Mining, Metallurgy & Exploration (2021) 38:1019–1029
https://doi.org/10.1007/s42461-021-00410-1

Why Do Haul Truck Fatal Accidents Keep Occurring?

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Received: 2 July 2020 / Accepted: 5 February 2021 / Published online: 22 February 2021

Abstract
Powered haulage continues to be a large safety concern for the mining industry, accounting for approximately 50% of the mining fatal accidents every year. Among these fatal accidents, haul-truck-related accidents are the most common, with 6 of 28 and 6 of 27 fatal accidents occurring in 2017 and 2018, respectively. To better understand why these accidents continue to occur and what can be done to prevent them, researchers reviewed the 91 haul-truck-related fatal accidents that occurred in the USA from 2005 to 2018 and performed bow-tie analyses using the final reports published by the Mine Safety and Health Administration. The analyses explore the context of the accidents with a focus on the initiating event, event outcome, hazards present, and possible preventative and mitigative controls. Overall, the vast majority of the accidents resulted in a haul truck colliding with the environment, and the majority of these events were initiated by loss of situational awareness or loss of control. The majority of the hazards were related to design and organizational controls. The results of this study suggest a need to investigate operator decision-making and organizational controls and to focus on improving design and operation controls such as mine design and operational procedures.

Keywords Administrative controls · Engineering controls · Haulage trucks · Qualitative analysis

1 Introduction

Powered haulage remains a large concern for the mining industry as it continues to account for approximately 50% of the mining-related fatal accidents each year [1]. Among powered haulage in mines, haul trucks are the most common piece of mobile equipment [2] and the most commonly related to fatal accidents. In fact, 6 out of 28 and 6 out of 27 mining fatal accidents that occurred in the USA in 2017 and 2018, respectively, were related to haul trucks [3]. Despite years of effort to address haul truck health and safety issues, the question remains—why do haul truck fatal accidents keep occurring?

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Over the years, numerous researchers have performed surveillance analyses on data collected by the Mine Safety and Health Administration on haul-truck-related accidents and injuries [4–9]. In general, these accidents[1] have been shown to be related to vehicle control and hazard recognition. An analysis of 152 fatalities from 1995 through 2014 found that 42% of the accidents involved the loss of control of the haul truck (e.g., speeding, backing over a drop-off, drowsiness) and 11% of the fatalities involved berming hazards [7]. Similarly, an earlier analysis of nonfatal accidents also found that operator failures (e.g., fatigue, error) and ground control hazards (i.e., hidden voids) were two of the most commonly reported contributing factors to accidents [6]. The previous analyses also recognize the contribution of human performance [4]. Monotonous driving, rough roads, rapidly changing conditions, limited visibility, and low responsiveness are common mine-site hazards that make operating haul trucks challenging.

However, while surveillance analyses can identify high-frequency classifications, they commonly lack more nuanced information about the context of the accident and the latent causes (e.g., poor policies and procedures) necessary to more fully understand why an accident may have occurred [10, 11].

[1] The term accident is used here and throughout the paper to describe an unexpected event with a negative or unwanted outcome that caused harm

Additionally, surveillance analyses do not give insights into sequential problems, which can evolve or develop over time [12]. The presence of a hazard does not necessarily lead to loss of control of the hazard; it is the trajectory of the accident. Therefore, knowing the sequence of events is critical in understanding an accident [13]. Human factors analyses, such as that by Drury, Porter, and Dempsey, can supplement surveillance analyses by identifying repeating patterns [14].

Additionally, to combat these limitations, accidents are now more frequently being examined through a system perspective [15]. One example is the fault tree analysis on West Virginia haul-truck-related accidents completed by Zhang, Kecojevic, and Komljenovic [16]. The fault tree analysis method allowed the authors to define the root causes of the fatal accidents by creating a logic diagram. However, fault tree analyses de-emphasize contributing factors and do not address controls, and the logic diagram may be difficult to communicate to end users [17]. A more holistic risk-based approach may improve end-user communication. Cockshott [18] suggests that bowtie methods excel at "assembling information on hazards, initiating events, control measures and consequences in a form suitable for process operator understanding and training." Furthermore, the focus on health and safety controls and risk of a bowtie can help operators evaluate the effectiveness of their current controls as well as better manage risk [17, 19]. While bowtie analyses have been previously conducted for the mining industry [20], they were not focused on haul trucks Fig. 1.

Mining industry partners have also been working to improve communication around risk management and health and safety controls. The Earth Moving Equipment Safety Round Table (EMESRT) has recently updated their vehicle interaction group's nine-level defensive control model as a part of their performance requirements for vehicle interaction systems (PR-5A) [21]. The model was developed in conjunction with manufacturers and mine operators to provide a more practical interpretation of health and safety controls This has also been adopted by the International Council on Mining and Metals (ICMM) and included as a part of their critical control management approach [22]. The model is helpful in systematizing the preventative and mitigating controls when comparing to the bowtie analysis.

