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HAZARDOUS PROXIMITY ZONE DESIGN FOR HEAVY CONSTRUCTION EQUIPMENT

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Abstract: The construction industry continues to be among the leading industries for workplace fatalities in the U.S. After experiencing 824 fatal injuries in 2013, the construction industry continues to rank as one of the most dangerous work environments when compared to other private industrial sectors in the U.S. Conditions of construction sites often produce hazardous proximity situations by requiring ground workers and heavy equipment to operator at close proximity. The gathered injury and fatality statistics indicate that current safety practices of construction workers have proven inadequate. The objective is to design hazard zone around pieces of heavy construction equipment in which ground personnel should not enter during construction operations. The scope is limited to construction sites and equipment at a horizontal grade and hazards between heavy construction equipment and workers-on-foot. A framework for creating the hazard zone around any piece of construction equipment is presented including detailed methodology discussions for each step. The hazard zone for a dump truck, excavator, and backhoe are shown using the created framework. Construction resource tracking data was used to validate the created hazard zone around a dump truck. Results indicate that hazard zones for ground workers can be created around construction equipment to increase hazard awareness for workers. Furthermore, additional safety standards can be formulated based on the ability to design and eventually implement hazard zones on construction equipment.

1 INTRODUCTION

Construction environments are typically comprised of multiple resources that perform dynamic activities in a specific space. This often requires construction resources, such as ground workers and heavy equipment, to operate at close proximity to each other creating potential hazardous proximity situations. The risk of injuries and fatalities increases as contact collisions between ground workers and heavy construction equipment occur.

A majority of past research efforts for hazardous proximity situations have collected and analyzed statistics for injuries and fatalities resulting from contact collisions between heavy construction equipment and ground workers (CFOI, 2011). Safety standards for hazardous proximity situations between heavy construction equipment and ground workers include Personal Protective Equipment (PPE) and equipment back-up alarms (OSHA, 2014). These regulations signify the hazards associated with ground workers and construction equipment working at close proximity, but have proved inadequate to prevent incidents from occurring.

A review of current construction worker fatality statistics resulting from hazardous proximity situations between heavy construction equipment and ground workers is completed. The created framework for designing a hazard zone for a piece of construction equipment is presented and followed by a discussion of identified limitations, benefits, and recommendations. Position tracking data of a dump truck on an active construction site was used to validate the created hazard zone. Future research work on proximity detection and alert systems for the construction industry is also addressed.

2 LITERATURE REVIEW

Construction sites are dynamic in nature and each site typically has a unique size and set of working conditions. The movement and resulting interaction between various construction resources including ground workers and heavy equipment can create hazardous proximity situations. A multitude of movements of construction resources coupled with the densely populated nature of construction sites can account for safety concerns resulting from proximity issues (Cheng et al., 2011). The following review covers current fatality incidents associated with proximity issues in the construction industry and current safety practices of construction workers with regards to hazardous proximity issues.

2.1 Construction Accident Statistics

The construction industry experiences one of the highest accident fatality rates per year when compared to other industries in the U.S. In 2012, the Bureau of Labor Statistics (CFOI, 2011) reported the construction industry experienced 806 fatalities of which 17% (136 fatalities) resulted from workers coming into contact with objects or construction equipment. Fatalities resulting from workers being struck by pieces of construction equipment accounted for 3% of the total workplace fatalities experienced in 2012 by the U.S. private industry sector (CFOI, 2013). Since 2003, the construction industry has averaged 191 fatalities resulting from construction equipment or other objects striking workers per year (BLS, 2013). Figure 1 provides the total construction fatalities and those causes by ground workers contacted with objects or equipment between 2003 and 2012 (CFOI, 2013).

