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Improving Safety in Hauling Operations: Predicting and Analyzing Collision Probabilities with Discrete Event Simulation

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Ensuring safety in off-highway raw material handling systems is critical, as the high risk of truck collisions poses a significant threat to both human lives and mining equipment, leading to costly damages. While various safety and risk assessment methods exist—such as probabilistic models (e.g., Fault Tree Analysis), reliability-based models (e.g., Failure Mode and Effect Analysis), simulation-based models (e.g., Agent-Based Models), and incident analysis frameworks (e.g., Tripod)—most struggle to capture the complexity of dynamic traffic interactions. These methods often lack the flexibility to accurately model real-world conditions and require substantial computational resources, making them impractical for real-time applications. This study proposes a discrete-event simulation (DES) approach, which provides a time-based simulation of discrete events and effectively manages randomness, process interactions, and resource constraints. DES can outperform static or probabilistic models in simulating truck traffic flow and conducting real-time accident analysis, offering a more practical solution for operational safety studies compared to high-level systemic or agent-based models. The proposed model simulates truck movements across a road network that reflects a realistic mine layout. The model then develops and evaluates various collision scenarios while capturing real-time truck interactions throughout the entire road network. The simulation modeling was performed using the OpenCLSim, an open-source library for rule-driven scheduling and comparison of cyclic logistics strategies. The results highlight areas and locations on the road network with high collision probability, particularly mid-road and junction locations. Based on these high-risk areas, different operational scenarios, along with dynamic shove-truck allocation and scheduling, can help enhance safety and decrease the probability of collisions. Furthermore, additional enhancements, including signage, speed limits, adaptive traffic control and automated vehicle-to-vehicle communication systems, are recommended to improve driver responses to changing road conditions and congestion, offering a flexible and computationally efficient approach to safety management.

Keywords: Hauling operations, discrete-event simulation, traffic flow safety, collision probability, mitigation measure, mining truck.

1. Introduction

The increasing global demand for raw materials such as minerals, metals, and coal highlights the critical role of the mining industry in meeting these needs. To fulfill this demand, mining operations must balance efficiency, safety, and environmental responsibility. Among these operations, hauling trucks are essential for transporting extracted materials from sources to crushers, dumps, or other designated areas. Ensuring the safety of these hauling operations is crucial to protecting human lives and protecting valuable equipment (Duarte et al., 2019).

Haul trucks operate under challenging conditions, including poor visibility, complex routes, and high-traffic zones, which significantly increase the likelihood of accidents. As a result, safety mitigation strategies have evolved to include advanced technologies, such as real-time warning systems that use GPS and virtual reality to enhance operators' situational awareness and reduce collision risks (Moniri-Morad et al., 2023). Despite technological advancements, collisions remain a significant concern in hauling operations. According to the U.S. Mine Safety and Health Administration (MSHA, 2025), powered haulage was the leading cause of mining fatalities in 2024, accounting for 12 out of 29 deaths, followed by machinery and slip or fall incidents, each with 4 fatalities.

A review of the existing literature reveals that most studies on collision avoidance systems primarily focus on vehicle-to-vehicle interactions, statistical evidence indicates that vehicle-to-environment interactions account for a significant proportion of accidents (Hrica et al., 2022). Bellanca et al. (2021) adopted a risk-based classification framework to investigate the root causes of fatal haul truck accidents, providing actionable recommendations to prevent recurring incidents. Hoebbel et al. (2024) explored the role of operator expertise in mitigating accident risks. A critical decision method was used in this study to gain insights from operators on how they experience near-miss events in challenging situations. To analyze safety berms in surface mining and quarry operations, Thoeni et al. (2024) investigated a comprehensive approach to highlight the impact of geometry, mass, and volume of the materials used. It is concluded that by setting speed limits based on specific berm geometries and designs, the risk of fatal accidents is reduced significantly and haul road safety is improved.