Fig. 1 EMESRT's nine-level defensive control model [21]

Therefore, the goal of this work was to take a practical systems approach to better understand why haul truck fatal accidents continue to occur. Researchers in this study combined an industry risk-based classification with a bowtie method in order to communicate identified control failures and preventative and mitigative controls that could be implemented. The possible causes and controls will be presented by each outcome type in order to prioritize general evaluation and improvement actions stakeholders can take to address haul-truck-related health and safety issues in the USA. Ideally, this analysis would include non-fatal accidents and near-miss incidents, but this data is less complete or not available. Completing this analysis with the MSHA fatality data provides a starting point.

2 Methods

In this study, the researchers analyzed 91 haul-truck-related fatal accidents that occurred from January 2005 through December 2018 in the US mining industry. The researchers included accidents that (1) fell under MSHA's jurisdiction, (2) happened to or because of a mineworker operating a haul truck, and (3) had a publicly available final MSHA fatality report. For this analysis, a haul truck was defined as a wheeled, enclosed-cab vehicle whose primary function is to haul material or equipment and is rated over ten tons. This includes fixed and articulated vehicles, large water, and service trucks, as well as mine and customer trucks, but only if they are being operated off public roads. This excludes light vehicles and primarily underground haulage vehicles such as battery haulers and scoops.

For each accident, researchers tabulated mine and accident classification data from MSHA's mine employment and accident and injury databases [23]. Mine demographics were taken from the year in which the accident occurred and included canvass code, mine type, and total employees. Accident information included classification, total experience, mine experience, and job experience.

Using the accident information and MSHA's final fatality reports [3], researchers then created bowtie representations for each accident following a qualitative approach based on the shell method [17]. Each bowtie included the following elements:

- **Initiating event:** The event that immediately led to the loss of control of hazard(s)
- **Causes:** All possible hazards that may have contributed or added to the severity of the accident
- **Preventative controls:** Possible controls that could have prevented all or part of the accident had they been in place

- **Mitigating controls:** Possible controls that could have reduced the severity of the accident had they been in place
- **Outcome:** The result of the event that led to the death of one or more mineworkers

Researchers generated codes for each element that were derived through the general process of content analysis [24]. First, all accidents were coded openly for each of the five elements by at least two researchers with a third reviewer serving as the subject matter expert (SME) as needed. Next, a structured codebook was developed for each element. The definitions for initiating event types can be found in Table 1. The types were based on those used by Burgess-Limerick [20]. The outcome types (Table 2) were focused on the cause of the fatality, and therefore, they were limited to one per accident. Generally, they were defined as the thing (i.e., vehicle, material, person) in motion followed by the thing(s) it interacted with (i.e., vehicle, material, person, environment). These definitions were based on the generic bowties in the Riskgate database [25]. Generic outcome definitions were selected to improve the generalizability of the accidents and more effectively group the results. Codes for causes and preventative and mitigative controls were developed based on the emergent themes. Researchers derived these emergent themes from only the information that was clearly described in the fatality report (e.g., fatigue needed to be documented by coworker accounts or a request for a break). Missing or incomplete information was not assumed (e.g., if no toxicology report was included, drugs and alcohol were not identified as a cause). Researchers identified possible controls at a feature level (e.g., collision avoidance not specific sensors) through internal expertise, previous investigations [20], stakeholder discussions, mine visits, and a survey of current technology. It is important to note that the causes were not taken directly from MSHA's root cause discussion because researchers could not assume consistent and systematic analysis and language were used across the entirety of the dataset. However, the corrective action was considered as support of a control not already being in place. These themes generally included policies and procedures, environmental hazards, mine, and equipment design, training, and experience, maintenance, and repair, as well as implementation of controls. Each of these categories included failures and solutions for all organizational levels including the individual, supervisor, site, and organization. For example, causes could be coded as "failure to follow policies & procedures," "lack of enforcement," and "lack of policies and procedures." Overall, there were 101 cause, 125 preventative control, and 36 mitigative control codes. The categories and counts are presented in Table 3. Using the developed codebook, the accidents were independently re-coded by two researchers. Any coding disagreements were resolved through discussion including the SME as needed. Lastly, the causes and controls were grouped according to EMESRT's nine-level defensive control model: (1) site requirements, (2) segregation controls, (3) operating procedures, (4) authority to operate, (5) fitness to operate, (6) operating compliance, (7) operator awareness, (8) advisory controls, and (9) intervention controls [21]. Table 3 details the high-level categories of the emergent codes associated with each level of control as well as the total code count for each category.

