Safety Assessment for the Implementation of Autonomous Haulage Systems in an Open-Pit Mine

By
Mario Alejandro Aguilar Rodríguez

Safety Assessment for the Implementation of Autonomous Haulage Systems in an Open-Pit Mine

By

Mario A. Aguilar Rodriguez

in partial fulfilment of the requirements for the degree of

Master of Science
in Applied Earth Science
of the European Mining, Minerals, and Environmental Programme

at the Delft University of Technology,
to be defended publicly on Thursday, August 24, 2023, at 2:00 PM.

Supervisor:	Dr. M. Soleymani Shishvan,	TU Delft
Thesis committee:	Dr. M.W.N. Buxton,	TU Delft
	Prof. Dr. B. Lottermoser,	RWTH Aachen University
	Prof. Mikael Rinne,	Aalto University

TU Delft

Dedication

I dedicate this work to the pillars of my life: my sister Oleigdi Aguilar, my father Olegh Aguilar, my mother Susana Rodriguez, and my uncle Humberto Cornejo. Your unwavering belief in me, your steadfast presence, and your ceaseless encouragement have been my guiding lights from the first step until now.

Thank you for standing by me, not only celebrating my achievements but also motivating me through your examples and your faith. May this work not only be a symbol of pride for us all but also a testament to the power of perseverance, inspiring us to never abandon our dreams, no matter the odds.

With all my gratitude and love,
Mario Alejandro Aguilar Rodriguez

Acknowledgments

First and foremost, I extend my deepest gratitude to my advisors, Masoud Soleymani Shishvan and Javad Sattarvand. Their guidance allowed me to embark on this incredible project and unearth potentials within myself that I never knew existed. The opportunities to grow, both personally and professionally, under their mentorship have been priceless.

Special acknowledgment goes to Malihe Goli and Amin Monirimorad. Despite their demanding schedules, they generously gave their time and support. Words fall short of expressing how their assistance enriched my research and personal development. My gratitude towards them is boundless.

The journey of the last two years in pursuit of my master's degree has been made memorable by my classmates. More than colleagues, they became my family away from home, providing exceptional academic and emotional support. While I greatly appreciate all, I want to single out Max, Sander, Ville, Busra, and Adytia for their unique contributions.

To the government of Panama who believed in me and financed my studies through the program "CONVOCATORIA DE MAESTRÍA EN ÁREAS ESPECÍFICAS DEL CONOCIMIENTO IDENTIFICADAS POR LA SENACYT".

To my friends who supported me from afar – Ariel, Abraham, Celso, Joel, Manuel – your encouragement has been a constant source of strength.

Last but certainly not least, a heartfelt thanks to Runo. Our shared experiences, through highs and lows, have shaped this journey. Your patience, unwavering support, and love since the moment we met have been a beacon guiding me to this milestone.

In gratitude,

Mario

Table of content

List of Figures

List of Tables

List of Equations

Abstract

The implementation of autonomous haulage systems in open-pit mines is a progressive step in the industry, but it brings potential safety risks that need careful evaluation. This study developed a discrete event simulation model to analyze and evaluate these risks in different operating scenarios - fully autonomous, hybrid (a mix of autonomous and human-operated vehicles), and non-autonomous operations.

The simulation model was developed using the HAULSIM and Anylogic software, integrated mine layout, haulage operations, and various fleet compositions. It provided insights into collision risks, a significant concern in mining safety literature. Results showed that collisions were inversely proportional to the number of autonomous vehicles in operation, indicating the potential safety advantages of fully autonomous operations. However, certain high-traffic intersections were identified as high-risk areas, emphasizing the need for targeted risk mitigation strategies.

Further, a profile risk matrix was developed to provide a comprehensive view of collision severity and likelihood in each scenario. This highlighted the impact of collisions on both human safety and project operations. Based on the results, risk mitigation strategies were proposed, with a focus on redesigning intersections, implementing strict rules for human-operated trucks in autonomous zones, and improving autonomous vehicle capabilities.

The study, while insightful, was limited by assumptions and the generic nature of operational data used in the simulation. Therefore, future research should seek to incorporate more detailed, mine-specific data and empirical insights from projects that have implemented autonomous haulage systems. Continuous advancements in autonomous technology and simulation modeling will be key to ensuring a safe and productive mining environment.

1. Introduction

1.1. Motivation

Mining, one of the most ancient human practices, carries a historic perception of being physically demanding and fraught with inherent risks. These risks can include but are not limited to, occupational hazards such as slope instability, collisions, flying rocks because of blasting, chemical exposure, and environmental concerns like water and air pollution. Over time, mining companies have sought to dispel this risky image by continuously improving worker safety and implementing more environmentally friendly practices.