Simulation-based analysis offers a powerful tool for addressing safety challenges in hauling operations. It enables researchers to evaluate various configurations, behaviors, and interactions without the risks associated with field experiments (Fahl, 2017). Among simulation techniques, Discrete Event Simulation (DES) stands out for its ability to model complex production systems and explore alternative scenarios in a controlled environment (Agalianos et al., 2020; Rossetti, 2015).

Recent studies demonstrate the flexibility of DES in the mining sector. (Baek and Choi, 2019) utilized big data from information and communication technology systems to simulate truck haulage operations. DES has also been applied to study truck-and-shovel systems in open-pit mines, analyzing fleet productivity (Upadhyay et al., 2020) and haulage production capacity (Moniri-Morad et al., 2019, 2022). In the context of the energy transition, Lindgren et al. (2022) explored the effectiveness of battery-electric haulage systems, while Young and Rogers (2022) analyzed the impact of dumping processes on operational productivity and safety of mining operations. However, simulation research has rarely addressed real-time monitoring and prediction of collision scenarios involving haul trucks. This study fills this gap by focusing on identifying high-risk zones, incorporating realistic assumptions into DES models for collision analysis.

To assess collision risks, this study develops a network layout for haul truck movements, tracking routes and estimating collision probabilities across the road network. For this purpose, OpenCLSim, a Python package for simulating logistics processes, is utilized. Originally developed to assess maritime operation scenarios (de Boer et al., 2023), OpenCLSim's capabilities in material handling, transportation, and queuing are adapted to model haul truck movements and evaluate safety strategies in mining operations. This study is the first to apply OpenCLSim, to model haul truck movements and traffic flow in mining operations.

The study is structured as follows: Section 2 outlines the research methodology, including the development of a DES model, road network representation, event scheduling, and collision probability calculations. Section 3 explores collision scenarios to identify key contributing factors and high-risk areas. Section 4 discusses the results and statistical analyses, while Section 5 concludes with key findings and future research directions.

2. Methodology

This study uses DES to model and analyze hauling operations, focusing on collision probability prediction and evaluation. DES is particularly effective for capturing stochastic behaviors, resource constraints, and system interactions by representing systems as sequences of states $S(t)$ that evolve in response to discrete events E_i occurring at specific times t_i. The system's state transitions are mathematically expressed as:

$$S(t_{i+1}) = f(S(t_i), E_i) \quad (1)$$

Where f defines how an event E_i modifies the system state. In hauling operations, DES tracks key system states such as vehicle positions, queue lengths, and resource (e.g., vehicles, routes) availability. To implement DES, this study employs the Python-based OpenCLSim library, an extension of SimPy, designed for modeling complex logistics. OpenCLSim offers a modular framework with components tailored to hauling operations:

- **Mixins**: Assign object properties, such as vehicle capacity or speed.
- **Activities**: Model operational processes like loading, traveling, or unloading.
- **Plugins**: Specify conditions such as environmental constraints or priority rules.

Table 1 outlines the OpenCLSim modules used in this study and their relevance to hauling operations. A notable feature of OpenCLSim is its support for shared resources and FIFO-based allocation, enabling realistic modeling of bottlenecks and congestion. For example, loading bays or limited-capacity routes can be simulated to identify delays and safety risks, providing actionable insights for operational improvement.

Table 1. Overview of OpenCLSim Modules

Type	Module	Hauling Operation
Mixin	HasResource	Assign a certain number of resources to trucks and sites.
	Locatable	Assign the geometry of sites and trucks.
	HasContainer	Assign capacity and level of material to sites and trucks.
	Movable	Assign movability to trucks.
	Processor	Assign loading/unloading processes to trucks.
	MoveActivity	Truck moving activities between sites.
Activity	ShiftAmountActivity	Truck loading/unloading activities.
	SequentialActivity	Cyclic hauling and loading activities.
	WhileActivity	Continues operations until a specific target is met.
Plugin	Delay	Simulates interruptions or waiting times.