3 Results

3.1 Mine and Accident Characteristics

Coal operations (40%) accounted for the largest percentage of fatal accidents, followed by stone (31%) (as shown in Table 4). Mine size was defined by the total number of employees, where small was 25 or under, medium was between 26 and 100, and large was over 100. Interestingly, similar numbers of accidents occurred at small, medium, and large coal mines, while metal/nonmetal mines were exclusively large. Stone, sand, and gravel mines were primarily small

Table 1 Initiating event definitions

Initiating event	Definition
Equipment malfunction	Some aspect of the vehicle or equipment failed (e.g., brake failures, failures of equipment during lifting or pulling loads, failure of platforms)
Ground failure	The ground or surface became unstable or failed (e.g., highwall failures, dumpsite, or stockpile failures)
Loss of balance	A person or persons lost their balance (e.g., fall from same level, fall from height).
Loss of control	The operator lost control of a vehicle due to the presence of performance-reducing factors (e.g., inclement weather, poor road conditions, impairment by drugs/alcohol)
Loss of situational awareness	All aspects of the event were under control, but the operator's awareness of the situation was inaccurate in some critical respect (e.g., location of other mineworkers, position of self)
Other	Not otherwise categorized (e.g., falling material from a suspended load)

Table 2 Outcome definitions

Outcome type	Definition
Vehicle-environment interaction	Operator loses control or otherwise drives vehicle into an environmental hazard (e.g., over berm, into pond, tips over)
Vehicle-pedestrian interaction	Vehicle has a collision with a pedestrian
Vehicle-vehicle interaction	Vehicle has a collision with another vehicle
Material-person interaction	Uncontrolled material contacts or engulfs mineworker (e.g., pipe, mined ore)
Material-vehicle interaction	Uncontrolled material contacts or engulfs vehicle (e.g., highwall failure, flying rock)
Person-vehicle-environment interaction	Mineworker falls to the ground from a vehicle or comes in contact with an environmental hazard that was created or exacerbated by the vehicle (e.g., falls off stairs, catches on fire from vehicle, asthma attack in enclosed truck trailer)
Other	Not otherwise categorized (e.g., person bumps head)

but were more closely proportional to the US stone, sand, and gravel mine distribution [26].

Of the 91 fatal accidents identified, 26% of accidents were not classified as powered haulage by MSHA. This included 7% slips, trips, and falls; 5% falling material; and 5% machinery. The victims' average experience was 11.5, 6.4, and 10.3 years for total mining, mine site, and job experience, respectively.

3.2 Outcomes

Most of the accidents were vehicle-environmental interaction (54%), where the haul truck collided with an environmental hazard (e.g., drove off highwall) as represented on an annual basis by the dark blue bars in Fig. 2. An example vehicle-environment interaction accident bowtie visualization can also be seen in Fig. 3.This was followed by vehicle-person (15%), person-vehicle-environment (11%), and vehicle-vehicle (9%) interactions. However, as shown by red bars in Fig. 2, a vehicle-person fatality has not occurred in the last 3 years at the time of this writing. Figure 2 also shows that vehicle-environment fatal accidents are fairly constant throughout the 14-year period apart from 2011.

3.3 Initiating Events

Figure 4 shows that loss of control was the most common initiating event with 29 of 49 (59%) vehicle-environment accidents and 33 of the 81 total accidents (36%) across the top four outcome types (shown in gray). Equipment malfunction initiating events were the next highest initiating event in the vehicle-environment outcome type with 15 of 49 events (31%), and 18 of 81 events (22%) across the four outcome types (shown in red). Loss of situational awareness accounted for 7 of the events in both the vehicle-person and vehicle-vehicle outcome types (50 and 88%, respectively) for a total 14 of the 81 events (18%) across the four outcome types (shown in green). Accidents initiated by the operator (loss of control, situational awareness, and balance) accounted for a total of 54 of 81 events (67%) across the four outcome types. However, as shown in Fig. 4, the initiating event types tended to result in different outcomes. Vehicle-environment interactions were mostly initiated by loss of control, while vehicle-vehicle interactions were predominately initiated by loss of situational awareness.

3.4 Causes

Each fatal accident had multiple causes, ranging from 2 to 10 causes per accident with an average of 6. Operating compliance, which is composed of predominately "failure to follow policies & procedures," was the most frequently coded cause. As shown in the first column of Table 5, L6: Operating Compliance control failures accounted for 24% of all causes and were present in 84% of the fatal accidents. As indicated in Table 3, this code was comprised of 17 emergent codes where the violated policies and procedures mainly included seat belts, maintenance, pre-shift inspections, traffic control, berms, dumping, and parking. This was followed closely by L1: Site Requirements failures which accounted for 21% of all causes and were present in 77% of the fatal accidents, which included roadway and equipment design and conditions as well as environmental conditions (Table 3).

Overall, the causes were predominately failures of low-level defensive controls (levels 1–6) including design and operational failures accounting for 33 and 60% respectively, which occurred in 97 and 100% of the fatal accidents, respectively. This trend also held true across the different outcome types. Figure 5 shows the percentage of the coded causes across the four outcome types, categorized by EMESRT's model. The only notable difference was that operating compliance was higher for vehicle-environment interactions (light blue), but it was balanced out by reductions in the other operational controls.

