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ANALYSIS OF U.S. SURFACE MINING HAUL-TRUCK-RELATED FATALITIES

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ABSTRACT

Powered haulage and haul truck-related fatal accidents are among the most frequent at surface mines. Industry organizations developed guidance on accident scenarios to address haul truck and mobile equipment collision-related accidents. However, there is a need to investigate accident data to prioritize these scenarios and identify factors relevant to developing validation methods for collision warning/avoidance technologies and determining their capabilities and limitations. Standards and effective validation methods are necessary for improving system efficacy within mining operations and promoting industry adoption. To address these needs, researchers from the National Institute for Occupational Safety and Health (NIOSH) investigated available powered-haulage and machinery-related fatal accident reports documented by the Mine Safety and Health Administration (MSHA). Their objective was to gain a perspective for informing the development of test protocols and validation methods through determining the most prevalent accident scenarios and related factors. Our findings afford insight for addressing the most prevalent haul truck scenarios and relevant factors within U.S. surface mining environments.

INTRODUCTION

In 2018, the Mine Safety and Health Administration (MSHA) published a proposed rule and request for information in part of its Powered Haulage Safety initiative [1]. This effort placed significant focus on improving safety around powered haulage equipment, including surface mine haul trucks. Following the start of this initiative, NIOSH researchers began a project to characterize safety and health-related issues surrounding haul trucks used at surface mines [2]. This project produced a research road map that identified validating collision warning and avoidance systems (CXS) as a priority for haul-truck-related research. To address this priority, a separate project was launched to investigate methods for validating the detection performance of CXS for surface mining haul trucks [3]. For this study, our aim is to determine from the most prevalent fatal accident scenarios factors that could be used to address haul truck-related safety concerns at U.S. surface mines.

BACKGROUND

Prior studies have been conducted to assess haul-truck-related fatalities. In 1996, Randolph and Boldt published a report on fatal and non-fatal haul-truck-related accidents from 1986–1995 [4]. Since then, research conducted by NIOSH continued to build on that work as new accident reports for the years following became available. Dump-point-related injuries and fatalities from 1988–1997 were examined. Although the researchers discovered that dump-point-related accidents accounted for a small percentage of injuries at surface mines, they were more likely to result in death or significant lost time than other accident types [5]. A study by Kecojevic and Radomsky on loader- and haul-truck-related fatalities from 1995–2002 revealed that the most common types of accidents are rollovers and collisions with pedestrians, and the most common root causes were mechanical failure and failure to obey warning signals [6]. Another study from Md-Nor et al. on haul truck accidents from 1995–2006 also found that mechanical failure was the most frequent cause of fatal accidents [7]. More recently, Bellanca et al. conducted a bowtie analysis focused on a holistic attempt for understanding the causes and general actions that can be taken for lessening haul-truck-related fatalities in the U.S. mining industry [8,9]. This study adopted the various levels of defensive control outlined by the Earth Moving Equipment Safety Round Table (EMESRT) [10]. Conclusions of this study allude to the need for the industry to primarily focus on low-level controls (EMESRT Levels 1-6) but also suggests that reactive controls, such as CXS (EMESRT Levels 7-9) may serve as a supporting line of defense in the mitigation of potentially harmful haul truck incidents.

A focused analysis of haul-truck-related fatalities is needed to prioritize scenarios and identify factors relevant to developing CXS validation methods. In 2018, MSHA presented an analysis of collision warning system preventable mobile-equipment-related fatal accidents occurring from 2003 through 2017 at surface mine operations [11]. Their analysis included haul trucks, light vehicles, and other surface equipment. For haul trucks, fatal incidents typically occurred in the frontal and operator cab areas, and the victims were primarily light vehicle occupants. We expand on this effort and prior work in our study of 54 haul-truck-related fatalities spanning January 2005 through June 2021 by examining the most prevalent incident scenarios and revealing factors specifically relevant to collision warning and avoidance control measures.

METHODOLOGY

NIOSH researchers collected 54 haul-truck-related fatal accident reports that occurred from January 2005 through June 2021 from the MSHA Fatality Reports webpage [12]. We used the site's search engine to identify accidents that occurred since 2008 inclusive of search criteria for the "Location of Accident" listed as "Facility," "Surface," and "Surface of Underground" and "Mine Categories" for "Coal" and "Metal and Non-Metal." Outside of this search engine, fatal accident reports from 2005 through 2007 were individually reviewed to identify accidents that occurred on the surface of coal and metal/non-metal operations. Information summarized within the respective Fatality Alerts and Preliminary/Final Reports were given a preliminary review to identify fatalities where a haul truck was involved. For this analysis, a haul truck is defined as an off-road rigid frame or articulated truck chassis that is typically equipped with a dump bed or utility payload (e.g., water tank). After the researchers identified the 54 surface- and haul-truck-related fatal accident reports, each was given a more thorough, in-depth review to summarize various data including the victim(s) location, whether a seatbelt was worn, haul truck data (year, make, model, payload), hazard-related data (type, scenario, location, speed/direction), date, mine, preliminary report overview, and additional information (root cause, weather, contributing factors, etc.).