2.1. *Hauling operation simulation*

The hauling operation simulation begins by constructing a mine's road network using geospatial data to ensure realism and facilitate the definition of location and vehicle objects. The network is then transformed into a NetworkX graph, where nodes represent locations and edges represent road segments. This structure allows for efficient route optimization and advanced road analysis.

The NetworkX graph is integrated into OpenTNSim, a simulation framework used to model transport operations. OpenTNSim works alongside OpenCLSim, and supports dynamic routing, enabling the identification of shortest paths, two-way routes, and other road features. The shortest path between two nodes is calculated using Dijkstra's algorithm:

$$d(u, v) = min_{p \in P} \sum_{(i,j) \in p} w(i, j) \quad (2)$$

where $d(u, v)$ is the shortest distance between nodes u and v, P represents all possible paths, and $w(i, j)$ is the weight (e.g., distance or time) of edge (i, j). Following the construction of the road network, location and vehicle objects are defined:

- **Location properties**: Include name, geometry, capacity (total material storage), level (current material), and the number of resources.

- **Vehicle properties**: Include name, origin geometry, payload, route, and speed.

This framework captures the possibility of collisions throughout the network by modeling dynamic vehicle interactions across all road segments, enabling comprehensive risk assessments. The hauling operation is modeled as a cyclic process, as shown in Figure 1.

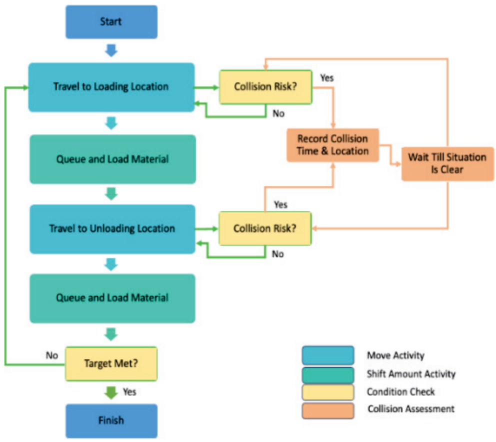

Figure 1. Simulation Methodology Flowchart

It begins with the vehicle traveling to the loading location using the *Move Activity*. This activity includes attributes such as the activity name, mover object (vehicle), source and destination locations, and duration. The duration is automatically calculated based on the distance and speed ($t = \frac{distance}{Speed}$) . In OpenCLSim, the vehicle's speed v is influenced by its load level, calculated using the following linear interpolation function:

$$v = x * \left(v_{full} - v_{empty}\right) + v_{empty} \tag{3}$$

Where, x is a fraction of the vehicle's payload ($0 < x < 1$), v_{empty} and v_{full} are the speeds of the vehicle when empty and fully loaded, respectively.

Upon arriving at the loading location, the truck executes the *ShiftAmountActivity*. If another vehicle is already at the location, the new arrival is queued according to the FIFO principle. This activity includes attributes such as name, location geometry, the amount of material to load, and the duration required for loading. Once loaded, the vehicle travels to the unloading location, where its speed is lower due to the load. Travel time is calculated as in the empty travel phase, accounting for adjusted speeds. At the unloading location, material is unloaded following the same FIFO queuing system if needed. The duration of both loading and unloading depends on the amount of material and the respective rates.

These activities — traveling, loading, and unloading — are grouped under a *Sequential Activity*, ensuring they are executed in a fixed order as part of a single hauling cycle. To simulate continuous hauling operations, a *While Activity* is defined. In the *While Activity*, the *Sequential Activity* is repeatedly executed until the material production target is achieved or the simulation time ends.

2.2. *Collision Prediction*

This section outlines a probabilistic framework for evaluating collision risks for three scenarios: Vehicle-to-Vehicle Collisions (V2V), Vehicle-to-Obstacle Collisions (V2O), and Vehicle-to-Pedestrian Collisions (V2P). The framework evaluates collision risks across the entire network by monitoring vehicle movements and interactions dynamically. Using OpenTNSim, each vehicle's trajectory is tracked as it passes through nodes and edges of the road network, to calculate collision probabilities.