Table 3 Code categorizations and counts

Control levels	Causes		Preventative controls		Mitigative controls	
L1: site requirements	Roadway	6	Mine planning and maintenance	9	Berms and barriers	4
	Equipment	6	Communication infrastructure	2	Equipment	2
	Environmental conditions	7	Equipment	7		
			Illumination	2		
L2: segregation controls	Hazardous work area	11	Warning signs and indicators	8	Remote operation	1
			Designated work areas	6		
L3: operating procedures	Lack of polices and procedures	17	Policies and procedures	23	Policies and procedures	5
	Lack of enforcement	6	Logistics and monitoring	11	Monitoring and reporting	4
	Lack of equipment	1	Personal protective equipment	2	Blocking and securing	2
					Personal protective equipment	3
L4: authority to operate	Training	7	Training	18	Training	2
	Inexperience	4	Additional personnel	3	Additional personnel	1
L5: fitness to operate	Unfit for duty	3	Fitness for duty test	1	Fitness for duty test	1
	Change in routine	3	Peer reporting	1		
	Distraction	4				
	Other	2				
L6: operating compliance	Failure to follow policies and procedures	18	Surveillance and enforcement	21		
	Improper use of equipment	2				
L7: operator awareness	Mechanical failure	1	Attention and fatigue monitoring	1	Attention and fatigue monitoring	1
	Illumination	3	Edge detection	1	Load monitoring	1
			Vehicle feedback	1	Vehicle feedback	1
			Video cameras	1		
L8: advisory controls			Edge of roadway warning	1		
			Collision warning	2		
L9: intervention controls			Automatic parking brake	1	Fire suppression	1
			Brake test interlock	1	Collision avoidance	2
			Speed limiter	1	Driver assist	3
			Seat belt interlock	1	Geofencing	1
					Seat belt interlock	1

Table 4 Accident mine demographics

Commodity	Type			Size*			Total	
	Facility	Surface	Underground	Small	Medium	Large		
Coal	3	26	7	8	12	16	36	40%
Metal		8	2			10	10	11%
Nonmetal		1	1			2	2	2%
Sand and Gravel		15		12	2	1	15	16%
Stone	4	20	4	13	8	7	28	31%
Grand Total	**7**	**70**	**14**	**33**	**22**	**36**	**91**	**100%**

*Small ≤ 25, Medium ≤ 100, Large > 100 Total Employees

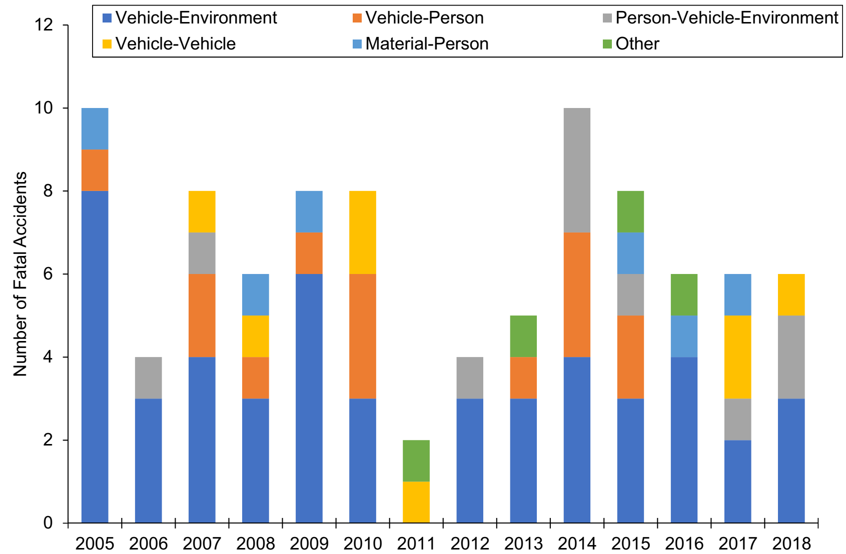

Fig. 2 Stacked graph depicting the frequency of haul-truck-related fatal accidents by outcome type and year ($n = 91$)

3.5 Preventative Controls

Researchers identified between one and eight preventative controls for each cause associated with each fatal accident. However, because of the diversity of the underlying circumstances, the identified preventative controls for each cause varied between accidents. Therefore, causes were associated with a maximum of 15 preventative controls.

In general, the preventative controls had a higher percentage of operational and reactive controls than the causes, but operational controls were still the highest (65%) and covered all fatal accidents (100%) (as shown in Table 5). More

