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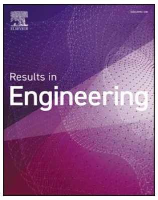

Review article

Powered haulage safety, challenges, analysis, and solutions in the mining industry; a comprehensive review

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ABSTRACT

Satisfying safety issues plays a critical role in mining operations. Although the use of emerging technology became a new trend in preventing powered haulage hazards in the mining industry, these technologies themselves posed new hazards to the problem that are necessary to be identified, assessed, and managed together with common hazards. This study investigates the existing gaps in powered haulage safety to establish a comprehensive framework for conducting risk analysis procedures. To achieve this purpose, a literature search methodology is employed to recognize the most relevant resources and extract the essential information. The most critical hazards in powered haulage operations are identified and classified into main groups. Then, root causes and consequences are designated for these hazards, providing substantial elements for risk analysis, which serves as an effective hazard measurement. Afterward, an overview of popular risk analysis techniques applied in the mining industry is provided to establish a holistic risk analysis framework. Finally, available hazard management strategies are discussed as solutions for mitigating and preventing potential hazards. The study results demonstrated the importance of establishing comprehensive safety protocols, continuously upgrading the advanced technologies, regular training, and continuous risk assessment to mitigate and prevent fatal and non-fatal hazards in mining operations.

1. Introduction

Powered haulage equipment is one of the most vital operational components in the mining industry. These types of equipment have recently become complex and expensive assets, demonstrating the necessity of their safe operation. Besides, automating these types of equipment has created serious challenges and opportunities in mining operations. In other words, these situations changed the fundamentals of the entire mining industry and conventional fleet management.

Safety issues substantially affect mining operations, particularly within powered haulage equipment. Since mining companies are transitioning from nonautonomous into autonomous mining fleets, it becomes crucial to perceive all aspects of mine safety with an integrated autonomous and nonautonomous fleet. Therefore, it is imperative to identify and evaluate the existing potential adverse events, their root causes, and subsequent consequences. While previous studies in the mining industry have primarily focused on hazard identification, they often overlooked providing measurements such as risk assessments for these hazards. However, the adoption of hazard management measures, which can be significantly costly, should be informed by these measurements. Consequently, establishing barriers for preventing and mitigating risks and uncertainties depends considerably on hazard measurements. These significant challenges motivated the authors to study this novel operating system, which is a combination of human, autonomous, and nonautonomous systems. Thus, this procedure suggests comprehensive insights into the potential hazards, their classifications, causes, consequences, hazard measurements, and the required barriers to mitigate or prevent them.

The rest of this paper is organized as follows. Section 2 expresses the proposed methodology for this study. Section 3 details the research objectives established for this study. Then, the literature search, screening, and selection processes are given in Section 4. Section 5 presents the achieved results by extracting and evaluating the essential information, providing a strong insight into the powered haulage safety and risk in the mining industry. Section 6 discusses operational hazard challenges and suggests management strategies as solutions for mitigating and preventing potential hazards. Finally, the conclusion and some important remarks are presented in Section 7.

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2. Methodology

This study is a systematic review based on collecting and analyzing the hazards associated with powered haulage operations in the mining industry. Fig. 1 indicates the proposed step-by-step procedure in this investigation. The principal elements of this approach are as follows:

2.1. Determining research objectives

The primary research objective is focused on a systematic review of the existing scientific studies to identify the patterns and trends in hazards associated with powered haulage operations and explore recent management strategies as solutions for mitigating and preventing potential hazards.

2.2. Literature search

The literature search is focused on establishing a comprehensive framework to acquire studies related to powered haulage hazards in the mining industry. This approach involves investigating various electronic databases and choosing relevant studies. The identified studies are filtered by determining pre-defined inclusion criteria and developing a two-stage screening process. This process first analyzes the titles, abstracts, and keywords of all resources, and then revolves around the review of the full text of the remaining resources. Thus, irrelevant studies are excluded from the investigation, and relevant studies that meet the inclusion criteria are considered for further analysis. This selection process ensures the study provides a comprehensive and up-to-date overview of the available knowledge and research findings on powered haulage hazards in the mining industry.

2.3. Results

According to the investigated studies, it is necessary to extract essential information from the selected studies and evaluate key findings by realizing common trends, patterns, and insights regarding the

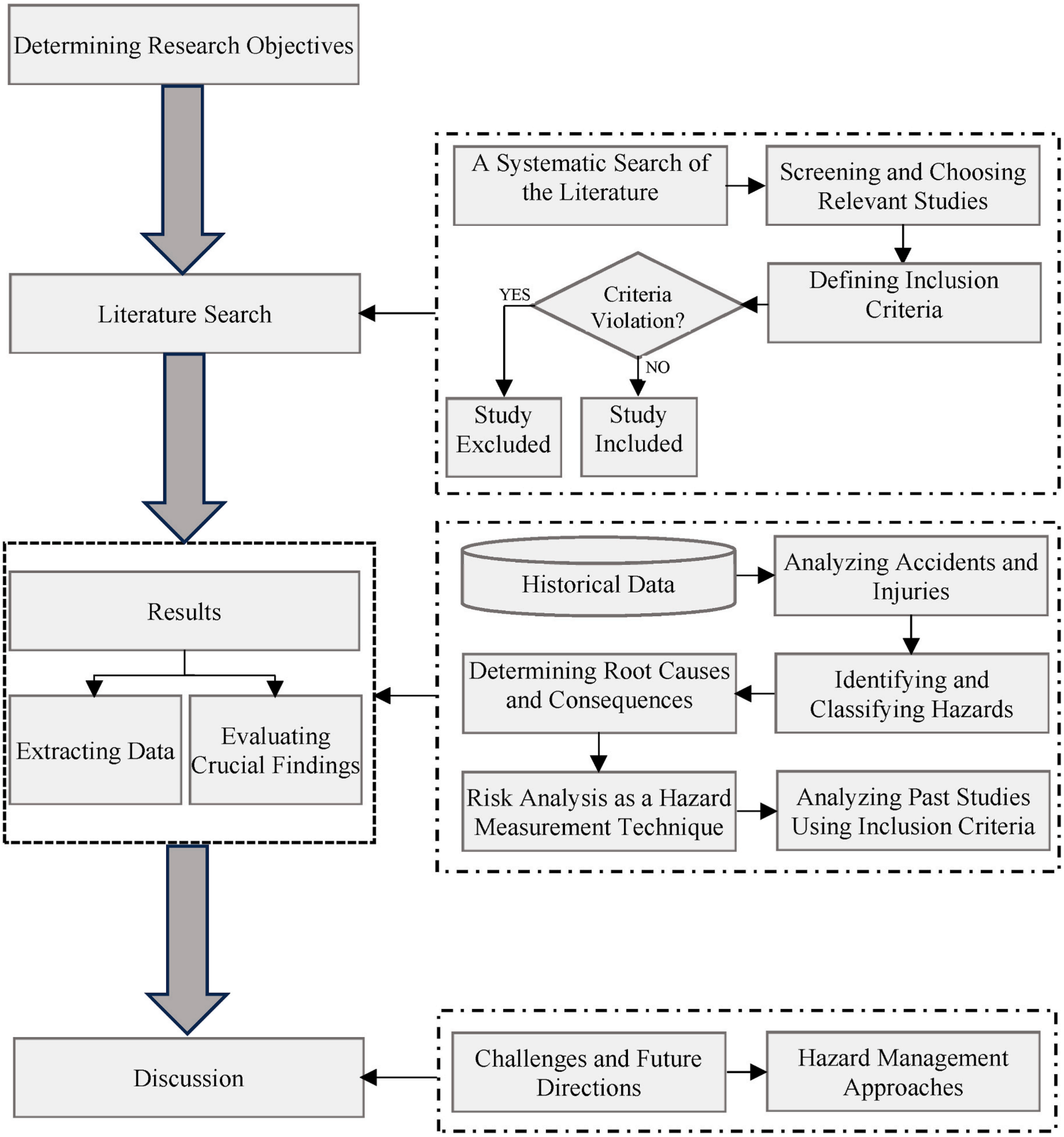

Fig. 1. The proposed step-by-step research procedure in this investigation.

methods, their pros and cons, and the outcomes. The analysis process involves examining historical data, identifying and classifying hazards that occurred during the powered haulage operations, determining root causes and consequences of these hazards, presenting risk analysis techniques as a hazard measurement approach, and providing an overview of past studies based on the risk analysis process employed in their studies.

2.4. Discussion

After identifying and analyzing the risk of hazards, it is crucial to discuss operational challenges and explore strategies for managing the most significant risks and enhancing powered haulage operation safety. This section presents both conventional and novel approaches for preventing and mitigating hazards as solutions for managing hazard risks.

3. Determining research objectives

In this review paper, the primary objective revolves around the comprehensive safety analysis of powered haulage operations in the mining industry, providing a systematic overview of the contributing factors and associated risks. The aim is to synthesize existing research to identify and classify hazardous patterns and offer measurement techniques for assessing the hazards. Additionally, it endeavors to explore recent advancements and practical strategies as solutions for managing powered haulage hazards.