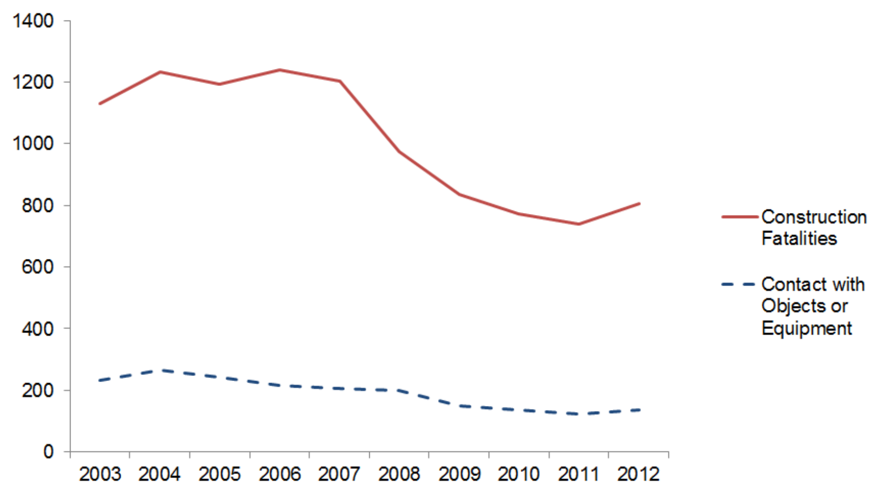

Figure 1: Construction fatalities caused by contact with objects or equipment (CFOI, 2013)

One longitudinal study identified minimal significant change in fatalities resulting from contact collisions between construction equipment and ground workers between 1985 and 2009 (Hinze & Coates, 2011). Although the number of fatalities resulting from contact collisions decreased during this duration, the ratio when compared to total construction fatalities remained largely unchanged. Even in highway work zones, more worker fatalities are caused by struck-by events from pieces of construction equipment rather than commuting vehicles (Pegula, 2010). Member companies of the Construction Industry Institute (CII) also reported that a significant portion of their worker fatalities were caused by struck-by incidents.

2.2 Human-Equipment Interaction

A majority of previous research in hazardous proximity situations is largely concentrated in worker behavior. One study identified two general problems resulting in hazardous proximity issues between heavy construction equipment and ground workers (Fosbroke, 2004): (1) Workers and equipment operators - Outdated or never implemented policies, a lack of knowledge of existing specific risk factors, and repetitive work tasks, (2) Incident investigation - All incident causation data is collected after-the-face resulting in no or limited real-time incident information.

Standards and regulations required by the Occupational Safety and Health Administration (OSHA) are imperative to enhance safety in construction (OSHA, 2013a). As per OSHA regulations, construction equipment must provide alerts when moving in the reverse direction (OSHA, 2013b). Research has found that these alerts can desensitize workers to existing hazards (Duchon & Laage, 2011). Other OSHA regulations require construction site personnel to wear hard hats, reflective safety vests, and other personnel PPE (OSHA, 2013b). Safety training and education, other required safety regulations, can increase the awareness of hazards associated with proximity issues between construction equipment operators and ground workers (Goldenhar et al., 2001; Huang & Hinze, 2006). Construction accident statistics indicate that back-up alerts and PPE are incapable of preventing contact collisions between workers and construction equipment.

2.3 Equipment Operator Visibility

Equipment operator visibility has impacted the overall safety of construction sites (Fosbroke, 2004). One of the leading causes of contact collisions between ground workers and heavy construction equipment is limited operator visibility (Fullerton et al., 2009). Data from an OSHA fatality database from 1990 to 2007 to shows that approximately 5% of construction fatalities during that period were caused by some type of equipment-related visibility issue (Hinze & Teizer, 2011). Table 1 shows the breakdown of visibility-related fatalities and pieces of construction equipment involved. Hazard zones were created for pieces of construction equipment that were most cited for each visibility-related fatality.

Table 1: Construction Equipment Evaluated (Hinze & Teizer, 2011)

Type of Equipment	Percentage of Visibility-Related Fatalities
Dump truck	29%
Truck (not specified)	12%
Excavator/backhoe	8%
Private vehicle (car, pickup, van)	7%
Dozer	6%
Grader	6%
All others	64%

3 OBJECTIVE AND SCOPE

The primary objective is to present and test a methodology for creating hazard zones around pieces of construction equipment in which ground personnel should avoid during construction operation. The hazard zone is created for several pieces of construction equipment to demonstrate and test each step of the methodology. The scope is limited to construction sites, equipment, and personnel at a horizontal grade and hazards between construction equipment and workers-on-foot. The consideration of interactions between other construction resources (such as equipment-equipment or equipment-material interaction) is out of the scope of this work.