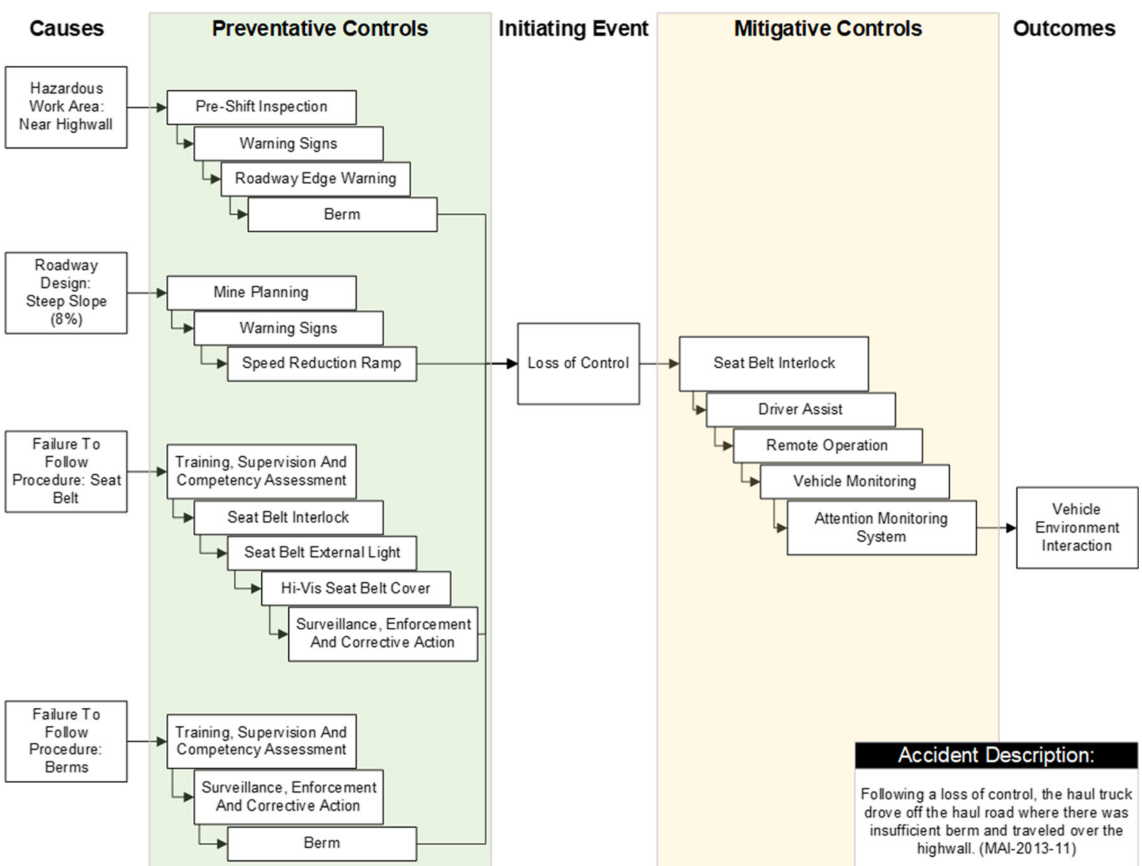

Fig. 3 An example of a loss of control bowtie visualization of single fatal accident using emergent codes. The preventative and mitigative controls are stacked in time order of applicability from first to last

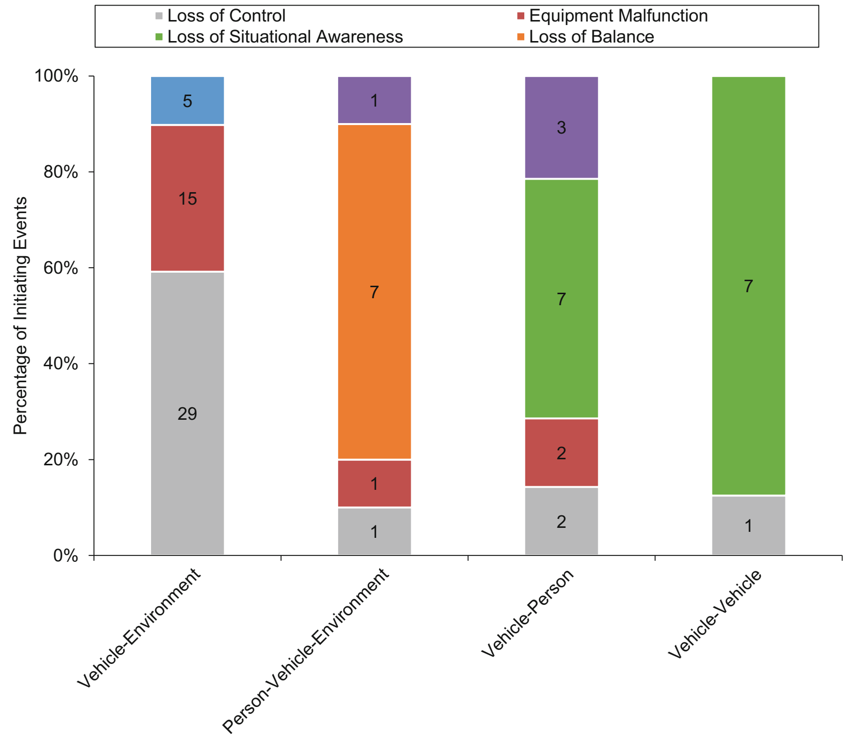

Fig. 4 Stacked graph depicting initiating events for the top four outcome types (labels are frequencies $n = 81$)

specifically, the preventative controls included more Level 3: Operating Procedures and Level 4: Authority to Operate controls than the causes, which are mainly composed of the creation or improvement of policies and procedures and training (as shown in Table 3). The policies and procedures identified as possible preventative controls included maintenance, communication, weather, drugs and alcohol, loading, and traffic control. The training included seat belts, hazard recognition, haul truck operation, maintenance, pre-shift inspections, dumping, traffic control, communication, and berms.