4. Literature search

The literature search was performed by identifying literature, screening it, and choosing relevant studies. Different electronic databases (e.g., Web of Science, SpringerLink, IEEE Xplore, Wiley Online Library, and Scopus) were searched using keywords and Boolean operators to identify research articles (i.e., academic journals and conference proceedings), books, book chapters, and handbooks. Also, multiple online resources (e.g., international and national standards, websites, and technical reports) were searched to provide a significant context about safety and risk analysis of powered haulage safety, hazards, and solutions. Then, a two-stage screening process was conducted to analyze all identified resources. Thus, irrelevant studies were excluded, and those meeting the pre-defined inclusion criteria were considered for further analyses. The inclusion criteria were associated with the publication date (above 1980) and language (English), scope and objective of the study, hazard measurement technique, and field of study. In this regard, the first screening stage of the documents involved collecting documents from the mentioned databases. The search process was executed by formulating various keywords and conducting searches in the title, abstract, and keywords. The search strategy was carried out as follows: (Powered Haulage AND Risk), (Powered Haulage AND Accident), (Powered Haulage AND collision), (Risk AND Mine Truck Collision OR Powered Haulage Accident), (Collision AND Truck AND Mine), (Mine Haulage Truck Accidents), (Haulage Truck AND Safety AND Mining Operation), (Mining Equipment AND Fatalities), (Truck Accidents AND Risk AND Mining Industry), (Surface Mine Accidents AND Classification), (Hazard Identification AND Mining Equipment), (Bow-tie AND Mining Industry), (Risk Management OR Risk Analysis AND Safety AND Mining Equipment), (Occupational Accidents AND Mining Trucks), (Autonomous Trucks AND Mine Accidents), and (Collision Detection AND Mobile Mining Equipment).

A total of 495 documents were initially gathered in the search database. Then, the title and abstract of each document underwent careful review to screen them based on the defined inclusion criteria. Among the collected documents, 15 % were identified as the most relevant studies with the scope and objectives of the current paper, focusing on powered haulage hazards and analyses in surface mining operations. Another 13 % pertained to safety and risk in underground mining operations. Also, 18 % of the documents did not match the current paper's targets, covering accidents in other industries, error matching of data mining techniques with the mining industry, and being related to other industries. Additionally, 14.3 % of the collected documents fell into gray areas; although not directly related to the paper's targets, they could offer valuable insights into hazard identification techniques, measurements, monitoring, analysis, and prevention methods. Most of these documents addressed aspects like human health, occupational injuries, production efficiency, automation, hazard detection technologies, equipment failure, and reliability, but not specifically powered haulage hazards.

Finally, 39.7 % of the documents were duplicated across different databases and were eliminated from the analysis process. These data analyses showed a limited number of studies fully related to the powered haulage hazards, totaling 68 studies. Table 1 provides a valuable insight into the contents of these studies.

These analyses revealed that none of the studies specifically analyzed hazards associated with the mixed operation of autonomous and nonautonomous trucks. In the mining industry, most studies focused on utilizing novel technologies as effective management strategies to mitigate or prevent hazards but often overlooked potential errors inherent in these technologies. While the majority of studies aimed to identify potential hazards by analyzing historical data in powered haulage operations, only a limited number considered hazard measurement techniques to calculate the exact magnitude of hazard risk. Understanding the hazard order is crucial for selecting an appropriate hazard management strategy, as it is not feasible to judge the mitigation or prevention of root causes without this information. Therefore, clarifying and maintaining the control strategy is essential in a cost-effective process.

The next screening stage of the documents involved reviewing the full text of the relevant studies, with detailed extraction and analysis presented in subsequent sections. The outcome of the second screening stage categorized the documents into five groups, including extraction of hazard data, classification, identification of root causes and consequences, hazard measurement techniques (i.e., risk methods), and the management and control barriers in powered haulage operations.

5. Results

This analysis results revolve around the extraction of essential information from the selected studies. This information is attained by analyzing historical safety data in the U.S. mining industry, identifying and classifying the most significant hazards and their root causes that take place in mining operations, describing the most prevalent risk analysis techniques as an effective hazard measurement, and providing an overview of the past studies to clarify various aspects of risks in mining operations.

5.1. Historical safety data analysis

The mining industry is recognized as one of the most hazardous operations worldwide. A mining disaster is one of the most vital indicators for safety analysis. It is an event with five or more fatalities [1]. Fig. 2 depicts the historical disaster data obtained from the National Institute for Occupational Safety and Health (NIOSH) for mine disasters from 1839 to 2021.

Table 1
An overview of the studies related to powered haulage hazards.

Topic Area	Percentage of Studies
Powered Haulage Hazard Investigation	28 %
Technology Application for Hazard Management	41 %
Analyzing Root Causes of Hazards	26 %
Safety Training	5 %

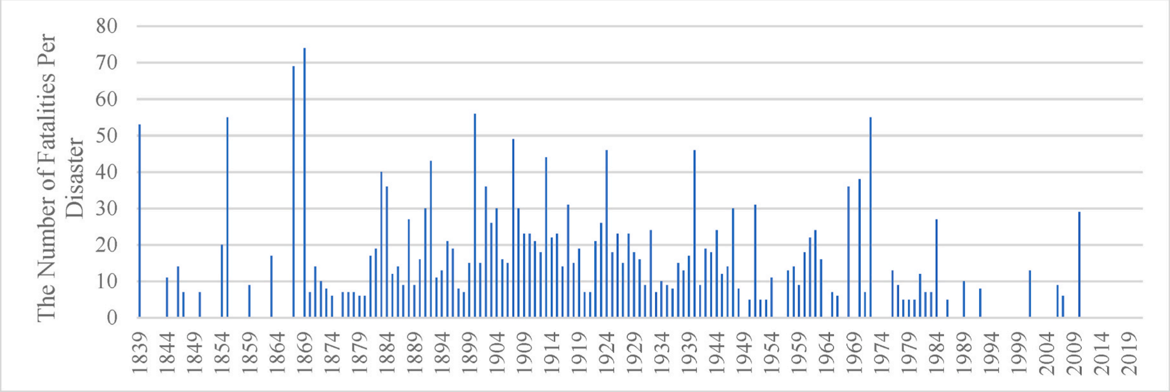

Fig. 2. Mine disasters from 1839 to 2021 [1].

As shown in Fig. 2, mining disasters have significantly decreased over time. The prevalence of mining operation disasters was notably high before the 1990's decade; however, since then, the number of disasters has substantially diminished. This trend demonstrates the effectiveness of safety enhancements implemented during these years. Nevertheless, the U.S. Mine Safety and Health Administration (MSHA) database reports that many fatal and non-fatal hazards still occur in the mining industry [2]. The total number of mining hazards was about 5600 in the United States in 2021. Fig. 3 indicates the percentage of hazards based on the operation process in the U.S. mining industry in 2021. Among these operation processes, surface and underground mining operations contribute to most hazards at percentages of 38 and 33, respectively [2].

Since surface mining operation causes the highest number of hazards in the mining industry, it is necessary to identify and classify the most significant hazards that occur in this operation.

The potential hazards in the mining industry cause various human consequences. The MSHA database categorized these human consequences into several classes, including occupational fatality, disabilities (i.e., permanent, partial, or total), occupational illness, without injury, and other types of injuries (e.g., days away from work and days of restricted activity). According to the MSHA database, the number of occupational fatalities was 37 individuals in 2021 [2]. Fig. 4 illustrates the contribution of each type of hazard to occupational fatality in 2021.

As shown in Fig. 4, powered haulage operation was the most frequent reason for occupational fatality. In this case, powered haulage fatalities were the hazards related to the motion of the haulage unit, such as ore haulage trucks, load-haul-dumper, conveyors, rail cars, and front-end loaders. Among these fatalities, ore haulage trucks were the leading cause of occupational fatalities. Therefore, understanding and analyzing the hazards and causes associated with ore haulage trucks provides a strong insight into the methods for preventing future fatalities and improves safety procedures. Various researchers studied several aspects of operation safety, potential hazards, and their corresponding risks in haulage trucks [3–5].

Fig. 5 exhibits a critical analysis of haulage truck-related hazards from 2000 to 2021, characterizing a significant trend [6]. Notably, there has been a substantial decrease in hazards, reducing from 216 hazards in 2000 to 82 hazards in 2021. This reduction underscores the positive impact of enhanced haulage monitoring, technological advancements, and the implementation of rigorous safety regulations on mitigating haulage truck hazards over the years. Additionally, the curve illustrates a promising trajectory in bolstering safety measures within the mining industry.