4 METHODOLOGY

Several variables and situations must be considered when calculating the hazard zone around a piece of construction equipment for a ground worker. These variables include equipment travel speed, equipment travel direction, equipment physical dimensions, equipment turning radius, equipment rotational capabilities, operator reaction time, and equipment braking distance. To create a process for determining the hazardous zone around a piece of construction equipment, a hierarchy was designed to assure each variable was considered. Figure 2 presents the methodology implemented to determine the hazard zone for any piece of construction equipment. A typical three-axle, tandem rear axle, 23,586 kg haul capacity dump truck is used as an example to demonstrate how each step is calculated and how the resulting hazard zone is determined (Harwood, 2003; Peterbilt, 2014).

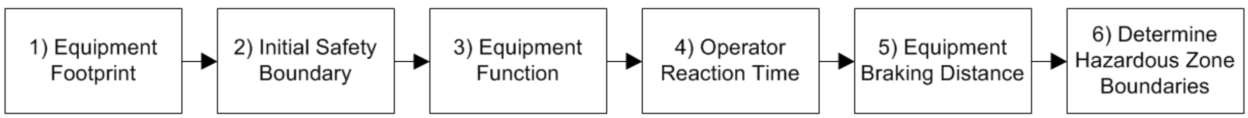

Figure 2: Steps for determining the hazardous zone around a piece of construction equipment

Step 1: Equipment Footprint - The outermost position from the centroid of the piece of construction equipment should be determined for all of the equipment components. To determine the equipment footprint, the outermost extension at any height for each point 360 degrees around the equipment should be projected onto a 2D (two dimensional) horizontal plane. The equipment footprint for a typical three-axle dump truck is shown in Figure 3. This footprint is derived from the equipment dimensions of a typical three-axle, tandem rear axle dump truck (Harwood, 2003; Peterbilt, 2014).

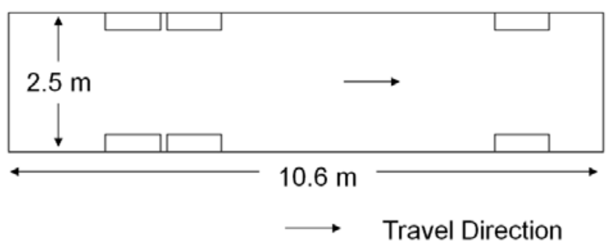

Figure 3: Equipment footprint for a three-axle dump truck

Step 2: Initial Safety Boundary - The initial safety boundary is a 2-meter distance extended from the equipment footprint that performs as a safety factor in the event that other hazardous zone design steps fail to provide protection. A parallel line 2 meters offset from the equipment footprint calculated in step 1 creates the initial safety barrier (see Figure 4). The initial safety boundary was assigned a 2 meter value to account for a ground worker that may have body parts (e.g. limbs) horizontally extended (e.g. a worker with an outstretched arm). This safety boundary extends beyond the length of a person's horizontally extended arm or leg as well as a person bending horizontally at their torso. This initial safety boundary zone can be modified depending on a unique set of working conditions.