Table 5 Control level code and fatality percentages of causes, preventative controls, and mitigative controls

Defensive control level		Causes		Preventative controls		Mitigative controls	
		Codes	Fatal accidents	Codes	Fatal accidents	Codes	Fatal accidents
Design	L1: site requirements	21%	77%	15%	88%	11%	30%
	L2: segregation controls	12%	57%	12%	77%	20%	59%
	Total design	33%	97%	27%	91%	30%	65%
Operate	L3: operating procedures	14%	54%	20%	86%	26%	58%
	L4: authority to operate	15%	57%	17%	98%	1%	4%
	L5: fitness to operate	7%	35%	2%	18%	0%	1%
	L6: operating compliance	24%	84%	20%	97%	0%	0%
	Total operate	60%	100%	65%	100%	28%	63%
React	L7: operator awareness	7%	41%	6%	58%	4%	10%
	L8: advisory controls			4%	42%	0%	0%
	L9: intervention controls			4%	48%	38%	76%
	Total react	7%	41%	14%	84%	42%	78%

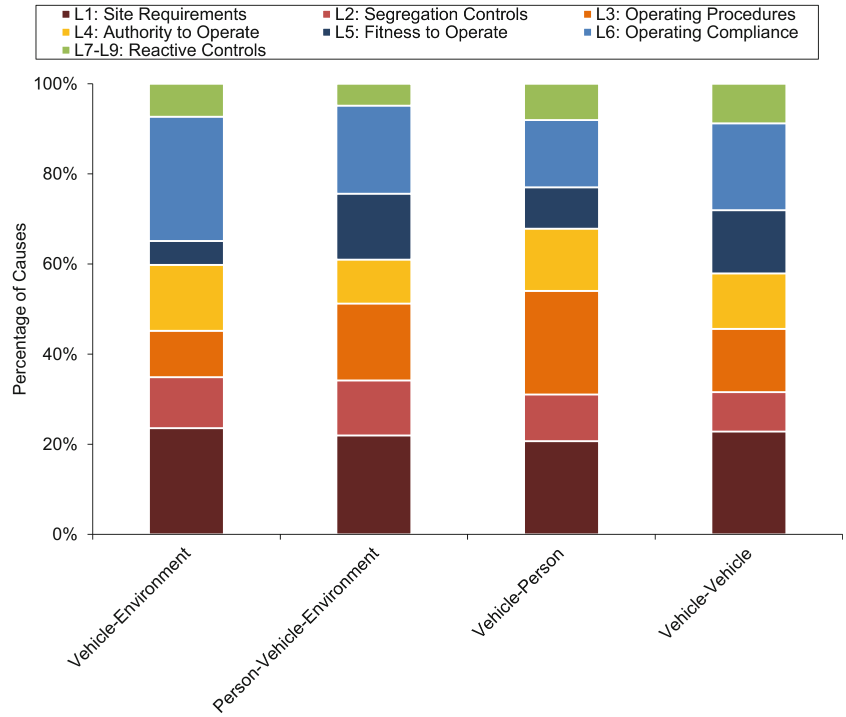

Fig. 5 Stacked graph depicting percentages (per column) of causes categorized by EMESRT's nine-level defensive control model for fatal accidents with the top four outcome types

3.6 Mitigative Controls

Researchers identified between one and six applicable mitigative controls per fatal accident with an average of 3.0. The mitigative controls predominately fell into Level 9: Intervention Controls (38%), Level 3: Operating Procedures (26%), and Level 2: Segregation Controls (20%), as shown in Table 5. Again referring to Table 3, Intervention controls consisted of driver assist, seat belt interlocks, collision avoidance, and other automatic systems (e.g., fire suppression, geofencing). For mitigative controls, operating procedures included monitoring and reporting systems, such as vehicle monitoring and personnel tracking. They also included policies and procedures, such as check-ins when working alone