Fig. 6 illustrates a histogram analyzing the frequency of haulage truck-related hazards in relation to workers' job experience. The analysis reveals a noteworthy trend: as workers' experience increases, hazard frequency significantly decreases. Particularly, the highest and lowest hazard quantities between 2010 and 2021 occurred in the 0–3 and 39–42 years, respectively. Moreover, the average experience of workers involved in hazards was found to be about 5.2 years, shedding light on the correlation between experience levels and hazard rates. This trend can be attributed to the use of advanced technologies, monitoring systems, and enhanced safety regulations.

These critical analyses revealed the impact of powered haulage hazards, particularly ore haulage truck-related hazards, in the mining

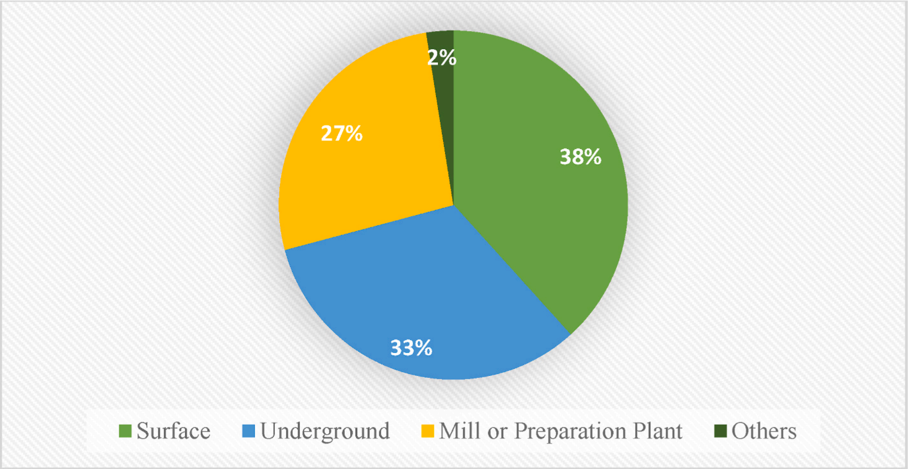

Fig. 3. The percentage of hazards that occurred in the United States in 2021.

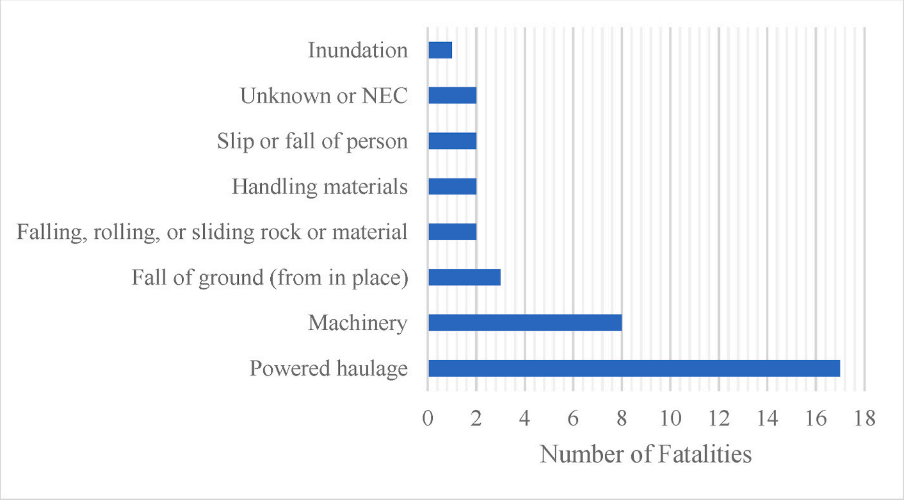

Fig. 4. The number of occupational fatalities due to different hazards.

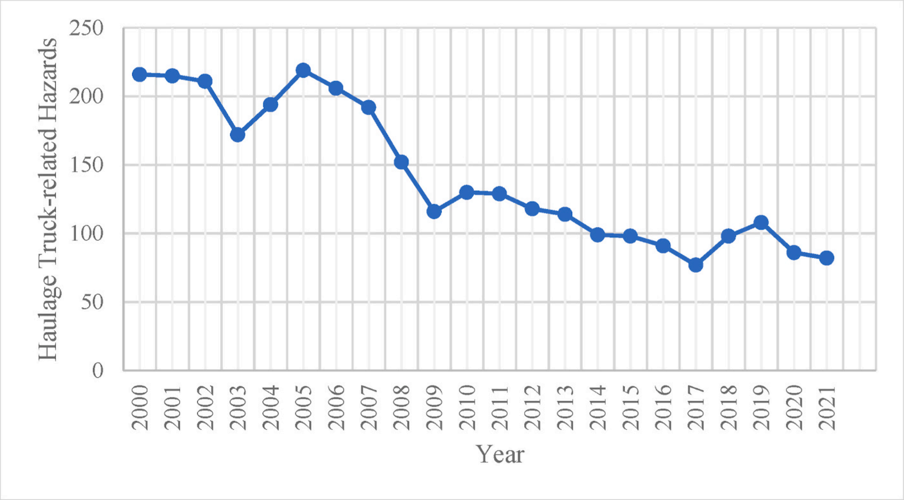

Fig. 5. The number of haulage truck hazards in the U.S. mining industry.

industry. These analyses underscore the necessity of comprehensive training for new employees, utilizing advanced training technologies, and enhancing the monitoring assets of workers—especially newly employed workers—as effective solutions for addressing these hazards.

5.2. Classification of hazards associated with mining haulage trucks

Using autonomous and nonautonomous haulage fleets poses different hazards that cause equipment hazards or human fatalities. Some of the hazards are in common between nonautonomous and autonomous systems. Various classifications are available for identifying and analyzing potential hazards associated with mining haulage trucks (Table 2).

According to Table 2, there are various classifications for identifying and analyzing potential hazards associated with mining haulage trucks. The MSHA [7] classification is based on root cause analysis, and haulage truck is a part of the hazards related to powered haulage equipment. ISO 17757 [8] is an international standard that provides guidelines for identifying hazards in autonomous and semi-autonomous earth-moving machinery and mining. This international standard includes various significant hazards for autonomous and semi-autonomous systems as follows: mechanical, electrical, navigational, collision, navigation and collision, and thermal hazards. Also, the Earth Moving Equipment Safety Round Table (EMESRT) [9] developed a performance requirement to prevent human injury or equipment damage. This performance requirement categorized the potential hazards into four groups, including equipment to person, equipment to equipment, equipment to environment, and loss of control of equipment. Moreover, ISO 19296:2018 [10] developed an international standard to establish safety requirements for mobile machines used in underground mining operations. This standard provides a list of potential hazards and hazardous scenarios associated with underground mining mobile machines during commissioning, operations, and maintenance. Additionally, ISO 3691–4:2020 [11] offers safety requirements for testing and verifying all types of driverless industrial trucks. This standard considers various hazards such as collisions, falling from vehicles, the environment, communication systems, vehicle sensors, software, maintenance, and battery charging.

In addition to these standards and major classification systems, various published studies investigated potential hazards for autonomous systems and haulage trucks. Malm et al. [12] categorized autonomous machine failures into several groups, including lack of situational awareness, failure in access control, improper system update, cybersecurity, failure in the lockout process, navigation failure, and stability control. Drury et al. [13] developed a fatality hazard pattern for mining haul trucks. The authors classified these fatal hazards into two main

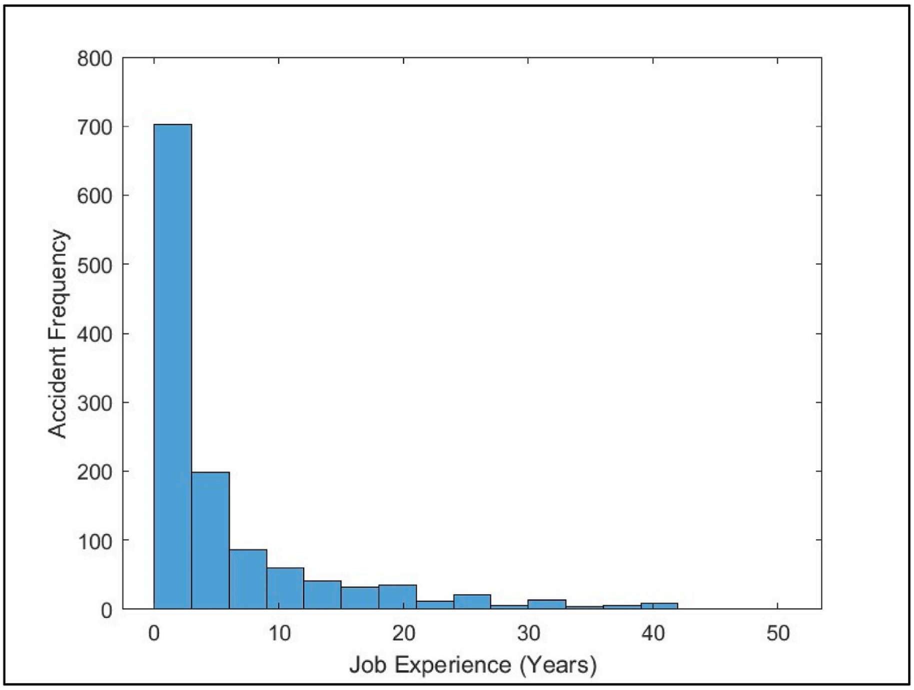

Fig. 6. The histogram of the haulage truck-related hazards in relation to workers' job experience.