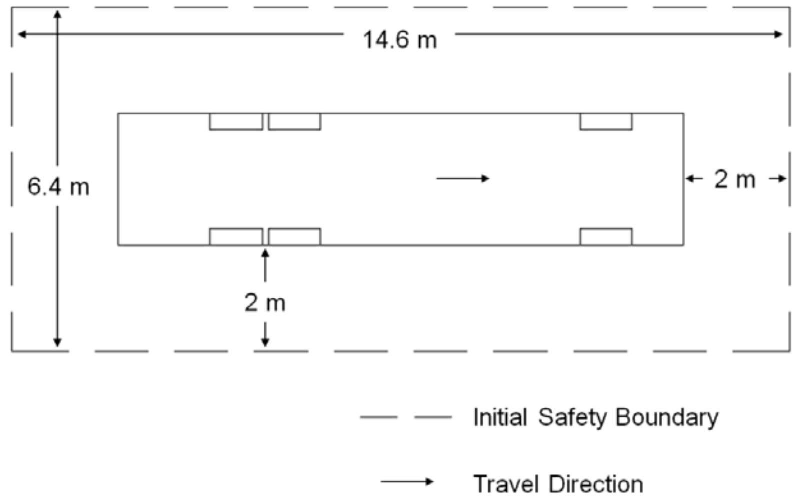

Figure 4: Initial safety boundary for a three-axle, tandem rear axle dump truck

Step 3: Equipment Function - The hazard zone must be designed to align with the specific function of a piece of construction equipment. For example, the equipment function of a hydraulic excavator with tracks and resulting hazard zone mainly follows a circular pattern with the maximum hydraulic arm reach as the circle's radius. Other pieces of construction equipment such as a dump truck or scraper will have a hazard zone largely based on their turning radius and maximum speed on a construction site. The equipment function is taken into consideration to determine the hazard zone for a typical three-axle dump truck as shown in Figure 5. Most pieces of construction equipment provide specific details about turning radius in the equipment specifications (Peterbilt, 2014).

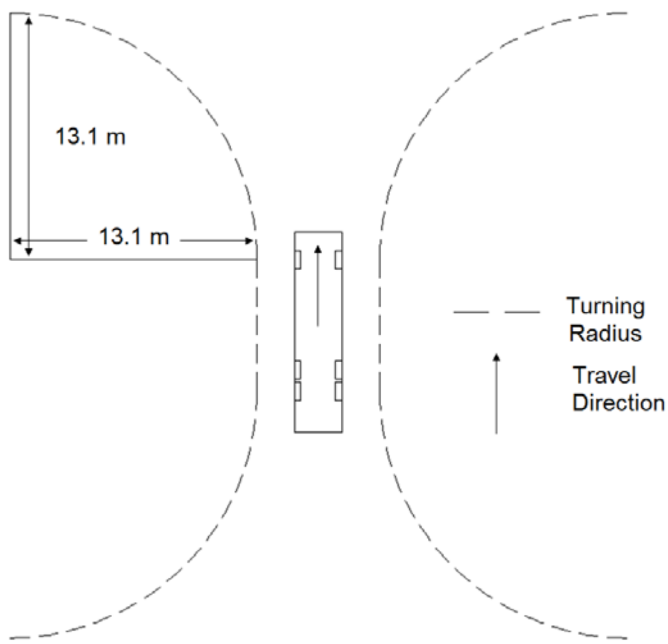

Figure 5: Hazard zone based on dump truck function on a construction site (Peterbilt, 2014)

Step 4: Operator Reaction Distance - This metric is used to determine the travel distance of a piece of construction equipment during the period in which a construction operator reacts to the identification of a hazard. An equation typically used for commuter traffic driver reaction time is implemented to determine the equipment operator reaction time (see Equation 1). An average operator reaction time of 2.5 seconds to a recognized hazard is utilized (MUTCD, 2013). The resulting reaction distance is plotted at intersecting points along the existing hazard zone from the previous step 3.

[1] Reaction Distance = 0.278Vt where V = velocity and t = time (2.5 s)

Step 5: Braking Distance - The braking distance of the piece of construction equipment is added to the operator reaction time as an additional factor in determining the hazard zone. To calculate the braking distance, an equation typically used to measure the braking distance of commuter traffic (including semi-trucks) is used and shown in Equation 2. After the operator identifies a hazard, a separate reaction time is required for the operator to apply brakes to stop the equipment. The same average operator reaction time of 2.5 seconds is used as was discussed in step 4 (MUTCD, 2013). The resulting braking distance is plotted at all locations extended outward from the reaction distance calculated in step 4.

[2] Braking Distance = $0.039(V^2/a)$ where V = velocity and a = acceleration (3.41 m/s^2)

Step 6: Determine Hazard Zone - To determine the resulting hazard zone, steps 1 through 5 should be calculated and compared to identify the maximum calculated distance for each point around a piece of construction equipment. It is important to note that each step of determining the hazard zone builds from the previous step. For example, the initial safety boundary calculated in step 2 is added to the maximum extent of the equipment footprint for each point calculated in step 1. The maximum calculated hazard distance along the centerline of forward travel for the dump truck is the combined reaction time and braking distance of 6.3 meters. This value was added to the equipment function and initial safety boundary and equipment footprint that were calculated in step 3 and step 2 respectively. The resulting hazard zone for a typical three-axle, tandem rear axle dump truck is presented in Figure 6.