2.2.1. *Vehicle-to-Vehicle Collisions*

Vehicle-to-vehicle collisions are identified when two or more vehicles simultaneously occupy the same road segment or node. For realistic collision probability estimation, a defined time tolerance and distance tolerance are applied. These tolerances account for the time it takes for two vehicles to completely pass each other, ensuring that near-misses and close interactions are accurately considered. The probability of vehicle-to-vehicle collisions, P_c, at a specific node is calculated as:

$$P_c = \frac{\text{Number of Overlapping Events}}{Total\ Vehicle\ Passages} \tag{4}$$

Here, overlapping events refer to instances where vehicles are present at the same node within Δt and Δd while total vehicle passages account for all vehicle entries at the node during the simulation. Δt and Δd are determined based on the vehicle's speed and length.

To compute P_c, the simulation tracks vehicle locations and timestamps, identifies overlapping events, and normalizes these by the total traffic volume at each node. Nodes with higher P_c values indicate greater collision risk, enabling the identification of high-risk areas for targeted safety interventions. This approach leverages observed vehicle interactions to provide a realistic and scalable framework for V2V collision probability analysis across the network.

2.2.2. *Vehicle-to-Obstacle Collisions*

Collisions with obstacles, such as rocks or equipment, can occur anywhere along the road network. The simulation defines random nodes as obstacle locations, with each obstacle having a presence probability. The probability of a vehicle colliding with an obstacle depends on the vehicle's arrival frequency at these locations and the likelihood of obstacle presence:

$$P_o = P(vehicle\ arrives\ at\ obstacle\ location) * P(obstacle\ presence) \quad (5)$$

where:

- P_o: The probability of a vehicle colliding with an obstacle.
- $P(vehicle\ arrives\ at\ obstacle\ location)$: Determined by the density of vehicles at obstacle nodes.
- $P(obstacle\ presence)$: A stochastic input reflecting the likelihood of an obstacle being present.

The simulation identifies high-risk nodes where vehicle density and obstacle presence probabilities overlap significantly.

2.2.3. *Vehicle-to-Pedestrian Collisions*

Vehicle-to-pedestrian collisions occur when vehicles and pedestrians occupy the same location simultaneously. In the simulation, specific nodes are designated as pedestrian crossing locations. Pedestrian activity at these nodes is defined by a frequency parameter, which determines how often pedestrians are present. The probability of a vehicle-to-pedestrian collision is calculated as:

$$P_p = P(vehicle\ arrive\ at\ crossing\ location) * P(pedestrian\ presence\ at\ time\ t) \quad (6)$$

where:

- P_p : Probability of a collision with a pedestrian.
- $P(vehicle\ arrives\ at\ crossing\ locatio$ Likelihood of a vehicle being present at the node during a specific time.
- $P(pedestrian\ presence\ at\ time\ t)$: Probability of pedestrian activity at the node during the same time.

Using the calculated probabilities, the simulation identifies high-risk locations, such as nodes with frequent vehicle interactions, obstacle-prone areas, and pedestrian crossings with significant overlap between pedestrian activity and vehicle movements. These findings provide critical insights into collision-prone areas across the network. The next section presents the results and explores strategies to enhance safety and operational efficiency.

3. Results and Discussion

The simulation was conducted using real-world data from an open-pit mine in Nevada, U.S., where desert conditions introduce challenges such as dust control and signage clarity. The road network, shown in Figure 2, was constructed using the geometry of key points, including intersections, loading docks, and dumping areas, to define the network's structure. Truck data, as observed vehicle in this study, included payload capacities, speed ranges, and unloading times, while shovel data encompassed locations, bucket sizes, and loading rates.