From the perspective of mining companies and governing bodies, it is imperative to regularly evaluate and improve working conditions. This study finds its genesis in that necessity, focusing on truck haulage a crucial phase in mining operations that involves transporting ore, waste material, or overburden from one location to another. This process requires intricate planning and coordination, with factors such as load capacity, road conditions, equipment reliability, and weather conditions playing vital roles. The complexity of balancing these variables often leads to significant accidents, making haulage a critical area for safety improvement and risk management.

Conducting an on-field evaluation of these variables is virtually impractical, considering the myriad of safety factors involved and the potential disruption to the mine's production cycle. This situation leads us to the necessity of using simulation for our analysis. Among the various simulation methodologies, discrete event simulation (DES) was chosen for this research due to its ability to model the complex interactions and events within truck haulage operations. To enhance our understanding of the potential risks associated with truck haulage, we conducted an exhaustive analysis of different operation scenarios based on real-world data.

The study's purpose is to simulate diverse scenarios, assess their outcomes, and propose risk mitigation strategies. All of this is done without disrupting mining operations or placing personnel at risk, hence safeguarding production continuity and enhancing safety practices. Through this research, we strive to navigate the complexities of mining haulage and carve out safer, more efficient pathways for its implementation.

1.2 Introduction to the Topic and Study

Hauling Operation Risks:

Hauling operations in mining are complex and laden with risks. The multifaceted process involves the transportation of materials through rugged terrain, often leading to hazards such as equipment failures, collisions, environmental damage, and human errors. These risks necessitate constant monitoring and control to ensure safety and efficiency. (Xiaotong Zhang A. G., 2022)

Mobile Vehicle-Related Risks and Human Factors:

A significant portion of hauling operation risks are associated with mobile vehicles. Accidents involving these vehicles often account for many injuries and fatalities within the mining sector. The major causes typically stem from human factors such as operator error, fatigue, judgment lapses, and non-compliance with safety regulations. (Zhang, 2014)

Autonomous Trucks and Improving Safety:

The emergence of autonomous trucks offers a promising avenue for mitigating the risks inherent in hauling operations. Autonomous vehicles can significantly reduce accidents, improve productivity, and contribute to a safer working environment by eliminating or minimizing human error and enhancing adherence to safety protocols. (John Meech, An interactive simulation model of human drivers to study autonomous haulage trucks, 2011)

Exploring Opportunities through Simulation-Based Analysis:

Understanding the full potential of autonomous trucks requires a detailed analysis of various operational scenarios. Simulation-based analysis serves as an invaluable tool in this context, enabling the exploration of different configurations, behaviors, and interactions without the constraints and risks of on-field experimentation. (Fahl, Benefits of Discrete Event Simulation in Modeling Mining Processes, 2019)Purpose of the Project:

This study aims to investigate the safety implications of integrating autonomous trucks into mining hauling operations. Leveraging discrete event simulation, the project seeks to provide insights into the potential risks, benefits, and challenges of this technological advancement, thereby informing future decisions and strategies in mining safety and automation.

By leveraging real-world data and conducting a thorough safety assessment, this study provides critical insights that can guide decision-making processes during the integration of autonomous trucks in non-autonomous mining operations. The focus lies in the development of a discrete event simulation model for a mining project, allowing for the simulation of various scenarios, evaluating their associated risks, and importantly, proposing mitigation strategies.

1.3 Purpose and Objectives of the Study:

The primary purpose of this study is to conduct a safety evaluation for autonomous and non-autonomous hauling in a mining project, to define mitigating scenarios. To achieve this, a method was employed that will facilitate the identification, evaluation, and strategic mitigation of risks tied to the implementation of autonomous and non-autonomous trucks. More specifically, the steps taken in the study are as follows:

1. Review the literature on discrete event simulation modeling in mining operations, safety analysis, and haulage mobility within open-pit operations.

2. Develop an accurate simulation model that represents the haulage system using data from a mining project.

3. Identify and evaluate the risks associated with the implementation of fully man-driven (or non-autonomous), autonomous hauling, and a hybrid model of man-driven and autonomous trucks in mining operations.

4. Provide practical insights and recommendations for mining companies based on the results of the simulation models.

1.4 Research Questions and Hypotheses:

This study is guided by the following research questions:

1. What are the various types of risks associated with hauling operations in mining, and how can they be effectively evaluated to understand their impact on overall safety?

2. How do non-autonomous and autonomous trucks differ in terms of safety aspects, and what potential benefits can autonomous trucks bring to mining operations? What are the inherent challenges or drawbacks that need to be addressed?