Table 2
Different classification systems for safety issues.

Name	Description	Hazard Classifications
MSHA [7]	Hazard Root Cause Analysis; and Haulage Truck Hazard is a Part of the Powered Haulage Class	Electrical, Entrapment, Fire, Handling Material, Hand Tools, Machinery, Powered Haulage, and Fall of a Person
ISO 17757 [8]	The International Standard for Analyzing Safety and Risk in Autonomous and Semi-autonomous Earth-moving Machinery and Mining	Mechanical, Electrical, Navigational, Collision, Navigation and Collision, and Thermal Hazards
Earth Moving Equipment Safety Round Table (EMESRT) [9]	Performance Requirements to Prevent Human Injury or Equipment Damage	Equipment to Person Collisions, Equipment to Equipment Collisions, Equipment to Environment Collisions, and Loss of Control of Equipment
ISO 19296:2018 [10]	The International Standard for Safety Requirements in Mobile Machines Used in Underground Mining Operations	Mechanical, Hydraulics, Electrical, and Hazards associated with Stability, Ergonomics, and Visibility
ISO 3691–4:2020 [11]	Safety Requirements for Testing All Types of Driverless Industrial Trucks	Collisions, Fall from Vehicles, Environment, Communication Systems, Vehicle Sensors, Software, Maintenance, and Battery Charging

classes: driving (loss of control, ground failure, and vehicle collisions) and non-driving (unexpected movement, falling from a vehicle, and hitting by other vehicles) hazards. Bellanca et al. [14] studied the MSHA database regarding haulage trucks and categorized the fatality hazards into equipment malfunction, ground failure, loss of control, loss of balance, loss of situational awareness, and others (e.g., falling materials from a suspended load). Dindarloo et al. [15] classified the potential hazards into four groups: losing control of the truck, berm/dump failure, unsafe actions, and mechanical failures. Kecojevic et al. [16] used a statistical data-driven method to identify the hazards of underground mining equipment-related fatal hazards. The results showed that the maximum number of fatalities for the shuttle car, the LHD, the roof bolter, and the longwall were related to "Failure of mechanical components", "Failure of management to provide safe working conditions", "Working under unsupported roof", and "Failure of mechanical components", respectively. Also, the major hazard for continuous mining equipment-related fatal hazards was the "Failure of a victim to respect equipment working area".

According to the literature review, it is concluded that the potential hazards associated with haulage trucks (autonomous and nonautonomous) can be categorized into two main groups, including accidents and incidents (Fig. 7).

Accidents are one of the most considerable hazards in the mining industry. As shown in Fig. 7, equipment accidents result in three groups of top events, including equipment-to-equipment (EtE), equipment-to-human (EtH), and equipment-to-environment (EtEn) accidents. There are various accident scenarios in autonomous and nonautonomous haulage operations, such as moving two machines toward a bend, moving two machines toward an intersection (merge, tee, or 90-degree four-way intersection), moving objects too fast to be detected, moving a machine toward intersections with insufficient control, being an object or individual in the machine's blind areas, moving a machine toward occluded objects because of dust or fog (snow or rain), and moving a machine toward a road under construction or obstructed road.

Incidents are recognized as another significant hazard in the mining industry. This hazard results in three groups of top events: equipment loss of control, human loss of balance, and unstable material. The equipment loss of control involves various scenarios, such as moving a machine along a road with poor conditions, operating an overloaded machine, driver issues, and the machine's sudden failures. Besides, the human loss of balance refers to falling or slipping an individual from a height. Also, unstable material refers to unexpected collapsing material from a machine or slope that endanger equipment or individual in its path.

The above scenarios occur due to various basic events (causes). These basic events can be categorized into six main groups: equipment

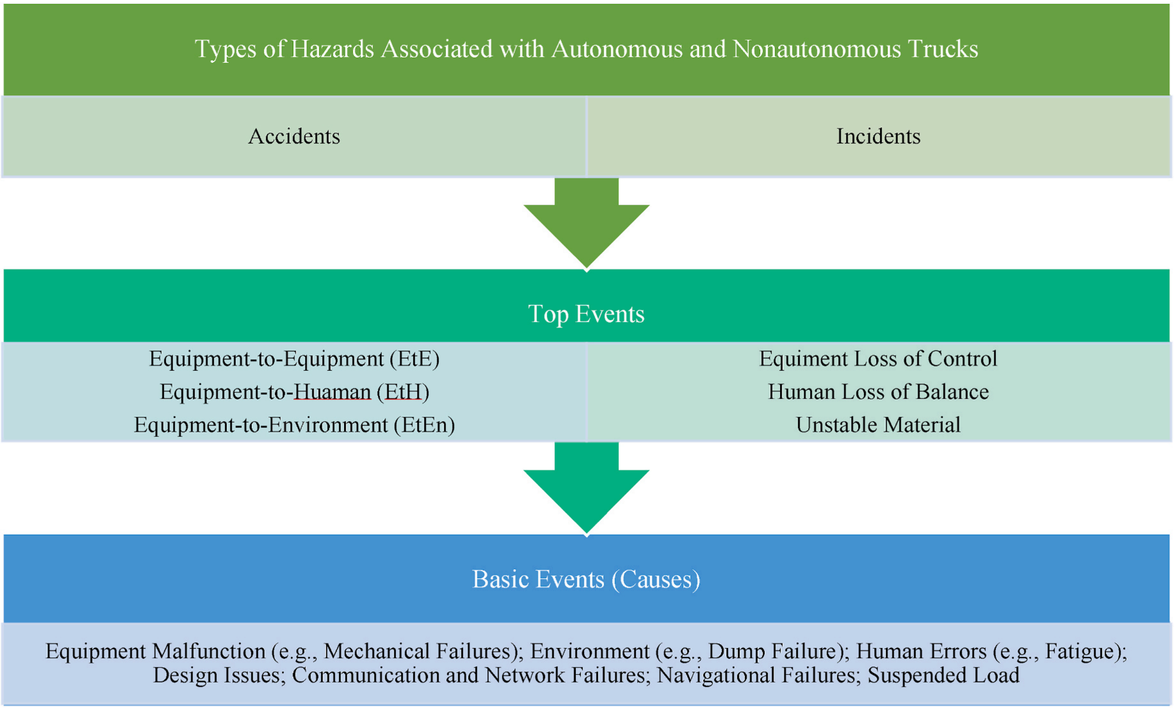

Fig. 7. Different types of mining operation hazards.

malfunction, environment, human errors, design issues, communication and network failures, navigational failures, and suspended load. Equipment malfunction is a critical basic event for accidents and incidents, leading to various consequences like fatality, equipment damage, or loss of production. This basic event occurs due to poor maintenance strategies, failure to preoperational checks, and corrective failures (e.g., truck tire explosions, steering component failures, brake problems, misalignment of sensors due to machine vibration, and loss of electrical power to the machine electronics). Besides, environmental basic events include berm or dump failures, climate bad conditions, poor road maintenance, rock burst, flyrock, and road construction or obstruction. The basic events associated with human errors are failure to follow the established rules, operator fatigue, operator distraction, inadequate training, health issues, and unsafe action. Also, the basic events related to design issues are blind areas or visibility issues (machine or road problems), poor lighting conditions, and lack of warning signs. In addition, communication and networks play a crucial role in the safety of autonomous and nonautonomous trucks. This basic event is due to various reasons, such as lack of access to situational awareness information, lost or delayed command input, lost or delayed hazard information, and loss of ability to activate the fire protection system. Furthermore, navigational failures may occur due to loss or deterioration in the digital terrain map (DTM) accuracy, lack of calibration between the DTM and the existing terrain, loading obsolete version of the DTM, inaccurate terrain data, failure to detect or late detection of an object, equipment movement to inaccurate places, and incomplete or improper system updates [8].

After identifying hazards, top events, and basic events, it is necessary to address the potential consequences. This procedure provides substantial elements for risk analysis as an effective hazard measurement. In this study, risk analysis is implemented via a graphical tool (Bowtie Diagram [17]), providing a list of causes, top events, and consequences. Fig. 8 shows a Bowtie diagram with the most frequent top events, their causes, and their consequences in mining haulage operations. As shown in Fig. 8, this diagram presents the causes that can lead to a top event and the consequences that can result from this top event. Once this relationship is recognized, it becomes possible to manage consequences (i.e., loss of production, non-fatal injury, fatal injury, and property damage) by preventing or mitigating them. This visualization structure provides a better perception of the relationships between potential hazard elements.