The 54 identified accidents were then classified by type into four categories: pedestrian-/vehicle-related, berm-related, dump-point-related, and other-type incidents. To accomplish this, the four researchers used a consensus-based approach. Pedestrian-/vehicle-related fatalities include interactions that involve pedestrians, vehicles, or other similar objects that are struck by a haul truck moving forward or in reverse and resulting in one or more fatal injuries; these exclude interactions with berms and dump-point features. Accidents classified within this category were further assessed in terms of their relevance

to CXS. In terms of being CXS-relevant, each pedestrian-/vehicle-related incident was specifically determined as "Yes," "Potentially," or "No," where CXS technology has clear application, potential application, or no relevance in terms of mitigation and prevention of related events.

The berm-related incidents include mechanical failure or loss of control incidents that resulted in a haul truck traveling through a berm or boundary and over a highwall, into water, or other hazardous area resulting in operator/occupant fatalities. NIOSH researchers identified a few factors that could lead to berm-related incidents inclusive of mechanical failure, inadequate berm, loss of control, and impairment of the haul truck operator. Inadequate maintenance of the haul truck braking system could be a reason for mechanical failure. Inadequate berm refers to the inability of the berm to bring the vehicle to a complete stop or the absence of the berm in a hazardous area like a highwall. Loss of control could be the result of speeding, road conditions, inadequate training, or a combination of various factors. An impairment of the haul truck operator could be the result of alcohol and/or drug consumption. All four of these factors could cause the haul truck to travel through or over a berm. On the other end of the berm, there was either a body of water or other hazardous area that resulted in fatal injury of the haul truck driver and other occupants of the haul truck. Berm-related incidents were also assessed with respect to CXS implementation affecting the outcome.

Incidents at dump points include situations where a ground failure or travel over results in a haul truck that was backing up falling or overturning and consequently resulting in the haul truck operator or occupants being fatally injured. Even though many dump-point incidents involve berms, there are a few differences between berm-related and dump-point-related incidents. Dump-point incidents involve a haul truck backing up to the potential hazard. The operator is usually aware of the berm and intentionally contacting the berm is considered a safe dumping practice. By contrast, in berm-related incidents, the haul truck operator inadvertently strikes the berm after veering off the intended path. Also, most berm-related incidents occurred while the haul truck was traveling forward. Once the dump-point-related incidents were classified, the researchers identified the main contributing factors in each accident based on the information given in the report. These factors included absent/inadequate berm, using the berm as a bump stop, undercutting of the stockpile, and not wearing the seat belt. Dump-point-related fatal incidents were also assessed in terms of being CXS-relevant.

Finally, the other-type category included the remaining haul-truck-related incidents that did not satisfy the criteria of the previous three categories. The other-type category includes slip/trip/fall, pinning/crushing of a victim working on a stationary haul truck, fires, and other-type incidents that are not related to collisions, berms, or dump points. While the nature of these accidents was irrelevant to CXS, they were included to present a complete overview of fatal accidents involving a haul truck.

RESULTS

The researchers classified data obtained from MSHA fatal accidents documented since January 2005 through June 2021. A total of 54 incidents involving a haul truck were identified and classified according to incident type as pedestrian-/vehicle-related, berm-related, dump-point-related, or other-type. Using this classification resulted in 13 pedestrian-/vehicle-related, 21 berm-related, 12 dump-point-related incidents, and eight incidents classified as other-type (Figure 1).

Pedestrian-/vehicle-related incidents

We classified a total of 13 incidents as pedestrian-/vehicle-related having either a pedestrian, vehicle, or similar object that was struck or crushed by a moving haul truck and resulted in one or more fatalities. Figure 2 shows a breakdown of these 13 incidents separated among the four subcategories used within our analysis: pedestrian, light vehicle, haul truck, and other. Among these results are five incidents that involved a light vehicle (LV) i.e., pickup truck or passenger van. One of these five incidents resulted in a double fatality and had the potential for six additional fatalities. Three involved a pedestrian on the ground in the vicinity of the haul truck, and three involved an interaction with another haul truck. The two incidents classified as other include a collision with a moving railroad freight car and crushing of a portable toilet and its occupant. Of these 13 incidents, 12 involved a forward-moving haul truck that collided with a vehicle, pedestrian, or related object in its forward path. The other incident involved a haul truck that reversed into another haul truck crushing the cab and operator who was standing on the deck just outside the cab.

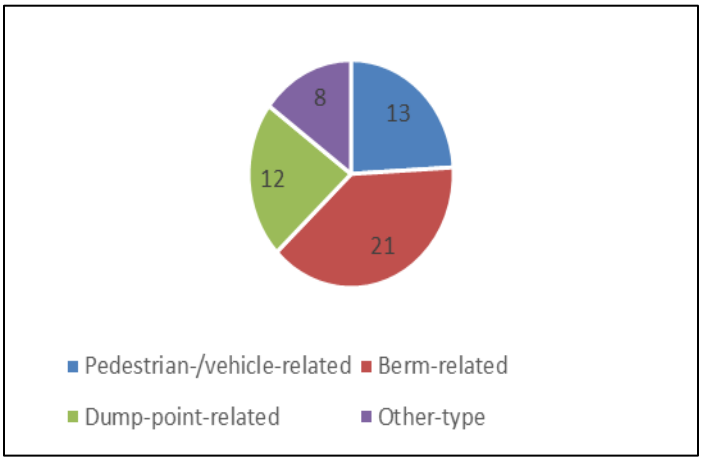

Figure 1. Incident types for haul-truck-related fatalities.