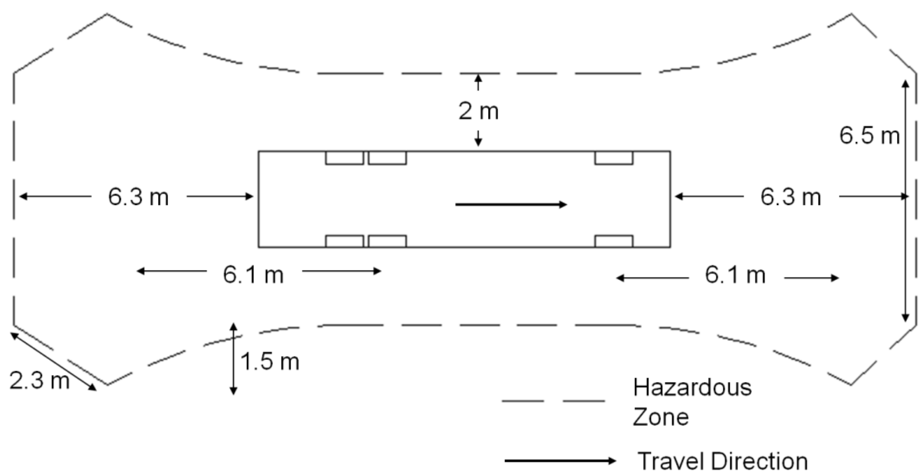

Figure 6: Hazard zone of a typical three-axle, tandem rear axle dump truck

5 HAZARD ZONE

The hazard zone for several pieces of construction equipment was created using the methodology presented in the previous section. Dimension values for a typical backhoe loader were used to create a hazard zone for ground workers. The backhoe loaded used was a single tilt loader and was equipped with a multi-purpose 1.0 m^3 (1.3 yd^3) front loading bucket (Caterpillar, 2011). The resulting hazard zone for the backhoe loader is presented in Figure 7.

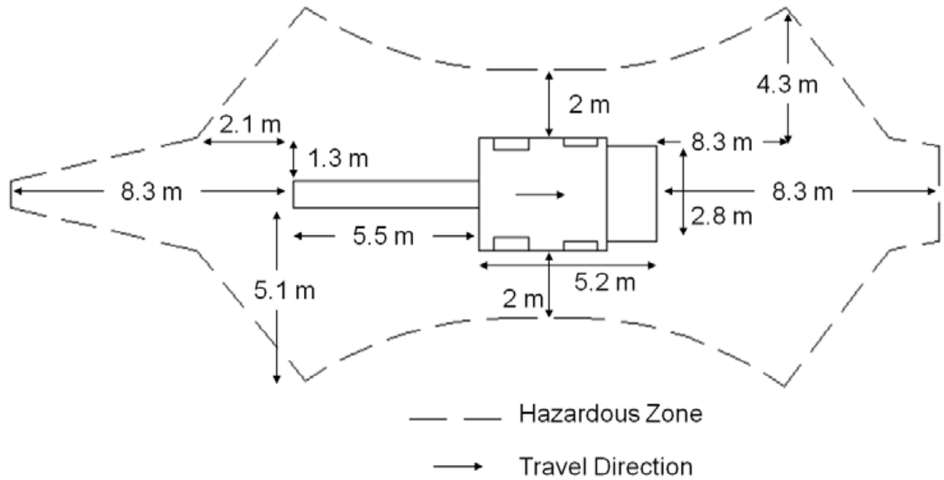

Figure 7: Hazard zone of a typical backhoe loader

The hazard zone for an excavator was also created using the previously discussed methodology. The excavator used was a typical three teeth digging 0.018 m^3 (0.29 yd^3) capacity bucket (Caterpillar, 2011). The resulting hazard zone for the excavator is displayed in Figure 8.