5.3. *Hazard measurement process*

Risk analysis is recognized as one of the most popular techniques for measuring hazards. Risk-based methods assess and manage the hazards associated with a component or system [18]. Thus, the risk analysis procedure can be categorized into three groups: risk assessment, management, and communication [19]. Fig. 9 shows the risk analysis steps for the risk-based methods.

5.3.1. *Risk assessment methods*

The mine production system is one of the critical elements of the mining operation process [20]. However, this operation is hazardous and may cause worker fatality [21,22]. Therefore, it is essential to assess and manage significant risks that occur during the operation process. Different researchers developed a wide range of risk assessment methods [23,24]. Nevertheless, it is possible to categorize the risk assessment methods from the mathematical viewpoint into two main groups: qualitative and quantitative techniques [19]. Table 3 provides the leading risk assessment methods employed in mining operations.

The following paragraphs describe each of the most popular risk assessment methods used in mining operations.

5.3.1.1. Fault tree analysis (FTA). FTA is a graphical technique to detect and quantify the hazard causes. A static fault tree consists of events (i.e., top, basic, and intermediate events), Boolean logic gates (i.e., “AND”, “OR”, and “Priority AND”), and transfers. It connects the lower-level events to upper-level events based on top-down architecture. Combining this logical model with quantitative algorithms (e.g., cut sets) makes it a quantitative method [19]. Fig. 10 indicates a sample FTA structure that estimates the probability of the top event (failure to control the haulage truck) by computing and combining the actual likelihood of various basic events. In this scenario, the haulage truck

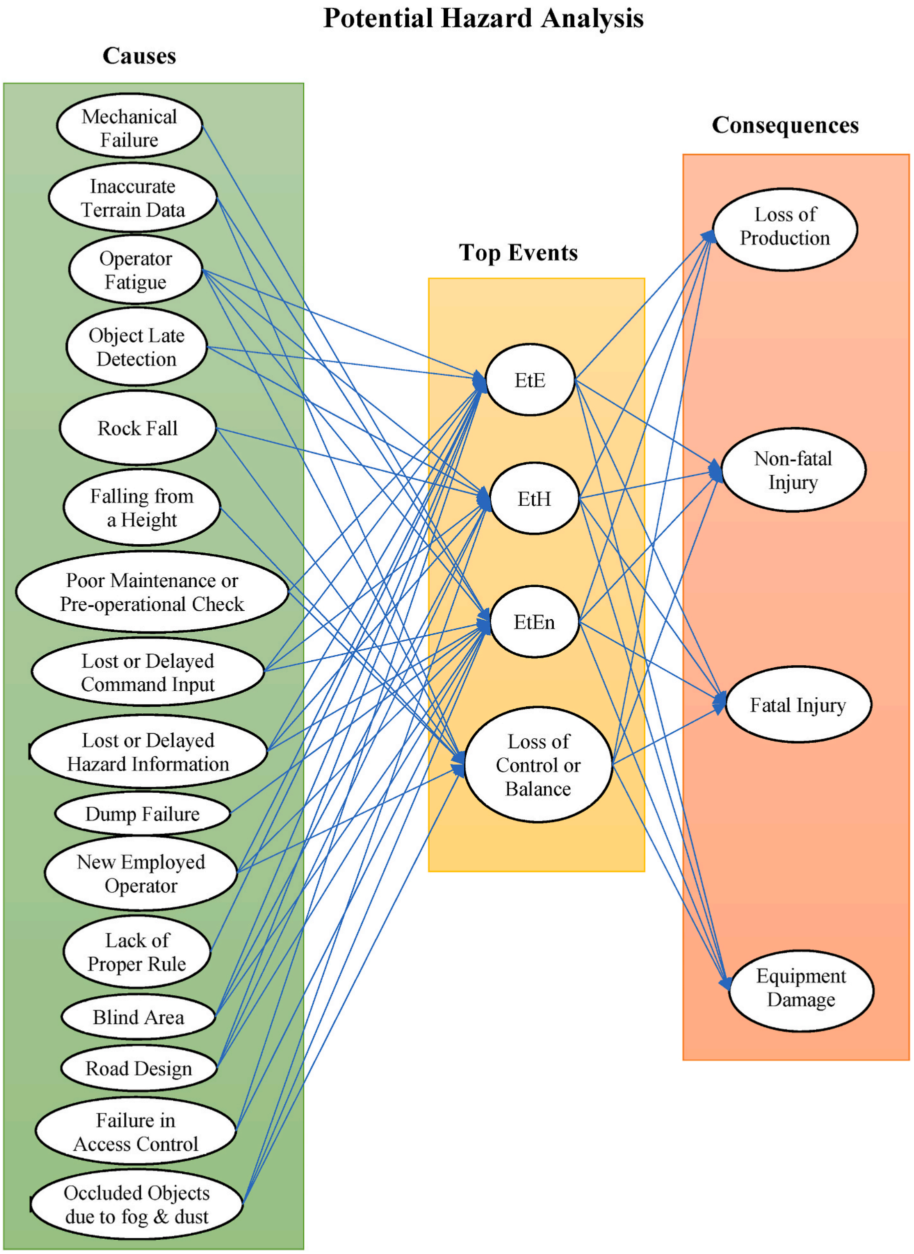

Fig. 8. A summary of the most frequent top events, their causes, and consequences in mining operations.

passed the safety berm, and the driver failed to control the truck. This top event may occur due to several basic events, including failure to conduct a pre-operational check, brake failure, inadequate training, and the operator experiencing control problems.

5.3.1.2. Bowtie diagram method. The Bowtie diagram method is a qualitative risk analysis technique applied to identify root causes and consequences of hazard scenarios and address the preventive and mitigative barriers for these scenarios. This method has been considered for risk assessment in various engineering fields such as oil and gas [25], marine [26], road transportation [27], chemical process [28], and aviation [29] industries. Besides, it provides a holistic view of potential hazard scenarios to control occupational [30] and operational hazards [31,32]. The Bowtie diagram contains several components: top events, threats (causes), consequences, barriers, and escalation factors. It is fundamentally composed of a fault tree and an event tree [33–35]. Fig. 11 illustrates a sample Bowtie risk analysis diagram based on a top event involving a four-way intersection accident. It includes the causes of poor maintenance strategies and mechanical failures, consequences of fatality and injury, and prevention barriers such as training and advanced warning systems, along with mitigation barriers like seat belts and airbags.

5.3.1.3. Failure mode and effects analysis (FMEA). FMEA [36] is focused on analyzing all feasible failure scenarios of a top event. It assesses the hazard risks using a bottom-up design. In other words, this approach initially revolves around the failure causes instead of top events. The FMEA procedure is conducted as follows [37]:

- Gathering a group of experts to specify the system's requirements, such as design, maintenance, reliability, and customer service
- Realizing the scope and objectives of the system
- Decomposing the system into multiple sub-systems or components
- Identifying the potential failure modes of the system and their effects
- Determining the severity of the failure effects and the frequency of each failure mode

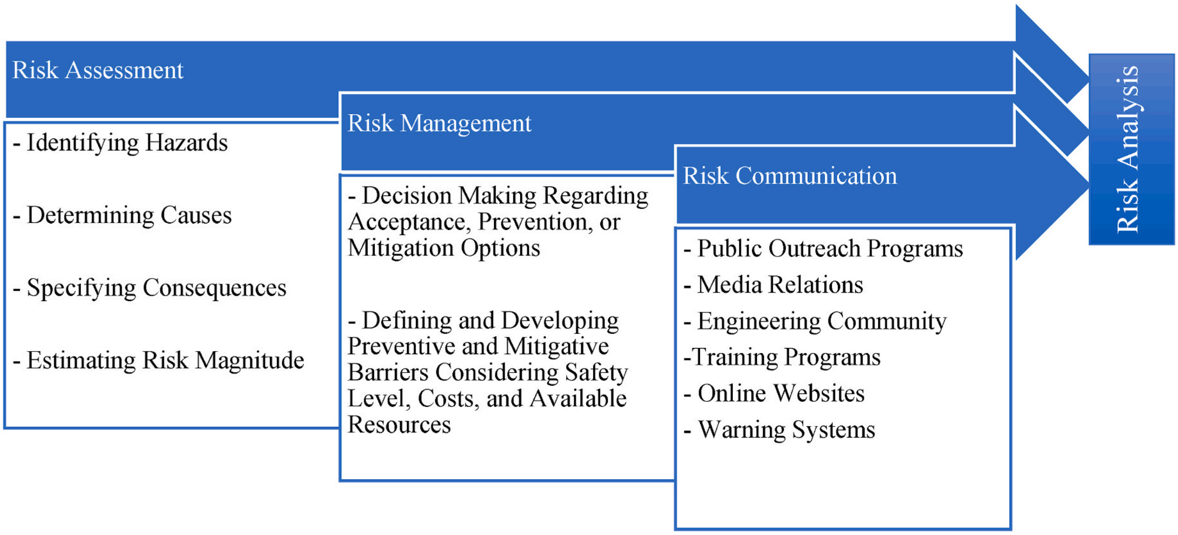

Fig. 9. The risk analysis steps in the risk-based methods.