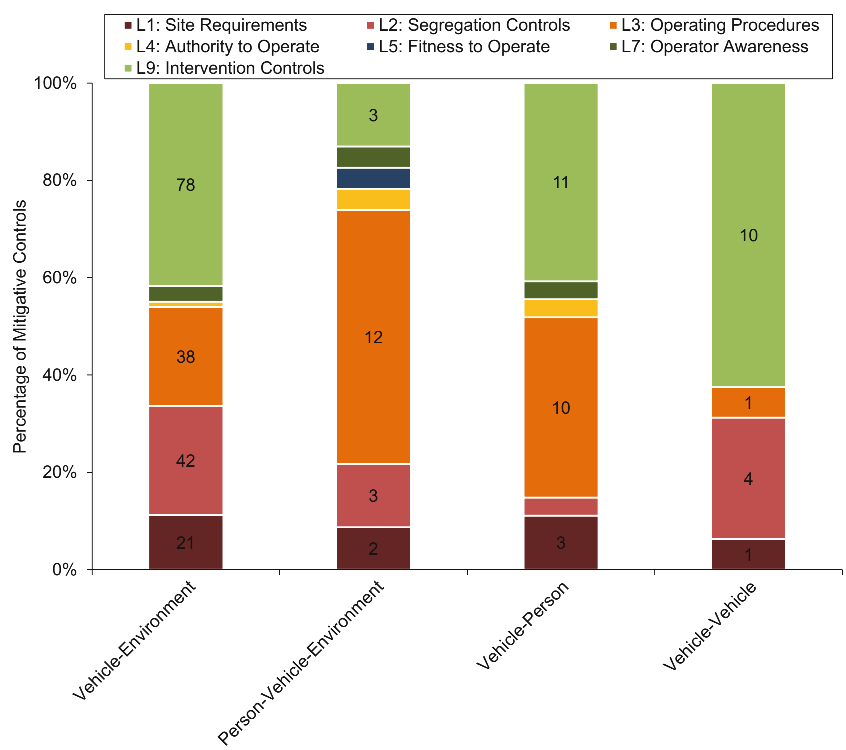

Fig. 6 Stacked graph depicting percentages (per column) of mitigative controls categorized by EMESRT's nine-level defensive control model for fatal accidents with the top four outcome types (labels are frequencies)

and emergency response. Lastly, operating procedures included personal protective and other equipment, such as respirators and blocking material (e.g., chocks). Mitigative segregation controls were all remote operation systems.

Different from the causes (Fig. 5) and preventative controls (not shown), Fig. 6 shows that the mitigative controls varied more between outcome type. The highest percentage (42%) of mitigative controls for the vehicle-environment outcomes was attributable to intervention controls. Intervention controls also vary over all the outcome types: person-vehicle-environment (13%), vehicle-person (41%), and vehicle-vehicle (67%). A higher percentage (52%) of the mitigative controls for person-vehicle-environment interactions are operating procedures.

4 Discussion

The goal of this research study was to gain a more holistic and practical understanding of why haul-truck-related fatal accidents continue to occur. Specifically, researchers were interested in taking a risk-based approach to identify possible causes and controls in order to prioritize general evaluation and improvement actions stakeholders can take to address haul-truck-related health and safety issues in the USA.

Overall, the results of this study suggest that haul-truck-related fatal accidents disproportionally occur at large coal, metal, and nonmetal mines but have occurred more proportional to the US' size distribution for stone, sand, and gravel mines [26]. This may be partially due to the differential use of haul trucks across commodities. For example, small coal mines may be less likely to have large plant or surface operations on mine property, limiting MSHA's jurisdiction of haul truck use (e.g., they use more on-road haulage), resulting in an under-representation. Conversely, haul trucks may be more integral to stone mines because of the specific mining methods, increasing mineworkers' exposure and thus the frequency of accidents. Either way, there is currently limited information on which mines use haul trucks and how the integration into site operations may differ. A more focused study may help clarify these differences and help develop more targeted solutions by commodity and mine size.

The results of this study also indicate that vehicle operation remains a core issue for haul-truck-related health and safety. This includes the ability and understanding required to safely operate a haul truck [7, 8]. Three of the top four outcomes and 78% of the fatal accidents relate to the inability to control a haul truck. Specifically, the most common outcome, vehicle-environment interaction was primarily initiated by loss of control of the vehicle and mechanical failure. Both initiating events have the potential to be mitigated through increased skill, support, or information. For example, if the operator was better able to recover from an overcorrection in steering, if the vehicle better assisted the operator to regain traction, or if the operator had more knowledge about the mechanical health of the vehicle, some of these situations may not have resulted in the death of the operator. Targeted training in vehicle control and equipment inspection could improve skills related to these initiating events as previously suggested by Kecojevic and Radomsky [9]. Support and informational systems like traction control, path departure warnings, or machine health monitoring could also improve outcomes. Similarly, in the pedestrian and vehicle collisions, more information about the operator's surroundings could potentially mitigate the fatal consequences. As described in EMESRT's model, reactive controls are intended to manage this residual risk [21]. So, if all else fails, reactive controls can provide a last line of defense in controlling hazards. Therefore, reactive controls should target initiating events to be most effective. These controls could include driver assist, collision avoidance, and vehicle feedback technologies as identified in the mitigative controls. While some development is underway, manufacturers and mine operators may consider additional investment and implementation of these solutions related to vehicle operation.

