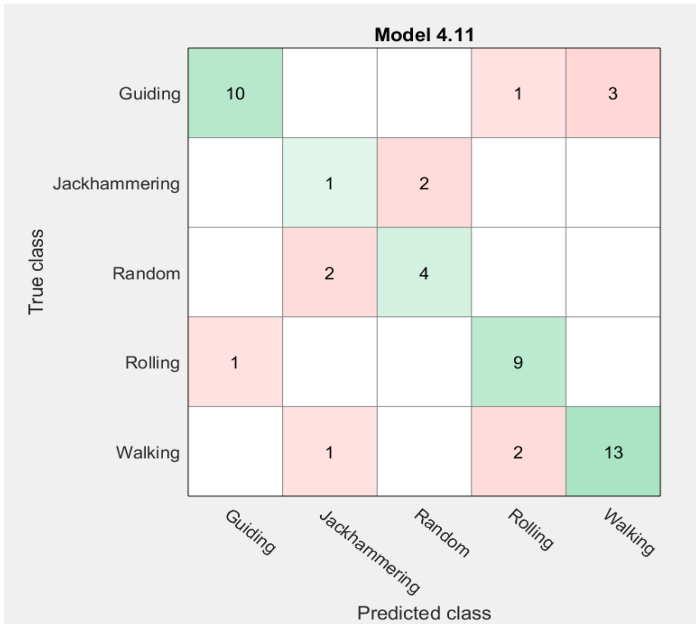


Figure 36. Confusion Matrix of Ensemble Bagged Trees

In addition, more activity samples are required to further confirm the feasibility of the model. Currently, the number of activity samples and participants are small. Also, the number of samples are not equivalent for different activities. The results can be improved with increasing activity samples in future research.

3.3 Demonstration

Informal demonstrations were held to evaluate the outcomes of the research. One CAV was used to test the proximity warning and 3 participants held the sensors as equipment and workers-on-foot. The demonstrations aimed to test the connection between the algorithm and the server and validate the feasibility of the hazard detection and message generation algorithm.

In the demonstration, 5 different scenarios were tested. In each scenario, CAV was driven in close proximity to the work zone border.

The scenarios include:

- Worker-on-foot was walking parallel to work zone border
- Worker-on-foot was walking perpendicular to work zone border
- Worker-on-foot was walking parallel with equipment in the same direction
- Worker-on-foot was walking parallel with equipment in the opposite direction
- Two workers-on-foot were walking in two random directions

```
data:Received message:  Threat,305,Vehicle/Equipment,Worker,304,is in your way
data:Received message:  Threat,304,Worker,MOVE to following direction(s),
data:Received message:  Threat,305,Vehicle/Equipment,Worker,304,is in your way
data:Received message:  Threat,304,Worker,MOVE to following direction(s), North      Southwest  West  Northwest
data:Received message:  Threat,305,Vehicle/Equipment,Worker,304,is in your way
data:Received message:  Threat,304,Worker,MOVE to following direction(s),     South  Southwest  West  Northwest
data:Received message:  Threat,305,Vehicle/Equipment,Worker,304,is in your way
data:Received message:  Threat,304,Worker,MOVE to following direction(s), North    Southeast  South  Southwest  West  Northwest
data:Received message:  Threat,305,Vehicle/Equipment,Worker,304,is in your way
data:Handshake complete.  Listening for messages on the TCP socket.  There are currently 1 active TCP socket connections.
data:Received message:  Safe,304,Worker,Other actors are away
data:Received message:  Safe,305,Driver,Other actors are away
data:Received message:  Threat,304,Worker,MOVE to following direction(s),   East  Southeast  South  Southwest  West  Northwest
data:Received message:  Threat,305,Vehicle/Equipment,Worker,304,is in your way
data:Received message:  Safe,304,Worker,Other actors are away
data:Received message:  Safe,305,Driver,Other actors are away
data:Handshake complete.  Listening for messages on the TCP socket.  There are currently 1 active TCP socket connections.
data:Handshake complete.  Listening for messages on the TCP socket.  There are currently 1 active TCP socket connections.
```

Figure 37. Received messages in the server

In the demonstrations, the connection between the algorithm in the MATLAB with the cloud server was successfully established. The data and corresponding messages received by the server successfully once the actors come close together as presented in Figure 37. In different scenarios, messages for different actors were received based on the unsafe proximities. With the collected data and safe/unsafe situations calculated by the algorithm, the status and trajectory of each actor were shown on VCC Monitor.

The messages for the equipment operator and vehicle driver were in a fixed form. For the workers-on-foot, as shown in Figure 37, the instructions were changing with the locations and status of the workers. Proximity detection was also tested during the demonstration. When the CAV was approaching the work zone, the algorithm sent out the proximity messages successfully.

Safety messages were also checked for the feasibility. As shown in Figure 37, safety message came after the threat or proximity messages. The proximity and safety messages only contain tag number, actor and fixed instructions.

3.4 Summary

The result chapter includes activity recognition model and the demonstration of hazard detection algorithm. 49 data sets from 5 categories were collected and used for training the supervised learning model in MATLAB. With the two-step machine learning process, the accuracy of the model is improved. Eventually, Ensemble Bagged Trees model with 75.5% accuracy is selected since it has the highest accuracy among the available classification models.

A demonstration was held to prove the usability of the algorithm. Through the demonstration, different scenarios were performed to test the algorithm. The connection between algorithm and the server was established successfully. The status of each actor was shown on the VCC Monitor. Moreover, the messages and instructions were generated and received successfully in real-time based on the scenarios.