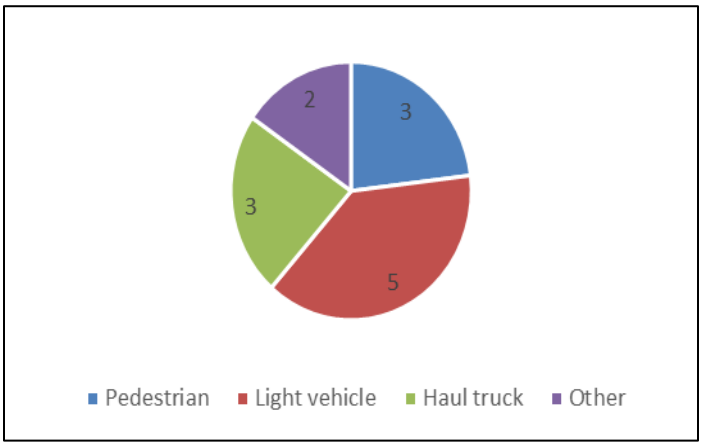

Figure 2. Collision types for pedestrian-/vehicle-related fatal haul truck incidents.

Further consideration was given to these 13 incidents in terms of their relevance to CXS; the results are summarized in Table 1. Of these, 10 were identified as CXS-relevant including the five incidents where a light vehicle was crushed by a forward traveling haul truck. Of these five incidents, two occurred in front of a haul truck that was transitioning from a stopped "idle" state to moving forward, two involved a light vehicle that was parked in the forward path of a haul truck traveling along a haul road, and one involved a haul truck and light vehicle that were approaching each other. We determined that one of these 13 incidents was potentially CXS-relevant since it involved a loss of control under adverse weather-related road conditions. In this case, it is unclear if CXS technology would have a role in mitigating or preventing adverse interaction induced by road conditions. The remaining two incidents that were determined to be unrelated to CXS involved a stopped haul truck that unintentionally moved or rolled forward and crushed a person on the ground. The 13 pedestrian-/vehicle-related collision incidents are summarized in Table 1.

Of the 10 incidents identified as CXS-relevant, subject haul truck payload capacities were distributed among four classification ranges that we defined for this analysis. These are: <100-ton – two incidents, 100-200-ton – four incidents, 200-300-ton – two incidents, and 300-400-ton – two incidents. It is notable that 40% (4) of the 10 incidents

classified as CXS-related involved a haul truck with a payload capacity within the 100-200-ton range.

Table 1. Summary of pedestrian-/vehicle-related incidents.

Haul Truck Motion	Victim(s) Position	CXS-relevant	Incidents
Forward Travel	Parked LV – Occupant	Yes	2
	Operator Cab	Yes	1
	Head-On Traveling LV – Occupant	Yes	1
	Pedestrian	Yes	1
	Railroad Car – Dropper	Yes	1
Forward Start	Parked LV – Occupant(s)	Yes	2
	Portable Toilet – Occupant	Yes	1
Reverse Start	Parked Haul Truck – Behind Cab	Yes	1
Loss of Control	Stopped Haul Truck – Occupant	Potentially	1
Forward Roll/Drift	Pedestrian	No	2

Berm-related incidents

To analyze the 21 berm-related incidents, five categories of contributing factors were used: (1) absent/inadequate berm, (2) impairment of the haul truck operator, (3) loss of control, (4) mechanical failure, and (5) a combination of mechanical failure and inadequate berm. As shown in Figure 3, loss of control accounted for nine of the berm-related incidents. The second largest contributor to berm-related incidents was impairment on six accounts. Mechanical failure accounted for 3, and the absence of berm or inadequate berm contributed to two incidents. The smallest contribution, one incident, came from a combination of both mechanical failure and the absence of berm.

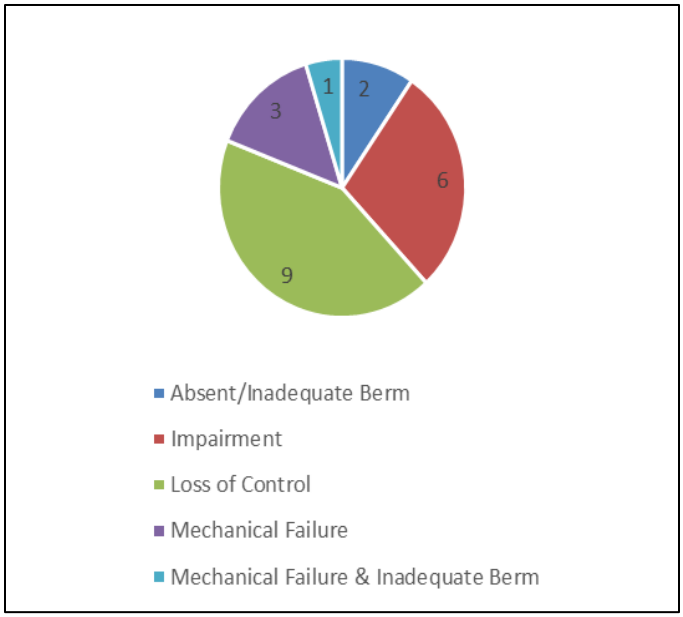

Figure 3. Contributing factors for berm-related fatal haul truck incidents.