3. What necessitates the development of a simulation model for analyzing these complex hauling operations, and how can discrete event simulation modeling be employed to create a realistic and accurate representation of a mining project's haulage system?

4. Based on the simulation model, how can a safety assessment be conducted to determine if the implementation of autonomous trucks can enhance safety in mining operations, and what are the key factors and considerations that must be addressed in this assessment?

This study proposes the following hypotheses:

The central hypothesis guiding this research is that the use of autonomous trucks can improve the overall safety of a mining operation.

This hypothesis is founded on the premise that autonomous trucks, by eliminating or reducing human error, have the potential to enhance the safety standards within a mining environment. Through the application of advanced technologies and control systems, autonomous vehicles can operate with greater precision and consistency, possibly minimizing the risk of accidents that are commonly attributed to human factors.

To examine this hypothesis, the study will conduct an in-depth evaluation of the different types of risks associated with hauling operations, compare the safety aspects of non-autonomous and autonomous trucks, and employ discrete event simulation modeling to create a realistic representation of a mining project's haulage system. Finally, a safety assessment will be carried out to determine whether the implementation of autonomous trucks indeed contributes to a measurable improvement in safety within mining operations.

The validation of this hypothesis could have significant implications for the mining industry, offering insights into how automation could be leveraged as a strategic tool to enhance not only efficiency but also the well-being and safety of personnel involved in mining operations.

1.5 Scope and Limitations of the Study:

The scope of this study concentrates on assessing the risks connected with the implementation of autonomous trucks in non-autonomous truck mining operations through a discrete event simulation model. The scope of the study includes:

- Analyzing various scenarios related to the use of autonomous and non-autonomous trucks, considering safety, years of experience, working hours, human error, and infrastructure factors.

- Developing an accurate simulation model grounded in real-world data to represent the haulage system.

- Providing practical insights

The study does, however, have certain limitations:

- The availability and quality of data from the mining project may impact the accuracy of the simulation model.

- Assumptions and simplifications made in the simulation model may introduce uncertainties.

- The findings may be context-specific and not fully generalizable to all mining operations.

1.7 Overview of the Thesis Structure:

This thesis is organized into six chapters, each addressing a distinct aspect of the research project. The chapter breakdown is as follows:

1. Introduction, provides an overview of the research project, including the background, significance, research questions, hypotheses, scope, and limitations.

2. Literature Review, presents a comprehensive review of the literature on discrete event simulation modeling in mining operations, traffic in mining operations, truck mobility safety assessment, and autonomous mobility traffic inside an open-pit project.

3. Methodology, outlines the research design and methodology used in the study, including data collection, simulation model development, and safety assessment.

4. Results and Discussion, presents the results of the simulation model, including its accuracy and reliability, and analyzes the risks associated with the use of autonomous and non-autonomous trucks in mining operations,

5. Conclusion, summarizes the main findings of the study, highlights its contributions to the field, and identifies directions for future research.

2. Literature Review

In the following sections, this chapter provides a comprehensive review of the existing literature on open pit mining safety analysis and assessment, with a focus on truck and loader transportation systems, mobility policies within an open pit mine, utilization of autonomous and non-autonomous vehicles, their relationship with each other for the development of the project and other relevant issues.

2.1. Introduction to safety in open pit mining

Open-Pit mining is the method by which mineral resources are extracted from the earth's surface, the most common way of extracting these minerals is by digging horizontally and in layers, this process is known as banks. This process is suitable for deposits located near the surface. It is important to note that open pit mining is a highly efficient way of extracting minerals such as iron, copper, gold, coal, diamonds, limestone, and uranium, However, it is also a complex process that involves various risks and safety considerations. When carrying out any type of open-cast mining extraction, all the different risks that this brings must be considered.

One of the main associated risks is the risk of the instability of the slopes, which can generate landslides and rock falls (Aleksandr Rakhmangulov, 2021). To mitigate the risks associated with open-pit mining, advanced technologies 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 (Shirong Ge, 2022).

These technologies are not only vital for monitoring slope stability but are also used in autonomous mining trucks to enhance their perception and decision-making capabilities and ensure safe navigation in mining operations (Shirong Ge, 2022). By integrating perception and decision-making capabilities, autonomous trucks can detect potential hazards and respond quickly to changing conditions, minimizing the risk of accidents, and improving overall safety in mining operations. These technologies can also be used to develop predictive models that help identify areas of high risk, allowing mining companies to take proactive steps to ensure worker safety.