Another major concern suggested by the results of this study is the high rate of operators failing to follow established site policies and procedures, which was the most commonly coded cause. Again, the violated policies and procedures mainly included seat belts, maintenance, pre-shift inspections, traffic control, berms, dumping, and parking. This finding more closely aligns with that of Zhang et al. with the exception of traffic control and parking [16]. Collision appears to be more of a hot topic [1] especially for larger western operations that were not included in the fault tree analysis. However, it is unclear what is motivating and driving these unsafe acts. A number of factors could be at play, including operator inexperience, inadequate training, lack of enforcement, inadequate policies and procedures, or a lack of information, all of which were also identified as common causes in these accidents. To better understand these unsafe acts, other analysis techniques, such as the Human Factors Analysis and Classification System, could be employed to categorize these errors as violations or perceptual, skill-based, or decision-based errors [27]. However, the ability to do so is severely limited by the quality of the data. Specifically, in the case of these haul truck fatal accidents, there is often limited detail about what happened at the time of the accident because the victim is frequently the operator themselves [7]. Additional research into near-misses and serious accidents may be able to better explain the underlying reasons for operators' decisions.

Additionally, though MSHA's fatal reports provide a better description of accidents than most occupations, they often do not give the full picture. For example, Level 5: Fitness to Operate was far less prevalent in the data than the other operational controls. This may be partially due to the lack of inclusion of a toxicology section in many of the reports. The lack of consistency makes it difficult to determine if there was nothing to report or if tests were excluded for other reasons. Another contributing factor may be the subjective nature of fatigue. There is currently limited means to assess fatigue. Therefore, it is difficult to objectively include it in a report. However, fatigue is a significant concern, because it has been shown to affect dynamic attentional control [28], which is particularly important for operating a haul truck. Fatigue also has other physical, cognitive, and emotional effects that can affect an operator's performance [29]. The lack of prominence of fatigue in this analysis also conflicts with other industry accounts [30] as well as what is seen in other industries [31]. This further supports the need for additional research into near-misses and serious accidents where the operator can be interviewed. Researchers need to better understand: Is fitness to operate really an underlying problem? Are the organizational policies and procedures adequate to address this problem? Are the organizational policies and procedures contributing to this problem? Additional research will improve the industry's understanding of the trajectory of the accidents (i.e., what actually led to the loss of control). Previous research similarly advocates for further study beyond systems-level accident analyses [11, 13]. Overall, more research is needed to better understand operator decision-making and the presence and effectiveness of organizational controls.

Furthermore, additional evaluation and improvement of organizational controls are supported by the emphasis on low-level defensive controls in this analysis (levels 1–6). Operational and design controls are the most common for both causes and preventative controls. Although in the hierarchy of controls, engineering solutions are said to be more effective than administrative controls, and the nature of the intervention must also be taken into consideration. Reactive controls that prevent or mitigate hazards may only be effective in certain situations, and it is better to enact controls that reduce risk more broadly or at an earlier time point. This affords more time for additional barriers closer to an event occurrence and is in line with systems thinking [11]. Furthermore, latent controls such as regulation and policies and procedures are necessary for enforcement and compliance, and they often produce the most benefit [11]. Mine operators may consider evaluating their existing controls, including communication, maintenance, and traffic controls related to haul truck operation, to ensure their effectiveness.

Lastly, the consistent distribution across the causes and controls for all accident types (i.e., outcomes) reinforces the multi-dimensional nature of accident causation [32]. Regardless of the consequence, it is necessary to ensure that all types of hazards are controlled and that multiple layers of controls are in place to minimize risk. From engineering to operations, safety, training, and labor, all work domains are involved. Mine operators may consider evaluating how well their departments interact and communicate to minimize hazard exposure.

5 Conclusion

This study's results highlight the need to refocus the mining industry's attention on effective low-level defensive controls (EMESRT's levels 1-6), design and operation controls. Improvements in the implementation of low-level defensive controls may have averted many of the accidents in this study and are believed to be the most effective. Overall, a systems view is necessary to ensure mineworkers' health and safety and provide a strong base for future technology development.

In the meantime, stakeholders may consider additional investment and implementation of reactive controls to address loss of situational awareness and loss of control. Supporting haul truck operators' ability to better understand their surroundings and maintain control of their vehicles could mitigate most of these types of accidents.

For a more complete picture of why haul truck fatal accidents continue to occur, this analysis of previous accidents suggests that more active research is needed to understand haul truck operators' decisions and evaluate organizational controls. As a part of that effort, researchers also need to better understand when, why, and how haul trucks are being used across different operations. Studying near-miss or serious accidents could shed more light on the established policies and procedures, chains of events, and operator decisions and actions leading up to these events. Armed with these new insights, safety professionals should be able to provide additional guidance to improve the safety of haul truck operators and their co-workers.

Authors' Contributions Bellanca designed and directed the project. Bellanca, Ryan, and Orr performed the qualitative analysis with methodological support from Burgess-Limerick. Bellanca primarily wrote the manuscript and created the figures, tables, and graphs with input from Ryan, Orr, and Burgess-Limerick. All authors discussed the results and commented on the manuscript.

Declarations

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 company names or products does not constitute endorsement by NIOSH.

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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