Consideration was also given to subjectively determine if CXS technologies could have affected the outcome of these 21 incidents; the results are summarized in Table 2. One of the nine incidents we classified as loss of control was CXS-relevant, and the eight others were potentially CXS-relevant. We determined that CXS may have relevance to the outcome for one of the two incidents involving an absent or inadequate berm and the six where operator impairment was a factor. For the three incidents caused by mechanical failure and the one incident involving both mechanical failure and an absent/inadequate berm we conclude that CXS would have no relevant effect.

Table 2. Summary of contributing factors for berm-related incidents.

Factor	CXS-relevant		
	No	Yes	Potentially
Absent/Inadequate Berm (A/I)	1	0	1
Impairment	0	0	6
Loss of Control	0	1	8
Mechanical Failure (MF)	3	0	0
MF & A/I	1	0	0

Dump-point-related incidents

We identified 12 fatal accidents occurring at dump points that involved a haul truck. All 12 of the dump-point-related fatal incidents were classified as potentially CXS-relevant. Each accident resulted in one fatality – the driver of the haul truck. In each scenario, there was nobody in the passenger seat of the haul truck. The dump-point accidents can be divided into two subcategories: reverse-over and ground failure. In reverse-over incidents, the haul truck driver backed over the edge of the dump point, often due to a lack of awareness or the mine operator failing to ensure that proper impeding devices such as berms or bumper blocks were in place at the dump site. Of the 12 dump-point accidents, six were classified as reverse-over. The other six were due to ground failure, in which the ground underneath the haul truck gives way, causing the truck to travel over the edge of the stockpile. Figure 4 shows the contributing factors that were identified in the 12 dump-point accidents and the number of times each factor was identified. Some incidents involved more than one contributing factor.

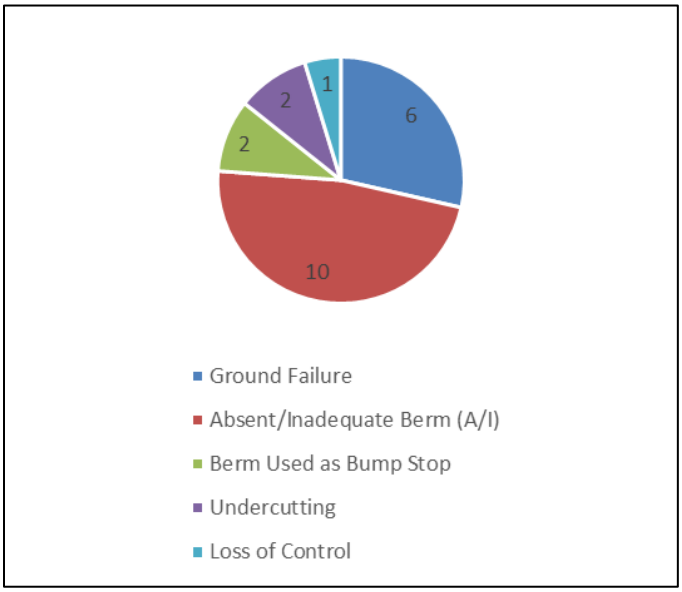

Figure 4. Contributing factors for dump-point-related incidents.

In most of these accidents the berm at the dump point was either inadequate or absent. There were 10 accidents that fell into this category. In two of the inadequate-berm scenarios, the drivers were using the berm as a bump stop. The constant pounding of the rear wheels of the haul truck pushed the berm back until it eventually became too close to the edge of the dump point.

Of the 12 dump-point incidents, the investigations revealed that the driver was not wearing a seat belt on seven occasions (Figure 5). In two of the incidents, the driver was wearing a seat belt. In the other three incidents, the report either did not state whether a seat belt was worn, or it could not be determined.

Undercutting of the stockpile was identified as a root cause for two of the ground-failure-related incidents. When material is removed from the bottom of the stockpile, the angle of repose is steepened, causing the ground at the dump location to be unstable. In one dump-point incident, the accident investigators could not determine how the

accident occurred. In this case, there were no witnesses when the accident occurred, there was no evidence of unstable ground or mechanical failure, and the berm was considered adequate. Subsequently, this accident was classified as loss of control.