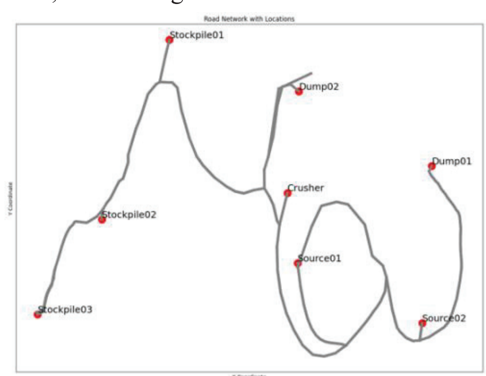

Figure 2. Road network of an open-pit mine

To enhance simulation realism, parameters such as loading rates, unloading times, and payloads varied across cycles using normal distributions. A dispatching plan outlined material quantities and production targets, while truck-shovel allocations established routes and schedules to optimize transport efficiency. Operational rules, such as payload limits and operating hours, were implemented to ensure safety and compliance. Table 2 summarizes the datasets and their parameter. These inputs and constraints form the foundation for evaluating collision risks and operational performance in the subsequent analysis.

Table 2. Summary of datasets and key parameters for simulation configuration

Datasets	Parameters	Units / Formats
Location	Name	NA* / String
	X,Y,Z Coordinates	NA / Float Number
	Description	NA / String
Truck	Model	NA / String & Number
	Number of Truck	NA / Integer Number
	Payload	Ton / Integer Number
	Speed (Min / Max)	m/s / Float Number
	Unloading Rate	s / Integer Number
Shovel	Model	NA / String & Number
	Location	NA / X,Y,Z Coordinate
	Bucket Size	Ton / Integer Number
	Loading Rate	s / Integer Number
Truck – Shovel Allocation	Source Name	NA / String
	Destination Name	NA / String
	Model of Truck	NA / String & Number
	Number of Truck	NA / Integer Number

* NA: Not Applicable

3.1. *Collision Scenarios Analysis*

Building on the simulation framework and dataset, the model analyzed collision risks under three scenarios: V2V interactions, V2O collisions, and V2P incidents. These scenarios were designed to evaluate safety risks and identify critical areas within the mine's road network requiring intervention. The simulation, spanning 10,000 hours of hauling operations, computed collision probabilities for each scenario. These results highlight high-risk locations and inform targeted strategies to enhance operational safety.

Vehicle-to-vehicle collisions: The V2V scenario evaluated collision risks across the entire road network, focusing on areas with high vehicle density and overlapping movements. Figure 3 presents a graph-based representation of the road network, where node sizes correspond to vehicle densities. Larger nodes indicate areas with frequent vehicle interactions, which are potential collision hotspots. In this analysis, collision probabilities were determined based on the density of vehicles passing each node and the frequency of overlapping movements within defined time and distance tolerances. The results identify high-risk locations, such as intersections and segments with heavy traffic, as critical points for targeted safety interventions.

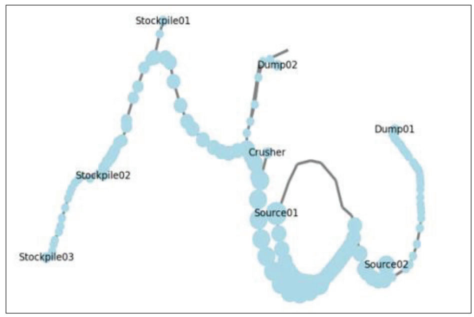

Figure 2. Traffic density on road network

By visualizing these high-risk nodes, the analysis provides actionable insights for mitigating collision risks. Strategies such as traffic control measures, route optimization, and dynamic scheduling can be implemented to reduce overlapping movements and enhance safety throughout the network.

Vehicle-to-obstacle collisions: These collisions were simulated by randomly placing obstacles, such as rocks, at specific points along the hauling routes. Two types of nodes were considered: mid-road nodes and junction nodes, to analyze differences in collision probabilities based on location type. Collision risks were quantified by tracking vehicle arrivals at these nodes and calculating the likelihood of an encounter with an obstacle. Figure 4 illustrates the selected obstacle locations across the road network, distinguishing mid-road and junction nodes.