The integration of technology and safety measures in the realm of open-pit mining showcases a comprehensive approach to addressing the inherent risks of this mining method, with a particular focus on slope stability and the innovative use of autonomous trucks. This reflects a broader trend in the mining industry to leverage technology to enhance efficiency, safety, and environmental stewardship.

Another safety issue in surface mining is the use of heavy equipment, such as haul trucks, excavators, and bulldozers, which can pose a significant risk to workers on site (Michelle Blom, 2018). To reduce the risk of accidents, mining companies implement strict safety protocols, such as equipment operator training and certification programs, as well as implement safety features on the equipment itself, such as collision avoidance systems and collision detection systems' proximity (Global Mining Guidelines Group, 2021).

Effective traffic management is also crucial to ensure the safety of workers and equipment in surface mining operations. This requires the implementation of dedicated haul roads for different types of trucks, as well as the establishment of speed limits and zones that can be enforced with GPS and other tracking technologies (Bastos, 2010). Clear signal and communication systems should also be in place to provide drivers with real-time information about the location and movement of other vehicles on the site, as well as any potential hazards (Michelle Blom, 2018). In addition to safety considerations, open pit mining operations also require effective planning and management to ensure the sustainable extraction of mineral resources. This implies a hierarchy of planning activities, from operational decision-making regarding equipment positioning and trucking to strategic decision-making regarding mine infrastructure and regions (Michelle Blom, 2018).

Table 1 shows examples of possible risks already mentioned and their mitigation strategies within open-pit mining projects.

Table 1 Examples of Risk Mitigation Strategies in Open Pit Mining Operations

Risk	Mitigation Strategy
Slope instability	Regular geotechnical monitoring and analysis of slope stability, implementation of slope reinforcement measures, and establishment of exclusion zones
Equipment failure	Regular maintenance and inspection of equipment, implementation of condition-based maintenance programs, and use of backup equipment
Dust exposure	Regular maintenance and inspection of equipment, implementation of condition-based maintenance programs, and use of backup equipment
Vehicle collisions	Implementation of speed limits, the 3establishment of dedicated haul roads for autonomous trucks, and the use of advanced tracking and monitoring systems

To provide a comprehensive risk analysis of open pit mining operations, this chapter will explore various topics related to risk management, safety considerations, and simulation modeling, as well as provide examples of specific technologies used in the industry.

2.2. Overview of Safety Measures and Mitigation Strategies in Open-Pit Mining

In open-pit mining operations, safety is a top priority, particularly when it comes to the safe mobility of trucks within the mine site. One important factor is the establishment of traffic rules and procedures, which can include the use of dedicated haul roads for autonomous trucks and the establishment of speed limits and zones for different types of trucks (Global Mining Guidelines Group, 2021). Another important aspect of safety in open pit mining operations is the safe introduction of autonomous trucks. This requires careful planning and consideration of factors such as communication systems, cybersecurity, and training programs for personnel (Shirong Ge, 2022). Table 2 provides an overview of the key considerations for the safe introduction of autonomous trucks in open-pit mining operations.

Table 2 Key Considerations for the Safe Introduction of Autonomous Trucks in Open Pit Mining Operations

Considerations	Description
Communication systems	Reliable and secure communication systems are necessary to enable remote control of the trucks and ensure real-time monitoring of their movements.
Cybersecurity	Autonomous trucks are susceptible to cyber-attacks, such as Wi-Fi De-Auth and GPS attacks, which can compromise their safety and efficiency. Appropriate cybersecurity measures are necessary to mitigate these risks.
Training programs	Proper training and certification programs are necessary for drivers, operators, and other personnel involved in traffic management and autonomous truck operation. These programs should include training on traffic rules and regulations, emergency procedures, and cybersecurity measures.

In addition to this, it is also necessary to take into account how difficult is to predict the human factor for risk: people make mistakes, may not succeed in operating, or may experience health conditions during work (Snezana Kirin, 2020) & (Zhang, 2014). To reduce all these risks that can occur during mining operations numerous safety measures that are put in place to protect workers in open-pit mining operations. For instance, the use of personal protective equipment (PPE) such as hard hats, safety glasses, and steel-toed boots is mandatory in most mines. Additionally, mines typically have safety protocols and training programs in place to educate workers on best practices and to ensure that they are aware of potential hazards. Another key aspect of safety in open pit mining operations is traffic management.

The main objective of any mining project is to maintain safe operations, and achieving this goal requires diligent focus and commitment. Regular safety inspections and audits are of the utmost importance, ensuring that equipment is in proper working order and that safety protocols are being followed. By identifying potential hazards and addressing them before they can cause harm to workers or damage to equipment, these practices contribute to a safer working environment.