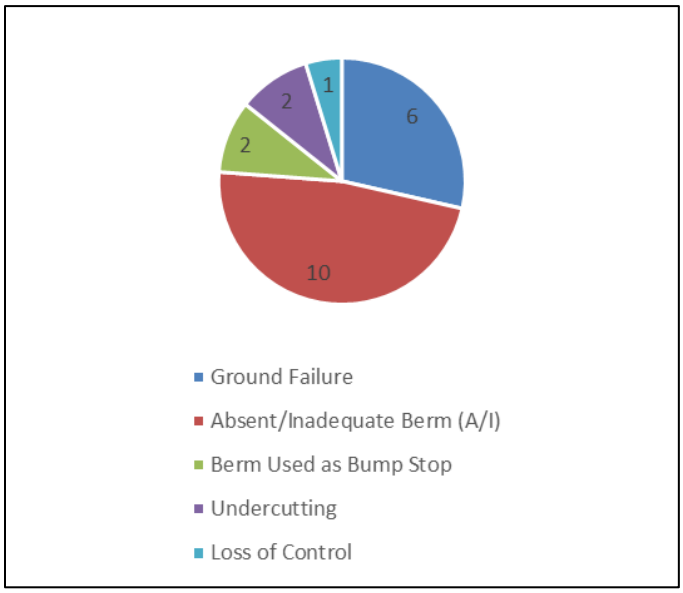

Figure 5. Seat belt usage for dump-point-related incidents.

Other-type incidents

Eight other-type accidents involving a haul truck that resulted in nine fatalities were identified. This category was divided into the following subcategories: fire, falling material, bumping, pinning/crushing, and slip/trip/fall. The other-type category may not be strictly limited to these subcategories. However, these were the five observed subcategories from haul-truck-related incidents that occurred from January 2005 through June 2021. Figure 6 indicates the number of occurrences for each of these subcategories.

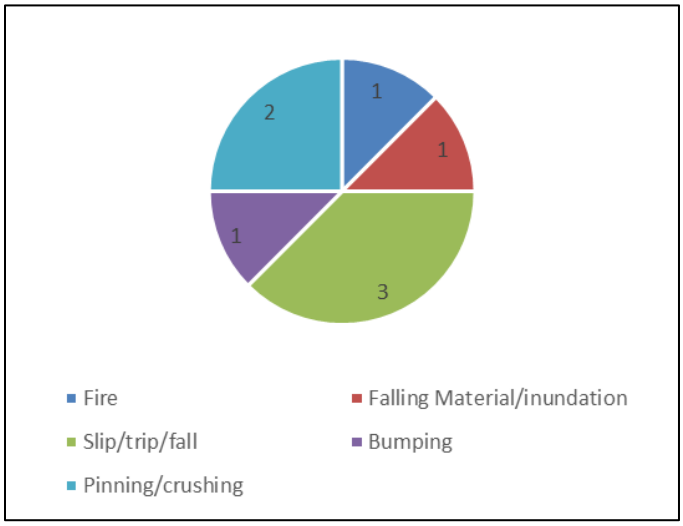

Figure 6. Occurrences of other-type fatal haul truck incidents.

These eight accidents were considered unrelated to CXS. One accident involving a fire was caused by a ruptured hydraulic hose and subsequent fire near the engine. The haul truck was equipped with a fire suppression system, but its hoses, which were not fire-jacketed, were routed through the engine compartment, and, consequently, damaged by the fire. It was also found that the primary egress stairway's hydraulic hose was likely damaged by the fire, and the alternative egress ladder was guarded with a chain improperly secured using fasteners that could not be removed by hand. The inundation incident occurred at a dump point. However, the victim was located at the bottom of the highwall, and the accident was caused by falling material. Three slip/trip/fall accidents occurred with the victim falling from an elevated location such as an access ladder or operator's deck. One bumping incident occurred when a mechanic bumped his head on an unknown object while performing maintenance under a haul truck. It was assumed that the victim was not wearing a hard hat. Lastly, the two pinning/crushing incidents occurred because of inadequate blocking to prevent motion of machine components. In one case, an operator was investigating an oil leak between the operator's cab and dump body with the dump body raised. The dump body control was left in the float position with no blocking in place. In the second incident, a mechanic was removing a strut cap. Since no blocking was in place, the truck frame dropped abruptly when the cap was loosened.

Data resulting from our classification of the 54 incidents documented since January 2005 through June 2021 are summarized in Table 3 (see APPENDIX). The table includes a comprehensive listing of sub-categorical results determined among the four categories involving a haul truck defined as pedestrian-/vehicle-related, berm-related, dump-point-related, and other-type.

DISCUSSION

The primary objective of this study was to gain a perspective for developing test protocols and validation methods for CXS. The basis for our approach is determining the most prevalent scenarios and related factors relevant to U.S. surface mining. The following sections will discuss the results in terms of achieving this objective as related to the categories of pedestrian-/vehicle-related, berm-related, dump-point-related, and other-type incidents. Further discussion will be presented as related to preventing these incidents including consideration of the application of CXS and relevant technologies.