Table 3
A list of the most popular risk assessment methods utilized in mining operations.

Qualitative Risk Methods	Quantitative Risk Methods
Fault Tree Analysis (FTA)	Probabilistic Risk Analysis (PRA)
Bowtie Diagram Method	Bayesian Theory
Failure Mode and Effects Analysis (FMEA)	Event Tree Analysis (ETA)
Preliminary hazard analysis (PHA)	

- Obtaining a detection ranking based on the failure modes and/or effects
- Computing the Risk Priority Number (RPN) as follows:

$$RPN = Severity \times Occurrence \times Detection \tag{1}$$

5.3.1.4. Preliminary hazard analysis (PHA). PHA is a semi-quantitative risk analysis technique that identifies and classifies the system hazards at the design phases. A Preliminary Hazard List (PHL) can be prepared

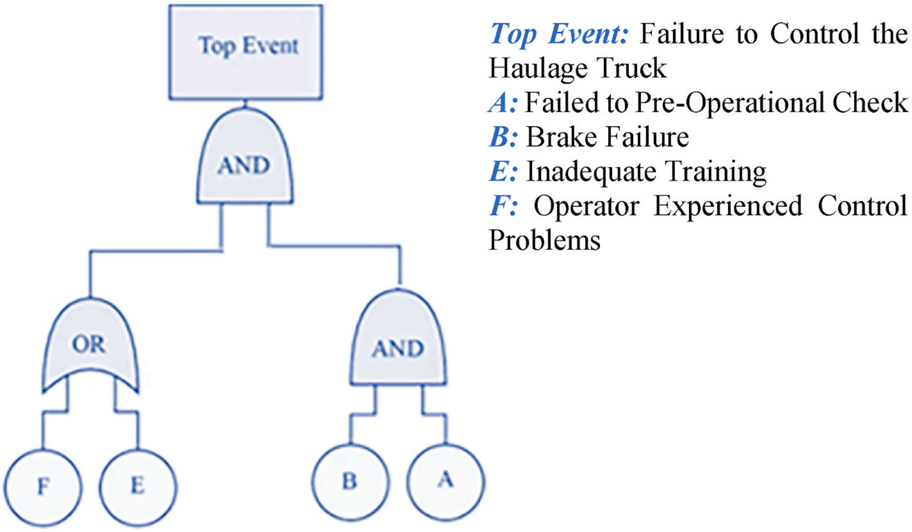

Fig. 10. An FTA structure for a scenario that the driver failed to control the haulage truck.

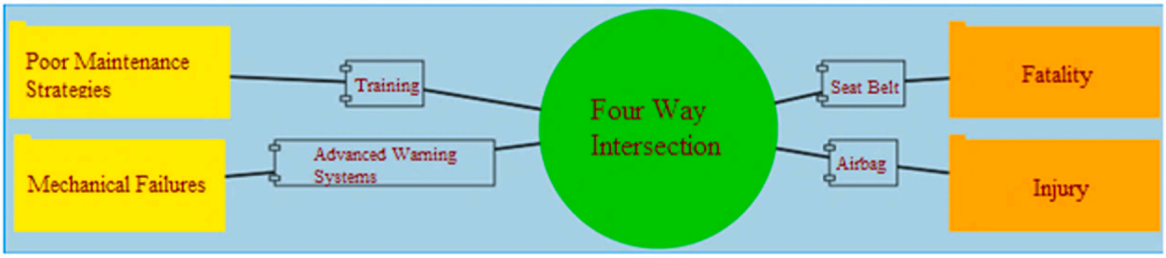

Fig. 11. A Bowtie risk analysis for a four-way intersection accident.

before starting the PHA. This procedure makes a basis for hazard control measures and demonstrates the need for more analyses, such as the Subsystem Hazard Analysis (SSHA) and the System Hazard Analysis (SHA) [38]. Also, it recommends various control actions to reduce the frequency or consequences of the prioritized hazards.

5.3.1.5. Event tree analysis (ETA). Event tree analysis [39] is considered to investigate the occurrence of a hazard via principal functions or sub-systems. It is a graphical logic model with a top-down design architecture that illustrates branches via logical expressions and Boolean algebra paradigms. ETA is classified as a quantitative risk analysis technique. This procedure is performed by defining the system, identifying hazard scenarios, detecting initiating and intermediate events, estimating the probability of each event, identifying the risk consequences, and assessing the risk. Fig. 12 depicts a sample hazard scenario with an initiating event (IE) in which a person slips or falls during boarding or alighting from a truck. In this scenario, consequences (States) include fatality, severe injury, and mild injury. Additionally, intermediate events are as follows:

- Regular Maintenance and Pre-operational Checks (EE): Keeping boarding (alighting) areas clear of debris (mud or other potential trip hazards).
- Regular Design or System Assessment (TH): Installing and maintaining sturdy steps or ladders and non-slip surfaces for safe boarding (alighting).
- Advanced Warning Systems (BC): Lack of advanced warning systems to detect persons in the immediate vicinity of the truck, leading the driver to come to a full stop while boarding or alighting.

5.3.1.6. Probabilistic risk analysis (PRA). The PRA is a systematic and comprehensive method, including system logic, human factors, risk ranking, and uncertainty sources. It is a quantitative risk assessment method that comprehensively assesses the risk by combining several risk assessment methods. The risk can be quantitatively represented by a set of triplets (Equation (2)). The mathematical equation for the risk assessment is followed by Equation (3) [19,40].

$$R = \langle S_i, P_i, C_i \rangle; i = 1, 2, \dots, n \tag{2}$$

$$R_i\left(\frac{Consequence}{Time}\right) = Likelihood\left(\frac{Event}{Time}\right) \times Consequence\left(\frac{Consequence}{Event}\right) \tag{3}$$

where R is the risk of scenario i, S_i is defined as a hazard scenario, P_i is the likelihood of scenario i, and C_i is the consequence of the occurrence of scenario i.

5.3.1.7. Bayesian method. The Bayesian method is one of the efficient approaches for analyzing risk [41]. Bayesian network consists of nodes, directed links, conditional probabilities of nodes, and a directed acyclic graph. It is mathematically formulated using the Bayesian theory. This formula is defined as follows:

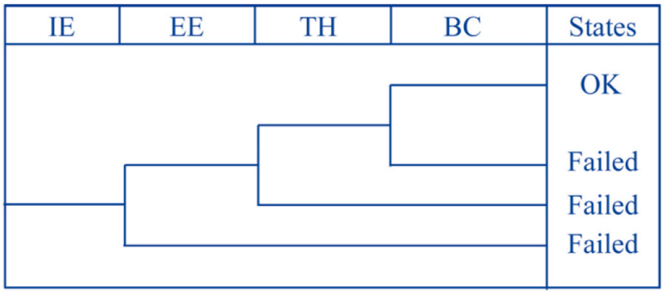

Fig. 12. A sample ETA with an initiating event in which a person slips or falls during boarding or alighting from a truck.

$$P(A|B) = \frac{P(B|A) \times P(A)}{P(B)} \tag{4}$$

where *P(A|B)* is the posterior probability of event *A*n under the occurrence of event *B*, *P(A)* is the prior probability of event *A*, *P(B)* is the prior probability of event *B*, and *P(B|A)* is the conditional probability of event *B* under the occurrence of event *A*.

5.3.2. *Advantages and disadvantages of the risk assessment methods*

Since risk analysis plays a key role in hazard measurement, choosing the most appropriate assessment method for the application field is vital. Therefore, it is necessary to provide a strong insight into the advantages and disadvantages of these techniques. The criteria for comparing these methods include the chosen risk assessment method (qualitative or quantitative), the effectiveness of visualizing risk items through graphical representation, the method's capability in assessing, managing, and communicating risk, the level of detail provided in presenting risk elements (i.e., causes, top events, consequences, and preventive or mitigative barriers), and the basis of the method (whether it relies on objective data or subjective judgments).

FTA is a qualitative approach that visually illustrates the root cause analysis and highlights the critical items. This approach can be combined with the cut set algorithms to be a quantitative approach. Nevertheless, this approach involves many logic gates and events, which makes it difficult to understand. Also, it ignores contributing factors and does not address control measures like preventive and mitigative barriers.

The Bowtie diagram can be employed for different purposes, including risk assessment and management. Besides, it is easily perceived by managers, engineers, and process operators. Also, it combines FTA with the ETA method, demonstrating its high-level performance. However, the bowtie diagram method is a qualitative technique that needs to be combined with a quantitative risk assessment technique to improve the outcomes.

The FMEA method is a qualitative risk analysis technique that specifies the predominant hazards and suggests actions to eliminate or mitigate the failures. Although FMEA technically functions like FTA, it does not provide a proper visualization of the causes and effects. Also, it is based on subjective analysis (human errors) and needs experienced managers [42].