A study by Satar Mahdevari, Kourosh Shahriar, and Akbar Esfahanipour (2014) illustrates the effectiveness of regular safety audits in open-pit mining operations for identifying and addressing safety issues. This research highlights the importance of a comprehensive approach to identifying and assessing safety risks, providing valuable insights into potential solutions that can mitigate these risks (Satar Mahdevari K. S., 2014).

The combination of advanced technologies, safety measures, and training programs has further helped to improve safety in open-pit mining operations. While there are always inherent risks associated with mining, the industry has made great strides in mitigating those risks, ensuring that workers can operate in a safe and secure environment.

2.3. Simulation in open pit mining

Discrete event simulation in mining has been increasingly used in the mining industry for optimizing various processes and operations, including open-pit mining. In open-pit mining, discrete event simulation models can be employed to analyze and improve the performance of complex systems, such as the hauling process, shovel-truck systems, and stockpile management. By modeling the real-world mining processes as a dynamic system with discrete events, stochastic variables, and queuing behaviors, discrete event simulation can provide insights into the system's behavior and help identify bottlenecks, inefficiencies, and opportunities for improvement. In this subchapter, we will discuss the key concepts, benefits, and limitations of using discrete event simulation in open pit mining and review some case studies and applications.

2.3.1. History behind the discrete event simulation in mining.

The historical table provided below showcases the application of Discrete Event Simulation (DES) in the mining industry. DES has a rich history dating back to the late 1950s when it was first used in the Kiruna underground iron ore mine (Panagiotou, 1999) model and investigates a train transportation system manually (Panagiotou, 1999). Despite the early success of DES, only a few studies related to simulation in mining were presented up until 1995 (Sturgul, 1999). However, the advancement of information technology and computers allowed this tool to be much more accessible for the development of mining projects, as shown in Table 3 which highlights the locations and years in which DES has been implemented in mining, demonstrating its evolution and impact on the industry. It is a useful tool for understanding the historical development of DES and its potential for further optimization in the future.

Table 3 Significant milestones in the history of DES application in mining

Year	Location	Application of DES
1950s	Kiruna, Sweden	Train transportation modeling in underground iron ore mine
1960s	Pennsylvania, USA	First APCOM conference focusing on computers and operations research in mining
1970s	Quebec, Canada	Modeling of truck-shovel operations in open pit mines
1980s	Western Australia	Planning and optimization of open pit mines
1990s	Chile	Scheduling and maintenance optimization in underground copper mines
2000s	South Africa	Equipment selection and simulation-based training for haul truck operators
2010s	Brazil	Environmental impact assessment and water management in iron ore mines
2020s	Mongolia	Simulation-based planning and optimization of a large coal mine expansion project

2.3.2 Applications of Discrete Event Simulation in Mining

The discrete event simulation (DES) technique offers several applications in the mining industry, becoming an essential tool for modern mine planning.

One of the key advantages of DES is the ability to simulate the behavior of mining systems before they are built or introduced. This allows mine-planning engineers to evaluate design alternatives, obtain improvements, eliminate problems, and justify cost figures (Panagiotou, 1999). Through DES, mining professionals can learn about the interdependencies of connected sub-systems, identify bottlenecks along the whole value chain, and optimize the performance of the entire mining system (Baafi, 1999).

Moreover, as the need to evaluate different scenarios within an open-pit mining extraction project without directly affecting production has grown, simulation models have become one of the main tools for mine development. They can be used to test different scenarios under varying conditions, such as changes in equipment, personnel, or geological conditions, and to assess the impact of these factors on the mining system (Fahl, Benefits of Discrete Event Simulation in Modeling Mining Processes, 2019).

One of the primary uses of simulation models in open-pit mining is to evaluate the performance of truck-loader haulage systems. For example, (Jeong Dahee, 2020) simulated a truck-loader haulage system in a South Korean open pit limestone mine, while (Mohammad Tabesh, 2016) developed a model that incorporated truck-shovel operations and equipment failures.

Other areas where simulation models have been applied include the development of dispatching policies, optimization of truck routing, and the overall risk assessment associated with open-pit mining operations (Amanda Smith, 2021; Guangwei Liu, 2019; Saurabh Parakh, 2021). For the work presented in this case study, the software HAULSIM was used, specializing in Discrete Event Simulation Haulage Simulation of open-pit mines. The design was adapted based on the obtained data, following the general procedure adapted from the Association of Germans Engineers (VDI) (Both, 2016).