Pedestrian-/vehicle-related incidents

In total, 13 pedestrian-/vehicle-related fatal incidents involving a haul truck were identified from years spanning January 2005 through June 2021. Of these, 10 were determined to be CXS-relevant and of interest to research and evaluation efforts aimed at testing and validating CXS applied within U.S. surface mining operations. Nine of these incidents involved a forward moving haul truck, and the other occurred during a reverse haul truck maneuver. Four of these incidents involved the haul truck initiating movement while the victim(s) were located within a 50-foot proximity. In these cases, CXS could have alerted the haul truck operator and affected persons when the pedestrian or vehicle was approaching, entering, and within hazardous proximity of the haul truck.

Eight of the 10 CXS-relevant cases involved the victim(s) in the forward path of a haul truck that was either in motion or starting from a stopped position. The other two incidents involved a haul truck initiating a reverse maneuver, in one case, striking the cab and operator of another haul truck, and the other, resulting in the haul truck being hit on the side after failing to yield to moving railroad freight cars. In all 10 cases, CXS could have detected when the haul truck was approaching the asset or on course for an exclusion zone. It is important to understand that CXS may need to account for scenario-specific conditions such as the haul truck's state of operation and ability to stop or change course. Human-related and technological factors such as detection performance are also critical to the ability of CXS to effectively prevent these incidents.

In five of the eight CXS-relevant instances where the victim(s) were in the forward path, a light vehicle was crushed by the haul truck. Two of the five light vehicle incidents involved the haul truck driving over a parked pickup truck where the light vehicle's strobe light was determined to be switched off. In one of these cases, inadequate illumination was cited to be a factor affecting visibility. In the other of these two light vehicle incidents, it was determined that visibility of the victim's pickup was momentarily obstructed by the haul truck's cab pillar. These two cases exemplify that visibility is certainly an issue concerning smaller vehicles in the vicinity of moving haul trucks and indicate that leveraging CXS to detect the presence of light vehicles within the potential forward path of a haul truck will further control efforts taken for preventing pedestrian-/vehicle-related incidents.

Control measures have inherent challenges and require a thorough understanding of their capabilities and limitations. For example, in many of the incidents classified as pedestrian-/vehicle-related, a lack of establishing or following rules for traffic control is cited in terms of ensuring safe operation of mobile equipment [13,14]. As an added measure of control, regulations require warnings prior to moving large equipment, inclusive of haul trucks [15,16,17]. These requirements are typically addressed using horns and backup alarms. The investigation reports for incidents involving a haul truck initiating a forward/reverse maneuver indicate that a warning was given by sounding the horn prior to initiating movement. Despite these warnings, in almost every instance noted here, it appears to be critical that the operator could not feasibly see the hazard, either directly or indirectly, due to obstructions and limited coverage afforded by installed mirrors and, in some cases, cameras. Not being able to see obstacles and assets, especially in hazardous proximity is a recurring factor for most of these vehicle-/pedestrian-related fatalities. As a best practice, flags and strobe lights are often used in conjunction to increase the visibility of smaller vehicles operated in the vicinity of haul trucks. Despite the significant benefits afforded by established rules and use of technology, controls must be implemented with careful consideration and a comprehensive understanding of the associated impacts, benefits, and limitations. By example, in one case a flag installed on the victim's light vehicle was barely visible from the haul truck operator's position while within the determined range that the accident occurred. In hindsight, this would have been improved by increasing the flag visibility and height. In another case, visibility of the victim's light vehicle flag to the haul truck operator was potentially impaired by a lack of adequate illumination at the accident scene. In another example involving camera technology installed on the haul truck, it was noted that the coverage was likely inadequate to capture the victim's light vehicle. In a separate case, the victim's vehicle was in view of the forward camera, however it was determined as unlikely to be detected.

We conclude that additional measures afforded by higher-level technology like CXS may serve to further mitigate and prevent fatal injury in cases involving pedestrians, light vehicles, and related objects. In terms of their occurrence, incidents involving a light vehicle in the forward path of a moving haul truck account for 50% (5) of CXS-relevant incidents and, thereby, may yield the greatest benefit in terms of focus on test and validation methods for CXS. The incident data investigated here further suggest the significance of knowing the capabilities and limitations surrounding haul truck and CXS performance, especially as afforded for their intended use and application. It is of equal importance and significance to address the efficacy of CXS to prevent the occurrence of false/nuisance events when a system is expected to refrain from providing an alarm or acting [18,19]. To address these points, there are various standards and guidance that are developed and underway that establish a means for testing and evaluating the performance of CXS and other technologies intended to prevent and mitigate the occurrence and potential consequences of unwanted haul truck incidents [18,19,20,21]. However, additional measures are needed to validate factors relevant to detecting light vehicles, pedestrians, and related objects especially within the scope of scenarios and related factors disclosed within the fatality reports considered in this study.

Control measures surrounding haul trucks primarily focus on improving operator awareness to overcome challenges associated with impaired and limited visibility. Typically, technology-based control measures are centered around making smaller vehicles more visible to haul truck operators by implementing low-level technology including the use of mirrors and cameras installed on the haul truck and flags and strobe lights on light vehicles. CXS are available technology specifically intended to address pedestrian-/vehicle-related collisions among surface mining haul trucks; however, they are implemented to a much lesser extent in the U.S. mining industry.