The PHA is a quantitative risk assessment technique used during the design phases. Also, it gives a structured approach to communicating the risk results. However, the drawbacks of this approach include subjective judgments, limited scopes, and being a time-consuming method.

ETA is a risk analysis technique with several benefits, such as quantitative technique, graphical representation of the impacts of functioning or failure of a system, illustration of failure and success paths, and proper visualization. However, it is difficult to ascertain the success and failure probabilities. Also, it does not address the causes of hazards and control barriers.

The PRA is a quantitative risk analysis technique, and it is formulated based on integrating multiple methods, including ETA, FTA, and human reliability analysis. Although this technique can identify causes and hazards and assess risk, it does not address control measures like preventive and mitigative barriers.

The Bayesian method is a quantitative risk analysis that addresses uncertainty, makes appropriate data mining, recognizes the risk of nodes in potential hazards, and applies subjective information. However, choosing the prior distribution is difficult, and the posterior distribution varies by changing the prior probability [41]. Although these variations are eliminated via the accumulation of data, most cases deal with a lack of enough data. Also, this method does not provide prevention and mitigation measures.

5.4. An overview of the past studies in the mining industry

Different researchers have developed risk analysis techniques as hazard measurement for addressing the impacts of hazards on mining operations. Table 4 expresses a summary of past studies in the mining industry. These studies have been organized based on the risk analysis methods used in the mining engineering sector.

In addition to hazard measurement techniques from a risk analysis perspective, some studies adopted a reliability standpoint when examining powered haulage equipment. This hazard type primarily revolves around the loss of control of equipment attributed to causes such as equipment malfunction, acknowledged as one of the most critical contributors to mining equipment hazards. Various studies have investigated equipment malfunction, including mechanical failures, from a reliability viewpoint. These studies have analyzed the mining equipment's reliability, availability, and maintainability. Roy [69] evaluated

Table 4
A summary of the past risk studies in the mining industry.

Author Name	Risk Method	Risk Element	Assessment Method	Hazard or Parameter List	Mine Type
Matsimbe et al. [35]	Bowtie Diagram	Risk Assessment Risk Management	Qualitative	Driving machinery, hoisting, working at height, and hanging rock	Coal Mine
Burgess-Limerick et al. [43]	Bowtie Diagram	Risk Assessment Risk Management	Qualitative	Collisions	Coal mine
Franzen [44]	Combined Bowtie Diagram and Business Intelligence	Risk Assessment Risk Management	Qualitative	Fatality	Gold Mine
Xu et al. [45]	Combined Gray Rational Analysis and Bowtie Diagram	Risk Assessment Risk Management	Quantitative	Job Change (Post Variation)	N.A.[a]
Jian et al. [46]	Combined Rough Set and Neural Network theories	Risk Assessment	Qualitative	Harmful Gases	Coal Mine
Xu et al. [47]	Combined Bowtie Diagram and Bayesian Network	Risk Assessment Risk Management	Quantitative	Rail Haulage Hazards	Tunnel
Targoutzidis [48]	Bowtie Diagram	Risk Assessment	Quantitative	Human Factors	N.A.
Aust et al. [49]	Combined Bowtie Diagram and 6 M structure	Risk Management	Qualitative	Engine Maintenance-related Hazards	N.A.
Cockshott [50]	Probability Bowtie	Risk Assessment Risk Management	Qualitative	Chemicals	NA
Bellanca et al. [14]	Bowtie Diagram	Risk Management	Qualitative	Truck-related Fatal Hazards	U.S. Mines
Liu et al. [51]	Hierarchical Gray Analysis	Risk Assessment	Quantitative	Geological Conditions, Technological Equipment, Human Diathesis, Security Education, Environment Security, and Management Level	Coal Mine
Chu et al. [52]	A Two-Class Fuzzy Comprehensive Evaluation	Risk Assessment	Qualitative	Geological Structure, Hydrology, Surrounding Rock Characteristics, and Tunnel Characteristics	Tunnel
Moniri-Morad et al. [40]	Combined PRA and Discrete-Event Simulation	Risk Assessment	Quantitative	Truck Failure Incidents	Copper Mine
Zhang [53]	FTA	Risk Assessment	Quantitative	Truck-related Fatalities	Coal Mine
Randolph et al. [54]	Data-Driven Method	Risk Management	Quantitative	Truck-related Fatalities (i.e., Collisions and Loss of Control)	U.S. Mines
Maiti et al. [55]	Binary and multinomial logit models	Risk Assessment	Quantitative	Occupational Injuries (i.e., individual and workplace characteristics)	Coal Mine
Yasli et al. [56]	Combined FTA and Fuzzy Approach	Risk Assessment	Quantitative	Loading and Conveying Hazards	Chrome Mine
Shi et al. [57]	Fuzzy FTA	Risk Assessment	Quantitative	Dust and Gas Explosions	Coal Mine
Jiskani et al. [58]	Combined FTA, Z-numbers, and Fuzzy Theory	Risk Assessment	Qualitative	Vehicle Rollover, Collisions, Blasting, Explosive Fumes, Dust, Vibration, Slope Failure, and Slips	Surface Mines
Ruilin et al. [59]	Combined FTA and Artificial Neural Network	Risk Assessment	Qualitative	Gas Outburst Hazards	Coal Mine
Md-Nor et al. [60]	Preliminary Hazard Assessment (PHA)	Risk Assessment	Qualitative	Machines and Geological Failures, Human Errors, Loss of Control, and Weather Conditions	U.S. Mines
Paithankar [61]	Risk Rating Matrix	Risk Assessment	Qualitative	Dust, chemicals, Explosives, Gravitational energies, Mechanical Energies, and Work Environment,	Iron and Coal Mines
Özfırat et al. [62]	Combined FMEA and ETA	Risk Assessment	Quantitative	Conveyor Belt Hazards	N.A.
Esmailzadeh et al. [63]	FMEA	Risk Assessment	Qualitative	Car accidents, Rock-Fall, and Diamond Cutting Wire Breaking, Workplace, Falling a Person, Fire, and Electrical Shock	Quarry Mine
Tripathy and Ala [64]	FMEA	Risk Assessment	Qualitative	Hazards associated with Rope Haulage, Belt Conveyor System, and Load Haul Dumper	Coal Mine
Voulvoulis et al. [65]	Source–Pathway–Receptor Linkages	Risk Assessment Risk Management	Qualitative	Engineering, Geographical, Organizational, Operational, Mining Phases, and Natural Needs	N.A.
Cooper et al. [66]	Health Belief Model	Risk Communication	Quantitative	Understanding risk perceptions, behavioral intentions, and related factors	N.A.
Zhang et al. [67]	Regression, Pearson Correlation, and Structural Equation Model Analyses	Risk Communication	Quantitative	Miners' Risk Perception	N.A.
Jardine et al. [68]	Dual-Mode Model of Trust	Risk Communication	Qualitative	Trust in Decision-Maker Actions	Giant Mine Remediation Plan

[a] N.A. stands for Not Available.

the reliability of a fleet of electric rope shovels. In this paper, the failure and repair data of four shovels were recorded to determine their reliability and maintainability characteristics. Other researchers, such as Samanta [70] and Patnayak [71], evaluated shovel reliability. Also, some studies assessed haul truck reliability and availability using different methods such as reliability-centered maintenance [72], reliability-based covariate analysis [73], parametric standard distribution functions [74], and a comparison between reliability models from the mechanical failure viewpoint [75].

6. Discussion

According to the analysis results (Fig. 4), numerous fatal and nonfatal hazards continue to occur in mining operations. Therefore, it is essential to discuss tools for effectively managing the hazards associated with powered haulage operations. In other words, managing hazards identified as significant through risk assessment methods is necessary. A risk management process involves either prevention or mitigation barriers. Risk mitigation involves an action taken to avoid or minimize the severity of potential risks, while risk prevention is a measure taken to prevent a risk from occurring at the initial phase [76]. These mitigation and prevention barriers include various safety procedures and protocols, such as technology application, automation, risk assessment processes, training employees, and emergency response plans.

Different prevention and mitigation strategies have been considered for haulage fleet's hazard management, such as training, technology application, safety protocols, and maintenance policies. Among these strategies, smart mining has attracted the attention of specialists and become a new trend in the mining industry. Various hazard management approaches, such as collision avoidance systems, lane departure warning systems, and fatigue detection systems, can be mounted on trucks to improve their safety and prevent hazards [77]. Besides, autonomous haulage trucks are one of the most promising technologies to address safety issues during the material handling process. Table 5 provides recent hazard management strategies applied to mitigate and prevent truck hazards in the mining industry.

Table 5
Some of the management strategies used for preventing and mitigating truck hazards.