Limitations of Discrete Event Simulation in Mining

While the applications of DES in mining are extensive, there are also some limitations to consider. One such limitation is the difficulty of modeling complex systems with many interdependent components, requiring significant data and computing power. Additionally, the requirement for expert knowledge in developing, validating, interpreting, and analyzing simulation models can be a challenge (Fahl, Benefits of Discrete Event Simulation in Modeling Mining Processes, 2019). Furthermore, the models may not fully encompass all the uncertainties and complexities of real-world mining operations, leading to discrepancies between the simulated outcomes and actual performance.

To better illustrate the applications and limitations of DES in mining, the following table 4 provides some examples:

Table 4 Application and limitations of the discrete event simulation in mining.

Applications	Limitations
Performance optimization of mining systems	Modeling complex systems
Dispatching policies in open-pit mining	Expert knowledge and experience
Truck-shovel allocation	Discrepancies with real-world operations
Evaluation of haulage systems	Computational resources
Risk assessment in mining operations	Complexity of the model

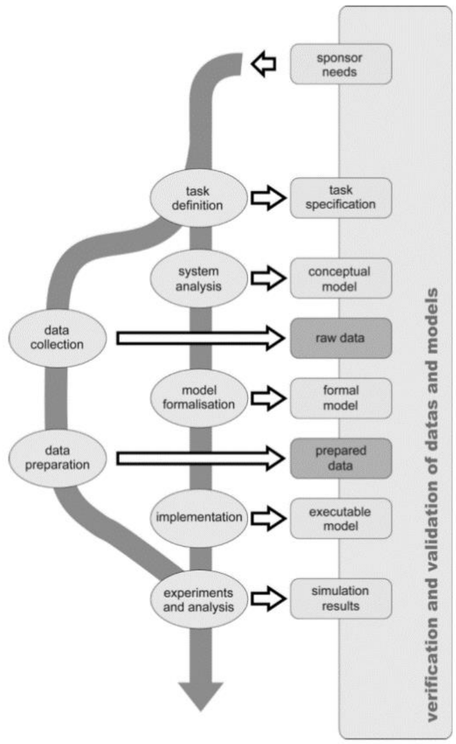

Figure 1 Procedure model for Discrete Event Simulations of VDI, translated to English version by (Both, 2016)

2.4. Truck-loader haulage systems in open pit mining

2.4.1 Safety Aspects of Truck Loader Haulage in Mining Operations.

Truck-loader transport systems are of paramount importance for open-pit mining operations. Due to this significance, planning the transportation of material from the extraction front of the mine to the processing plant or landfill is of high importance. Whether it is for the evaluation of the productivity and the general profitability of the open pit mining project, it is important to ensure that the efficiency of these truck and loader transport systems is high. However, the operation of the truck and loader transport systems loaders also presents significant safety risks to workers and equipment. According to (Satar Mahdevari K. S., 2014), mining operations are associated with a range of health and safety risks, including geomechanically, geochemical, electrical, mechanical, chemical, environmental, ~~personal~~, social, cultural, and managerial.

(Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023) developed an alternate mineral transportation system to evaluate the risk of truck accidents in the mining industry using a critical fuzzy DEMATEL approach. The authors identified critical factors affecting the risk of truck accidents, such as driver behavior, road conditions, weather, and vehicle maintenance, and developed a risk assessment framework to identify the most effective risk mitigation strategies. The authors found that implementing advanced driver assistance systems, improving road infrastructure, and providing regular vehicle maintenance could significantly reduce the risk of truck accidents in mining operations.

Table 5 Factors affecting the risk of truck accidents in mining operations adapted from (Pandey & Mishra, 2023)

Factor	Category
Driver behavior	Human-related
Road conditions	Environmental
Vehicle maintenance	Technical
Load characteristics	Material-related
Traffic density	Environmental
Driver training and education	Human-related
Vehicle safety features	Technical
Weather	Environmental
Management commitment	Organizational-related
Regulatory compliance	Organizational-related

Note: Adapted from "Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach" by Pandey and Mishra,

2.4.2. Simulation models developed for truck-loader evaluation.

Simulation models have become an essential tool for evaluating the performance of truck and loader transportation systems in open-pit mining operations. These models allow researchers to visualize and analyze various scenarios and risks in transport operations and assess the effectiveness of different scheduling strategies (Both, 2016).

For instance, Jeong Dahee (2020) developed a discrete event simulation model for a truck and loader transportation system in a South Korean open pit limestone mine using AnyLogic software. This simulation model was effective in measuring key production indicators and the state of transportation systems in real-time during the simulation, which had not been achieved in previous studies (Jeong Dahee, 2020).

Similarly, Mohammad Tabesh (2016) developed a simulation model that incorporated shovel truck operations, road networks, processing plants, and equipment failures to assess the performance of a shovel truck haulage system in an open pit mining operation. The model was developed in the Arena simulation software, complemented with Matlab, Excel, Word, and VBA, and proved to be effective in evaluating the performance of transportation systems and identifying areas for improvement (Mohammad Tabesh, 2016).