Berm-related incidents

Berm-related incidents accounted for 21 of the 54 haul-truck-related fatalities identified from January 2005 through June 2021. Results indicate that CXS could have influenced the outcome of 15 incidents reviewed for this timeline. We further identified possible remedies that could be combined with CXS or used as stand-alone remedies to potentially influence the outcome of these incidents, depending on the five identified contributing factors. Although the narratives are limited in terms of critical parameters, we discuss possible remedies for each of the factor categories that contributed to the berm-related incidents.

NIOSH researchers first considered loss of control, the largest contributor of berm-related incidents, as an area for technology advancement or other remedies that could help improve the outcome. CXS combined with geo-fencing, technology-based geographic boundaries, could help the haul truck operators maintain control in incident scenarios related to poor road design, excessive speed, and inadequate berm designs. As some of the narratives suggest, one reason operators lost control of their haul trucks, resulting in a berm collision, was inadequate stopping sight distance due to excessive road curvature. Geo-fencing combined with CXS could have alerted the haul truck operator of this hazard and informed the operator or taken action to reduce the vehicle speed. Incident scenarios where haul truck operators are descending grades greater than 9% at excessive speed place the retarder at a disadvantage [22]. In these types of incidents, appropriate speed is necessary to reduce the momentum and probability of the haul truck to travel through or over a berm. CXS combined with geo-fencing can alert the haul truck operator of these conditions and advise the appropriate speed. In addition, other remedies such as reducing road curvature, implementing speed governors, minimizing grades, and providing adequate training could have helped operators to maintain control of their haul trucks.

Berm-related reports indicate that six incidents were due to impairment of the haul truck operator. In some of these incidents, the berm caused a speeding haul truck to overturn. In others, the haul truck tipped over into a pond because of an inadequate berm or ran through a berm into a body of water. In these cases, CXS may have improved the outcome by alerting the impaired haul truck operator, reducing the speed, or bringing the haul truck to a complete stop.

Technological remedies could be limited in terms of influencing the outcome of some berm-related incidents, such as those involving a mechanical failure. One possible solution for this type of problem is afforded through conducting routine preventative maintenance of braking systems before operating a haul truck. In addition, NIOSH researchers could consider berm-related incidents as a topic for further investigation beyond technology. For example, we could make the case for further investigation into berm design to help improve the outcome when no other options exist for stopping a haul truck.

Dump-point-related incidents

CXS and other technology, as well as administrative controls, could have prevented each of the dump-point-related fatalities identified in this review. MSHA published a handbook that provides information related to dump-point hazards and recognizing when dump-point conditions or practices are unsafe [23]. Miners and mine operators can use this handbook to ensure safe practices at their dump-point operations. MSHA informs of the many possible unsafe dump-point conditions. A few of these conditions were prevalent in our analysis of dump-point-related incidents, including an inadequate or nonexistent berm, weakened edge conditions, hitting into the berm, and operating equipment while not wearing the seat belt.

Regular inspections of the dump-point area can identify issues with ground stability before they can cause an accident. According to MSHA, there are four main features that suggest a dump point may not be able to support heavy equipment:

1. Tension cracks or settlement in the area where equipment operates near the edge of the pile.
2. A dump-point berm that is inadequate.
3. Dumping at the edge in an area where the pile has been loaded-out and made steeper than the material's angle of repose.
4. Movement of the slope material below the dump point.

In many of the dump-point fatal accidents, an examination of the dump area could have resulted in recognizing hazardous conditions. The handbook also includes requirements for berms and restraints at dump points to serve three functions: to provide a visual indicator of the location of the dump point, to serve as a contact point so the driver knows when the berm has been reached, and to impede equipment from traveling over the edge. To achieve these functions, the handbook requires that berms meet a minimum size, thickness, and firmness. They need to be at least mid-axle height of the largest piece of equipment that will use the dump area. MSHA notes that the mid-axle criterion is only a minimum; it is good practice to make the berms as large as practical. Earthen berms need to be firm enough so they are not easily penetrated by tires, and they must have a steep inside slope. If fine-grained material is used for the berm, then the material needs to be compacted, or the berm should be made larger. In situations where the berm is inadequate or nonexistent, the haul truck operator should dump the load short of the dump point, and a dozer should carefully push the material over the edge. MSHA also encourages this practice for every dump point, regardless of berm status, for maximum safety.

To avoid undercutting hazards, MSHA states that loading procedures should ensure that a truck never attempts to dump where material has been loaded out and the pile has become over-steepened. One practice that has shown to be effective is for the loader operator to use the initial buckets of material to block the access ramp to the top of the pile while material is being loaded. When loading-out is complete, the loader operator should push material from the top of the pile to broaden the slope and then construct an adequate berm before haul trucks can resume dumping at the top of the pile. Many dump-point accidents in this review could have been prevented by following the procedures and guidelines in the handbook.