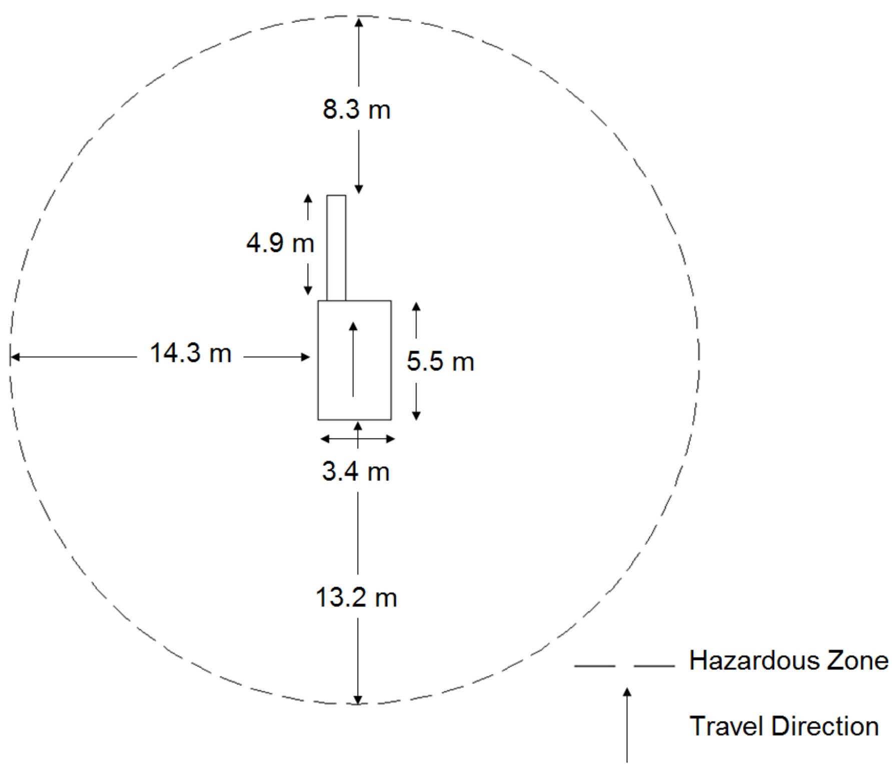

Figure 8: Hazard zone of a typical excavator

Resulting hazard zone area data was also calculated based on the creation of the hazard zone for the dump truck, backhoe loader, and excavator. The net hazard area is calculated from subtracting the area occupied by the equipment (B) from the full hazard zone area (A). This net hazard area is the region that should be avoided by construction ground workers during equipment operation. The resulting hazard zone data is shown in Table 2.

Table 2: Hazard Zone Results for Each Piece of Construction Equipment Evaluated

Item	Dump Truck	Excavator	Backhoe Loader
Area of full hazard zone (A)	169.8 m^2	803.7 m^2	179.9 m^2
Area occupied by equipment (B)	26.5 m^2	23.1 m^2	21.0 m^2
Net hazard zone area (A – B)	143.3 m^2	780.6 m^2	158.9 m^2

6 HAZARD ZONE DEPLOYMENT

Location tracking data of construction resources (including personnel and equipment) was used from a previous study (Pradhananga & Teizer, 2014). For this study, an active construction site was selected with an earthmoving operation involving excavators, dozers, rollers, dump trucks, and construction ground workers. Position-based data was collected using GPS identification devices calibrated to a frequency of 1 Hz mounted on various surfaces on pieces of construction equipment and to the hard hats of workers. The data was filtered using an existing filtering process (Vasenev et al., 2014).

Figure 9 shows the result of verifying the proposed hazard zone with location-based data from the construction site. Tracking data for the trajectory of one trip cycle of a single dump truck starting from the point it entered the construction site and ended when the truck passed the exit point. A hazard zone was created around the truck for its position every second based on the previously prescribed methodology.