Hazard Management Strategy	Description
Real-Time Monitoring Systems	Integrated systems that contain sensors, GPS, telematics, IoT devices, and LiDAR to provide real-time information on road conditions and truck location to remote sensing to detect potential hazards
Collision Avoidance and Warning Systems	Technologies that decrease the blind areas, warn operators regarding potential hazards, and automatically apply the brakes in emergencies
Lane Departure Warning Systems	Technologies that warn drivers if they are drifting out of their lane
Fatigue Detection Systems	Technologies that monitor drivers for signs of fatigue and alert them to take a break
Intelligent Maintenance and Inspection	Using sensors and data analytics to improve maintenance and inspection processes and perform predictive maintenance
Autonomous Trucks	Using a combination of sensors, GPS, and advanced algorithms to navigate, sense, and react to the surroundings and operate in harsh environments
Developing Safety Protocols for an Integrated Truck Fleet	Creating guidelines to ensure safe operation and interaction between nonautonomous and autonomous trucks (e.g., communication protocols, safety sensors, and risk analysis procedures)
Regulatory Compliance	Ensuring strict adherence to local and international safety standards and regulations involving mining operations
Safety Protocols and Training	Implementing strict safety protocols and offering extensive training to workers to ensure they understand and follow safety procedures in various mining scenarios
Conventional Management Strategies	Seatbelt use, Personal protective equipment, and other control systems

Some hazard management strategies, such as ground-based radar and LiDAR (Light Detection and Ranging), have been developed to monitor the stability of slopes and detect potential hazards in real-time [78]. These strategies are also implemented in autonomous mining trucks to enhance their perception and decision-making capabilities, ensuring safe navigation in mining operations [78]. By integrating perception and decision-making capabilities, autonomous trucks can detect potential hazards and respond quickly to changing conditions. These strategies can further contribute to the development of predictive models, aiding in the identification of high-risk areas and allowing mining companies to proactively ensure worker safety. Additionally, researchers have proposed the incorporation of safety features on equipment, such as a 3D assisted driving system to eliminate blind spots [79], a vision improvement system using an image processing technique [80], a driver fatigue monitoring system [81], electromagnetic proximity detections [82], collision avoidance systems, and collision detection systems' proximity [83–86].

One effective approach to hazard management is the establishment of strict safety protocols [87]. Moreover, operator training and certification programs serve as crucial measures in preventing hazards in mining operations. These programs include training on traffic rules and regulations, emergency procedures, and cybersecurity measures. The implementation of these training programs can be facilitated through various innovative technologies, including videos [88], virtual reality [89], and virtual environments [90]. Additionally, an integrated autonomous and nonautonomous truck fleet requires a new safety protocol and guidelines to address the unique risks associated with this integrated operation in different situations. Furthermore, safety protocols must continuously be evaluated and improved to minimize risks associated with this integrated fleet.

It was concluded that whilst the overall contribution to transportation hazards derived from inadequate road design alone was small, low-tonnage surface mining operations exhibited higher hazard frequency rates than the industry average. Furthermore, there was clear evidence to suggest that there was no formal recognition of road design and management in transportation management, especially in the case of smaller surface mining and quarrying operations. To improve awareness of the role of good design in reducing transportation hazards, a road extraction method was developed based on digitalization techniques such as the MD-LinkNeSt network [91]. Also, a mine haul road safety audit system was suggested. It is described and recommended as a means to attain a reduction in transportation hazards through the structured recognition and assessment of haulage hazards and the application of optimally safe designs for mine haul roads.

Effective traffic management is also crucial to ensure the safety of workers and equipment in surface mining operations. This process can be conducted by GPS, telematics, and other tracking technologies to track the movement of trucks on the dedicated haul roads and monitor compliance with traffic regulations [92,93]. By monitoring the location and speed of trucks in real-time, supervisors can ensure that trucks are in their designated areas, maintain safe distances from other vehicles, and adhere to speed limits.

Another remarkable aspect of safety strategy in open pit mining operations is the safe introduction of autonomous trucks. This situation requires careful planning and consideration of factors such as communication systems, cybersecurity, and training programs for personnel [78,94]. Indeed, clear signal and communication systems provide real-time information about the location and movement of other vehicles on the site and potential hazards [95].

Although advanced technologies, especially autonomous trucks, provide many advantages in mining operations (Fig. 13), there are still some limitations and concerns regarding these technologies in the

Fig. 13. Advanced technology advantages in mining operations.

mining industry (Fig. 14).

The adoption of advanced technologies has significantly enhanced mining operations, fostering a safer working environment by preventing and mitigating accidents in the industry. However, continual improvement and updates in these technologies are essential to address truck-related hazards effectively. Future studies should focus on eliminating current concerns and limitations associated with advanced technologies in mining, thereby advancing operational safety. Furthermore, there is a need for increased emphasis on worker training, as the current study analysis indicates a decrease in accidents with greater job experience. There is a significant gap in the existing literature concerning the provision of effective job-specific guidance and training for workers. Additionally, accurate risk assessment and the development of cost-effective management strategies are crucial for preventing or mitigating hazards.

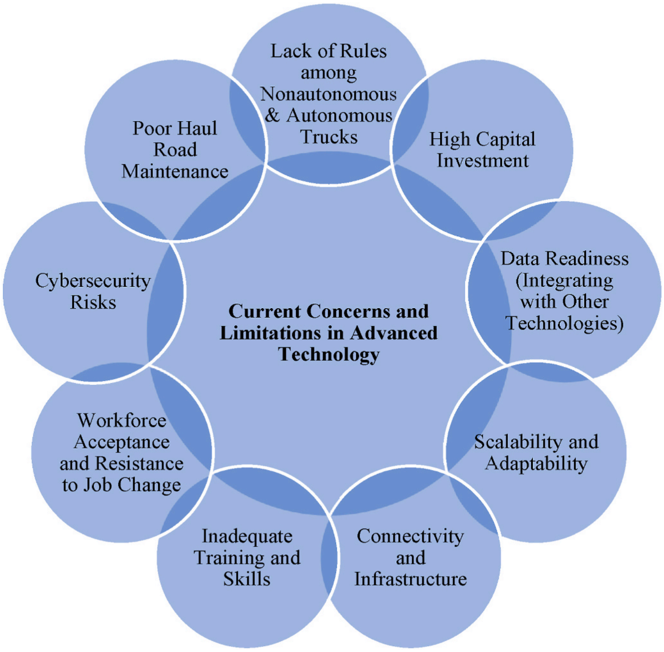

Fig. 14. The current limitations and concerns about using autonomous systems in the mining industry.

7. Conclusions

The search to maintain safe mining operations is the main objective of any mining project. Therefore, it is of the utmost importance to ensure that equipment is in proper working order, and safety protocols are being followed. This goal can be achieved by identifying potential hazards and addressing them proactively to prevent harm to workers or damage to equipment. Regular risk assessment and management procedures play a crucial role in providing safe mining operations. In this regard, choosing the best risk analysis technique is one of the most crucial phases of the problem solution. Most risk analysis techniques are focused on technical procedures and ignore providing a holistic visualization of the risk components. Also, the literature survey showed that combined quantitative and qualitative techniques efficiently analyze the risk. Among the risk analysis techniques, the Bowtie diagram combined with a quantitative risk assessment can be an efficient approach to analyzing the risk in the mining industry. This approach considers all the risk components simultaneously, and thus it is recommended to use this technique in complex industries, which operate in harsh environments.

Risk management is another key component of the risk analysis process. While the adoption of advanced technologies has garnered the attention of mining companies in recent years, it is crucial to note that these technologies are not fully secured. They have altered the nature of risks and introduced some other challenges to the industry. Some of the most significant hazards involving autonomous truck fleets include technical (software) malfunctions, dependence on infrastructure (e.g., communication network and GPS), inadequate training, and cybersecurity risks. Also, a significant change in risk management and safety protocols for autonomous systems is related to the need for a shift from reactive to proactive measures. However, these deficiencies can be resolved using regular monitoring, maintenance, improvement (upgradation), training, and risk assessment of these systems. In addition, a combination of advanced technologies, safety measures, and training programs helps improve safety in mining operations and minimize hazards.

Furthermore, the transition era from an integrated nonautonomous-autonomous truck fleet to a fully autonomous fleet requires a cooperative approach, including technological solutions and organizational culture to ensure operation safety. Some of the solutions for this situation are as follows: effective communication and collaboration between nonautonomous and autonomous trucks using communication tools (e.g., signaling devices, radios, and GPS tracking), designating separate traffic lanes, considering advanced sensors and cameras to increase the visibility of all types of fleets, enforcing the speed limit in specific areas, regular monitoring and maintenance, developing clear guidelines and protocols, conducting regular safety training, and continuous risk assessment.

CRediT authorship contribution statement

Amin Moniri-Morad: Conceptualization, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Masoud S. Shishvan:** Conceptualization, Funding acquisition, Investigation, Methodology, Validation. **Mario Aguilar:** Resources, Writing - original draft. **Malihe Goli:** Conceptualization, Data curation, Formal analysis, Investigation, Validation. **Javad Sattarvand:** Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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