Chapter 4

Conclusion

4.1 Summary and Concluding Remarks

Highway work zones create high safety risk for construction workers and drivers due to their close proximity to high-speed traffic. Workers-on-foot inside the work zone require sufficient protection from potential hazards caused by such proximity. However, construction workers in the highway work zone are still facing high fatality risk from collisions and many fatalities and injuries of workers, operators and drivers occur every year.

A connected hazard detection system for highway workers is developed in this research. The system proactively collects and transmits real-time location information of work zone actors, i.e. workers on foot, equipment and passing CAVs, extracts information from the developed database and hazard detection algorithm stored in the cloud server to detect potential hazards at highway work zones. Ultra-WideBand sensors were selected and used for real-time data collection and communication with cloud server. This system can help ensure safety of construction workers from hazards inside and outside of the work zone. The real-time trajectories and detected hazardous proximities are visualized on VCC Monitor in real-time to help planners and project managers in better management of their work sites.

To this end, threat zones are introduced for work zone actors including workers-on-foot, construction equipment and CAV, consisting of alert and warning zones. The threat zones are designed taking into account influencing factors such as speed, direction and trajectory of movement of actors relative to their activity. Other typical influencing factors for threat zones are also considered. The research separates curve and straight road sections when determining the threat zones for workers-on-foot as they impose different levels of exposure to threats. It also considers the workers-on-foot's distance to the work zone border. The closer the workers, the larger the threat zone they would have.

The threat detection algorithm enables real-time communication with server and detection of potential hazards and provides prompt warnings to help actors prevent the hazards. To this end, the algorithm receives real-time location data collected from the work zone actors, detects potential hazards taking into account all influencing factors and sends warning messages to server and drivers of passing CAVs when an imminent threat is detected. Furthermore, workers-on-foot are provided with instructions guiding them to safe directions to help prevent the detected threats. In case of CAVs, in addition to imminent threat, proximity warnings will be sent when they are 100 meters away from the first worker inside the work zone. This helps effectively raise drivers' awareness.

Activity recognition is also employed to accurately detect workers' activities and accordingly predict their movement trajectories. 49 data sets were collected to train the models and 5 common activity categories for work zone workers were used as the classification result. Ensemble Bagged Trees model is selected with the highest accuracy.

Through in-time prediction of potential imminent threats and considering all involved actors, i.e. workers, equipment and passing vehicles, and influencing factors, the method significantly contributes to reducing crashes in highway work zones. The system can be used not only for proximity warning but also for further study on work zone real-time situations and thus could assist in decision-making for managers.

4.2 Discussion

The connected work zone hazard detection system can provide proactive protection when comparing to passive personal protective equipment. Unlike available methods, the developed system provides a holistic solution to work zone safety problem by taking into account all factors contributing to a threat from inside as well as outside of the work zone. This innovative design combines workers-on-foot, construction equipment and CAV into one connected work zone system while other researches either consider collisions between workers and passing vehicle, or the collisions between actors inside the work zone. This research eliminates the redundancy of the separated hazard detection system for outside or inside the work zone. The holistic hazard detection system brings convenience for workers, equipment operators and vehicle drivers.

Furthermore, the developed hazard detection system operates in real-time. The system utilizes real-time data to predict the trajectories of each actor inside or outside the work zone to analyze the potential hazards and provides real-time warning messages about imminent threats. As such, potential imminent threats are detected before they occur and can be prevented. It is a multifunctional tool which can also detect the proximity of the approaching CAV and prepare drivers to enter work zone areas. The system also considers actual influencing factors when designing the threat zones for the actors.

The developed solution can also help project managers and safety personnel to manage highway work sites more efficiently. The VCC Monitor is a custom web-based situational awareness tool. The users can easily log in the website to monitor all the actors. With the installation of the hazard detection algorithm, managers or inspectors can conveniently keep track of the movements of each actor and the safety status. The system not only can prevent the collision accident from occurring with the hazard detection algorithm but also can help the managers to react regarding the situation inside or outside the work zone before an accident happens.

The activity recognition further elevates the accuracy of the threat detection system through detecting activities of workers and predicting their movement relative to their assigned activities. With the predicted result of the activity, the accuracy of the proactive hazard detection algorithm can be improved. Furthermore, the messages and instructions can be customized based on the predicted activity. The result of the prediction is also presented on the VCC Monitor to help project managers to monitor worker activities and progress of the project.

Consequently, the developed hazard detection system is expected to significantly improve safety level of the highway work zone. With proactive security and reducing false positive warnings, workers can focus on their roadway construction or maintenance work without being interrupted or concerned about being hit by a passing vehicle or equipment. Therefore, the productivity of the road construction work is also expected to be enhanced by the hazard detection system.

4.3 Future Work

Although the design of the current system was attempted to be comprehensive by taking into account different factors and actual scenarios, each construction site is unique and may involve factors not included in this research. As such, the system will be made more flexible to be adjustable to specific conditions governing various work sites. Other issues were also found during the course of the research that will be improved in future work.

During the data collection, UWB technology was used for communication but the received data was not stable. The communication was interrupted for reasons such as humidity, relative location, line of sight, height, etc. Other localization and communication technologies will be considered in future research. In the highway work zone, due to the importance of hazard detection, the consistency of communication technology is essential. Future research needs to select suitable sensors with higher consistency and resistance for outside interference.

The factors mentioned in this research can be extended to cover more actual situations, and more factors can be considered for an adjustable hazard detection system for the connected work zones. Some potential influencing factors include weather, daylight, project plan, worker density inside the work zone, etc. For activity recognition, more samples of activities will be collected and used in future research. In the next phase of the research, a new wearable safety device will be invented as a piece of personal protective equipment. The developed threat detection system will be imbedded in the designed device enable real-time bi-directional communication and receiving ad-hoc warnings.

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