Even if mine workers intend to follow the proper safety protocols at dump points, there is still the possibility for accidents to occur due to inattention or unforeseen hazards. In these cases, technology can further assist in accident prevention. For reverse-over incidents, CXS can notify the driver with an alarm when he gets too close to the edge. For example, technology may be able to detect the point at which it is not safe to travel beyond or to detect a void or absence of ground when preparing to dump a load. A rear-view camera could also help prevent over-travel by allowing the driver to see the area behind the truck in real time while reversing. The sensors and cameras can also inform drivers when they are approaching the berm, helping to avoid the unsafe dumping practice of using the berm as a bump stop.

In ground failure incidents, fatalities can be prevented with technology in addition to the previously discussed administrative controls. There is the possibility of using geotechnical instruments such as ground motion sensors and seismometers, which are used to detect landslides, to warn mine workers of ground instability. The haul truck operator can directly observe in passing or use a rear-view camera to detect cracks, sunken areas, or other signs of unstable ground before reversing. Sufficient camera resolution would be required for the operator to notice these details.

Other-type incidents

While the other-type incidents were not related to CXS, contributing factors were identified and recommended practices can be made. Recommendations for the other-type accidents are general but should be considered to prevent similar accidents in the future.

Ensuring that proper procedures are followed is critical for safety. For the other-type incidents discussed in the Results section, this includes but is not limited to properly installing all equipment components, conducting slope stability examinations, using proper personal protective equipment (PPE), and adequately blocking motion of machine components. For example, the fire incident may have been prevented if the fire suppression system hoses were not routed through the engine compartment or properly fire jacketed. It also may have been prevented if the proper, hand-removable fasteners were used to guard the alternative egress ladder. The inundation incident may have been prevented if the slope stability was deemed hazardous prior to the accident. Using the appropriate PPE during maintenance and other activities likely would have reduced the severity of the bumping incident. Likewise, ensuring that adequate blocking was in place prior to performing repairs or inspection may have prevented both pinning accidents. Remaining vigilant and exercising caution during work activities is proven to significantly improve worker safety. Likewise, maintaining awareness of one's surroundings will decrease the likelihood of an incident. Lastly, ensuring that initial, task-specific, and refresher trainings are adequate and completed by the appropriate individuals will improve safety of all operational activities.

CONCLUSIONS

From January 2005 through June 2021, berm-related incidents represent the most frequent among haul-truck-related fatal accidents in the U.S mining industry. The application of CXS for preventing and mitigating these types of accidents has potential but is mostly uncertain, primarily due to insufficient data to support their efficacy. CXS technologies combined with geo-fencing could advise the operator or assist with potentially harmful conditions that result in a berm-related incident. For pedestrian-/vehicle-related incidents, visibility is certainly one of the most significant contributing factors, and most of these incidents were determined to be CXS-relevant where technology shows promise in terms of their prevention. In addition, CXS technology has application and may play a role in preventing over-travel at dump points and detecting conditions that indicate the potential for ground failure.

The objective of this study is to afford direction in terms of developing test protocols and validation methods for CXS. In terms of this objective, it seems prudent to focus priority on detecting light vehicles in the path of a haul truck during startup maneuvers and forward travel. Following this priority would be preventing over-travel while reversing a haul truck at a dump point. While there are certainly several incidents involving berms, especially associated with a loss of control, berm-related incidents may present significantly greater challenges in terms of determining the application-specific suitability of available technologies as well as their efficacy. It is important to recognize that low-level controls are the foundation and consequential requirement for successful implementation of any technology-based control, especially CXS.

LIMITATIONS

The findings presented in this paper represent a broad overview of fatal incidents involving haul trucks at U.S. surface mines. The scope of this analysis is to ensure research and evaluation efforts are aimed to effectively address prevalent scenarios and relevant factors related to haul truck accidents. The approach used for this analysis is limited to the details provided within fatal accident reports made available by the Mine Safety and Health Administration. This study is further limited by the lack of data pertaining to nonfatal injuries and near-miss incidents involving a haul truck. Individual scenarios and incidents must be thoroughly investigated to accurately determine the specific relevance of CXS and other technologies that may mitigate or prevent their occurrence. The categories used within this analysis should not be considered all-inclusive, and the scope of analysis along with new or additional information may require changes.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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24. APPENDIX

Table 3. Summary Classification Data of Haul-truck-related Fatal Accidents, January 2005 through June 2021.

Category		Subcategory		CXS-relevant		
				Yes	Potentially	No
Pedestrian-/vehicle-related	13	Pedestrian	3	1	-	2
		Light vehicle	5	5	-	-
		Haul truck	3	2	1	-
		Other	2	2	-	-
Berm-related	21	Absent/Inadequate Berm	2	-	1	1
		Impairment	6	-	6	-
		Loss of Control	9	1	8	-
		Mechanical Failure	3	-	-	3
		Mechanical Failure & Inadequate Berm	1	-	-	1
Dump-point-related	12	Over-travel	6	-	6	-
		Ground failure	6	-	6	-
Other-type	8	Fire	1	-	-	1
		Falling Material/inundation	1	-	-	1
		Slip/trip/fall	3	-	-	3
		Bumping	1	-	-	1
		Pinning/crushing	2	-	-	2

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