Simulation models are useful in evaluating the impact of different transportation system configurations, identifying potential bottlenecks in the system, and assessing the safety risks associated with truck and loader haulage systems (Global Mining Guidelines Group, 2021). In addition, these models can be used to evaluate the environmental impacts of different transportation scenarios, such as air and noise pollution (Fahl, 2019).

By identifying potential risks and areas for improvement, simulation models can support decision-making processes and contribute to the sustainable and safe extraction of mineral resources. The use of simulation models in truck-loader haulage systems is crucial for improving safety, efficiency, and productivity in open-pit mining operations ((Bastos, 2010); (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023)).

2.5. Dispatching policies in open pit mining

Dispatch policies are of fundamental importance in what involves the whole issue of management of open pit mining operations. These policies help determine what type of equipment will be used and where, how much material will be moved, and the order in which mining activities are carried out. An effective dispatch policy can help maximize productivity and profitability while minimizing the costs and risks that bring the entire operation to the open pit.

Simulation models have been developed to evaluate the effectiveness of different dispatch policies in open-pit mining operations. For example, (Amanda Smith, 2021) tested two different dispatch policies for open pit mining operations: a nonlinear optimization model that incorporates tail effects to set target average flow rates between mine locations, and a discretized mixed integer scheduling (MIP) model in the time. The MIP model was found to outperform the average flow rate dispatch policy in a wide variety of operating configurations, and heuristics were developed to quickly produce high-quality feasible solutions.

In addition to simulation models, other approaches have been used to optimize dispatch policies in open-pit mining operations. For example, (S. Al-Thyabat, 2013) proposed a multi-objective optimization approach for truck dispatch in open pit mining operations, which was effective in minimizing the number of idle trucks, the amount of waiting time, and the total cost of the procedure.

What these studies demonstrate is the importance of dispatch policies as an essential aspect of open-pit mining operations. Simulation models and optimization approaches can help assess the effectiveness of different policies and identify areas for improvement.

Table 6 Dispatching policies in open pit mining.

Study	Objective	Method	Key Findings
Smith, 2021	Evaluate dispatch policies	Nonlinear optimization model, discretized mixed integer scheduling (MIP) model	The MIP model outperformed the average flow rate dispatch policy in a wide variety of operating configurations, and heuristics were developed to quickly produce high-quality feasible solutions.
Al-Thyabat, 2013	Optimize truck dispatch	Multi-objective optimization approach	The approach effectively minimized the number of idle trucks, waiting time, and total cost of the procedure.
Tavakoli et al., 2018	Evaluate dispatch policies	Multi-objective genetic algorithm	The study found that a hybrid dispatching policy, which combines truck sharing and idle truck elimination, was more efficient and reduced costs compared to other policies.

This table provides a quick summary of three different studies related to dispatching policies in open-pit mining. The first column lists the author and year of the study, while the second column provides a brief description of the objective of the study. The third column outlines the method or approach used in the study, and the fourth column summarizes the key findings of the study.

2.6. Autonomous trucks working inside an open pit mine

Over the years, the implementation of autonomous vehicles in open-pit mining projects has become increasingly common. These trucks offer a wide range of benefits, including increased productivity and efficiency, as well as improved safety and cost reduction. However, the introduction of autonomous trucks also requires a new approach to risk management and security protocols.

Simulation models have been developed to assess the effectiveness of autonomous trucks in open-pit mining operations. For example, (John Meech, An interactive simulation model of human drivers to study autonomous haulage trucks, 2011) developed a deterministic/stochastic model to compare autonomous haulage systems (AHS) with manual systems in a virtual 24/7 open pit mine. The model estimated key performance indicators (KPIs) and found that the AHS consistently outperformed the manual system.

The implementation of autonomous trucks also requires continuous monitoring and improvement of safety protocols. While autonomous trucks can reduce the number of accidents, the possibility of accidents still exists. Therefore, safety protocols must be continuously evaluated and improved to minimize any risk associated with the implementation of autonomous vehicles before any open pit project. This can start with regular maintenance of the autonomous trucks, as well as ongoing training of operators and mine personnel.

Moreover, adding autonomous trucks may require the development of new safety protocols and procedures to address the unique risks associated with autonomous technology. This may include developing protocols for autonomous truck interaction with other teams and personnel, as well as establishing clear guidelines for autonomous truck behavior in different situations.