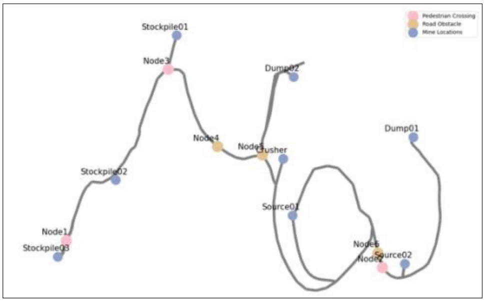

Figure 4. Network graph with selected nodes for V2O and V2P scenarios.

Figure 5 displays a scatter plot illustrating the collision probabilities for V2O scenarios, considering variations in obstacle locations and appearance times.

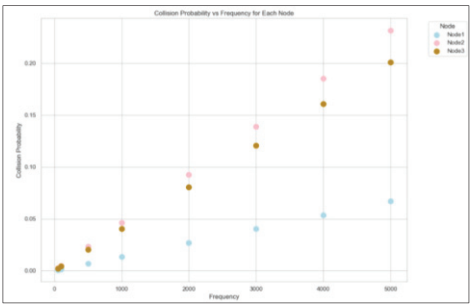

Figure 5. Collision probabilities for V2O

The plot highlights the relationship between these factors and the resulting collision risks. This analysis highlights the influence of node type and obstacle placement on collision risk.
collisions were simulated by introducing random pedestrian crossing points within the road network. Two types of nodes were analyzed: mid-road nodes and junction nodes, as shown in Figure 4, to assess the impact of location type on collision probability. Collision probabilities were calculated based on the frequency of pedestrian crossings at these points and the timing of vehicle arrivals. This analysis evaluates how variations in pedestrian activity and location influence collision risks. Figure 6 presents a scatter plot depicting the probabilities for V2P scenarios across various pedestrian crossing frequencies and node types. The plot highlights higher collision probabilities for junctions (Node5) and high-traffic nodes, emphasizing the increased risks associated with these locations compared to others.

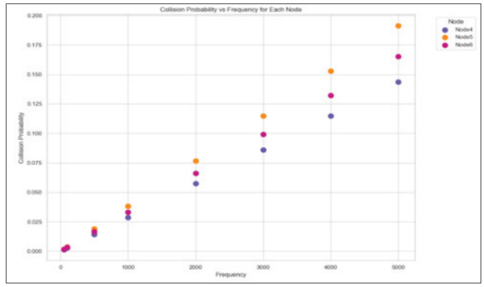

Figure 6. Collision probabilities for V2P scenario

This probabilistic framework provided actionable insights for improving safety. High-risk areas identified in the heatmap suggest specific locations where enhanced traffic controls, better scheduling, or redesign of road layouts could reduce collision risks. The model can integrate various mitigation scenarios and evaluate both productivity and safety, making it a valuable tool for optimizing mining operations.

4. Conclusion

This study presents a novel application of Discrete Event Simulation (DES) to model and analyze collision risks in off-highway hauling operations, specifically within mining environments. By leveraging the OpenCLSim framework, this approach allows for a detailed and dynamic simulation of truck movements, accounting for vehicle interactions, road network layouts, and real-time operational variables. The results highlight critical collision hotspots within the mine's road network, identifying high-risk locations such as mid-road and junction nodes where vehicle-to-vehicle, vehicle-to-obstacle, and vehicle-to-pedestrian incidents are most likely to occur. These insights provide actionable recommendations for improving safety, including the optimization of traffic control measures, dynamic scheduling, and enhanced driver awareness through technology like adaptive signage and automated vehicle-to-vehicle communication systems.
Furthermore, the flexibility and computational efficiency of the DES-based model offer a scalable solution for real-time monitoring and proactive safety management in large-scale mining operations. The incorporation of real-world data and various operational scenarios demonstrates the model's ability to inform both

immediate safety measures and long-term operational improvements. Future research could expand on this framework by integrating additional safety technologies, exploring more complex road network configurations, and conducting further validation in different mine settings. Ultimately, the approach developed in this study contributes a valuable tool for mitigating collision risks, improving safety outcomes, and enhancing the overall efficiency of mining operations.

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