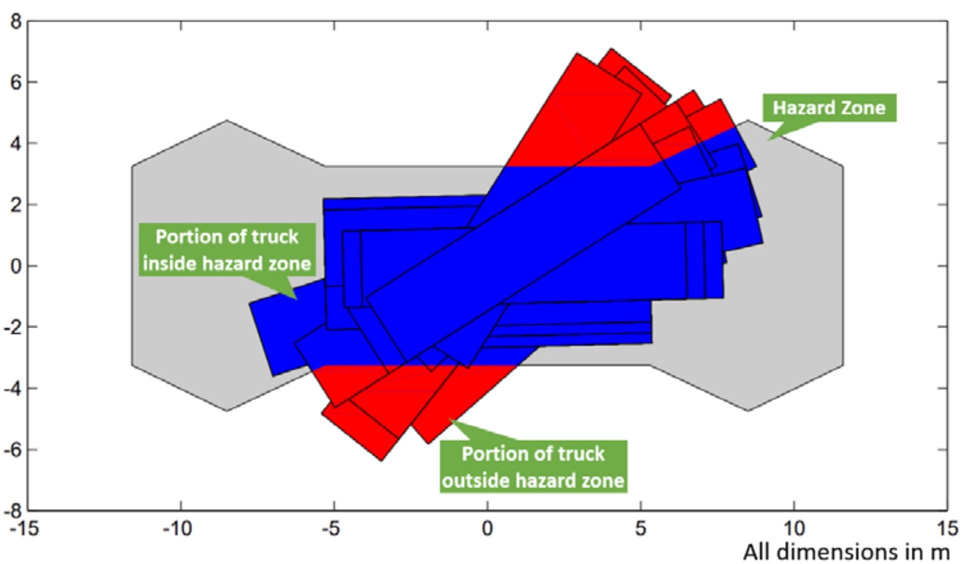

Figure 9: Verification of the proposed hazard zone

The tracked dump truck is expected to stay within the computed hazard zone. The equipment footprint of the dump truck with respect to hazard zone computed for its immediate previous position was checked for compliance with the hazard zone (i.e. did the dump truck remain in the zone after movement). The boundary of the equipment footprint should completely lie inside the hazard zone if the computed hazard zone is adequate for the equipment (truck). In Figure 9, the portion of the truck lying inside the hazard zone is plotted in blue and the portion that extended beyond the hazard zone is plotted in red. The gray area represents the hazard zone.

Instances in which the dump truck remained static were excluded from the analysis. A total of 106 location data points were assessed. Among those points, the equipment footprint was found to cross the hazard zone boundary 33 times. This implies that the computed hazard zone was able to envelope the dump truck's movement approximately two thirds of the times. Figure 9 also shows that red areas were only present in cases where the truck performed forward sharp right turns. Following the analysis, a recommendation on extending the hazard zone to include very sharp right turns can be implemented. The same methodology for creating hazard zones can be used to iterate through each step to optimize the hazard zone for an equipment.

7 CONCLUSIONS

The safety practices currently used in the construction industry for ground workers and heavy equipment operating in close proximity has proven inadequate by the continued injuries and fatalities resulting from workers being struck by equipment or objects. The purpose of this research was to create and test a methodology to design hazard zones around construction equipment. These hazard zones are areas that should be avoided by ground workers during construction operation. The methodology created includes six steps that include the following: 1) equipment footprint, 2) initial safety boundary, 3) equipment function, 4) operation reaction time, 5) equipment braking distance, and 6) creation of the hazard zone. The hazard zone was created for three pieces of construction equipment (dump truck, backhoe loader, and excavator) using the presented methodology. Results of the created hazards zones indicate that hazard zones can be designed and used to increase awareness of dangers around construction equipment for construction site personnel. Location-based data for a dump truck was used to evaluate the created hazard zone methodology. By creating hazard zones around construction equipment, ground workers can be informed of and avoid dangerous areas around heavy equipment on construction sites.

The presented methodology for creating a hazard zone for pieces of construction equipment is founded singularly on construction safety considerations. The hazard area accounts for potential movements of a piece of construction equipment which in some situations can result in a rather large hazard area. The created hazard area may not be feasible on select compact construction sites or working conditions. Further research is required to understand the hazard zone’s impact on other topics within the construction industry including productivity, economic feasibly, and sustainability.

Several limitations were cited during and after creating the methodology and designing hazard zones for construction equipment. The proposed methodology only allows for a horizontal plane hazard zone and doesn’t address three-dimensional hazards (i.e. crane applications and sloped conditions). The methodology presented currently addresses independent hazard zones for each piece of construction equipment, but future research could address the dynamic activity of all pieces of equipment on a construction site simultaneously. The created hazard zone could also be used to optimize the calibration of proximity detection and alert systems. Future research efforts can create a tool for automatically creating the hazard zone around a piece of construction equipment for safety managers. Future research should also address the implementation of these hazard zones. This includes a strategy to educate workers on where hazard zones are located and how to avoid them during construction operation.

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