A key change in risk management and safety protocols with the implementation of autonomous trucks is the need for a shift from reactive to proactive measures. With the advanced capabilities of autonomous trucks, there is an opportunity for mining operations to identify and address potential safety risks before they become hazards. This may include conducting regular risk assessments as it is shown in Table 7, implementing security controls, and developing contingency plans in the event of an emergency.

Table 7 Overview of the potential benefits and risks associated with the implementation of autonomous trucks in open-pit mining operations.

Benefits	Risks
Increased productivity and efficiency	Initial capital investment and ongoing maintenance costs
Reduced labor costs and increased worker safety	Potential job loss for drivers and other workers
Improved fuel efficiency and reduced environmental impact	Technical failures and downtime
Advanced safety features and reduced accident risk	Cybersecurity threats and hacking potential
Ability to operate continuously without breaks	Limited operability in extreme weather conditions
Improved data collection and analysis for process optimization	Limited flexibility and adaptability in changing conditions

2.7. Traffic rules inside an open pit mine

Every mining project needs to comply with internal mine traffic rules and regulations, be it a light vehicle, truck, etc. Any type of vehicle that is transiting inside the mine must follow these guidelines to the letter. When including autonomous trucks in our fleet of vehicles, it is necessary to guarantee that traffic regulations will continue to be complied with, for this it is important to establish effective monitoring, follow-up, and compliance mechanisms.

One approach is to use advanced technologies such as GPS and telematics to track the movement of vehicles on the site and monitor compliance with traffic regulations (John Meech, An interactive simulation model of human drivers to study autonomous haulage trucks, 2011). By monitoring the location and speed of vehicles in real-time, supervisors can ensure that vehicles are staying within their designated areas, maintaining safe distances from other vehicles, and adhering to speed limits.

However, while technology can be a powerful tool in ensuring compliance with traffic rules, it is important to consider the role of human factors in traffic management. It remains crucial to ensure that personnel involved in traffic management are properly trained and equipped to respond to emergencies and unforeseen situations (John Meech, An interactive simulation model of human drivers to study autonomous haulage trucks, 2011). This includes providing clear communication channels for reporting incidents and hazards, as well as regular training and refresher courses to ensure all staff are up to date with the latest protocols and procedures.

To complement technological solutions, regular safety inspections and audits can be conducted to identify any areas for improvement and ensure that all personnel complies with established transit rules and procedures (Global Mining Guidelines Group, 2021). This can include reviewing traffic flow patterns, identifying potential hazards or bottlenecks, and ensuring that signage and road markings are clear and visible.

To ensure that the inclusion of autonomous vehicles in the open pit mining project maintains a safe and efficient operation, a combination of advanced technologies, effective training and certification programs, and regular safety audits and inspections is required in Table 8. By mitigating the risks associated with the traffic of vehicles within the mining project, the project can continue to operate safely and efficiently.

Table 8 Examples of traffic rules and regulations in open-pit mining operations

Traffic Rule/Regulation	Description
Speed limits	Specifies maximum speed limits for different types of vehicles in different areas of the mine site
Right of way	Establishes which vehicles have the right of way in different areas of the mine site
Vehicle size restrictions	Limits the size of vehicles that can be used in different areas of the mine site
Seatbelt use	Requires all occupants of vehicles to always wear seatbelts
Pedestrian crossings	Establishes designated crossing points for pedestrians and requires all vehicles to yield to pedestrians in these areas
Vehicle inspections	Requires regular inspections of all vehicles to ensure they are in good condition and safe to operate
Driver training and certification	Requires all drivers to complete a comprehensive training and certification program before operating any vehicle on the mine site

2.8. Safe Mobility of Trucks in Open Pit Mining Operations

Open-pit mining operations rely heavily on truck transportation for the movement of materials and equipment. Maintaining safe and uninterrupted truck mobility is crucial to the success of these operations, as any disruptions can result in significant losses in time and money (Guangwei Liu, 2019). Several factors can impact the safe mobility of trucks in open pit mining operations, including the condition of the road network, weather conditions, and the type and size of the trucks being used.

To ensure safe mobility, a variety of strategies and technologies have been developed and implemented. Real-time monitoring systems can provide information on the condition of the road network and potential hazards, such as changes in slope, road damage, or rockfall. GPS and telematics can be integrated with monitoring systems to provide real-time information on the location and status of trucks (Guangwei Liu, 2019)

Technologies such as collision avoidance systems, lane departure warning systems, and fatigue detection systems can be installed on trucks to improve their safety and prevent accidents (Amanda Smith, 2021). Regular training and education of truck drivers are crucial to ensuring safe driving techniques, while regular maintenance and inspection of trucks are necessary to ensure their safe operation (Global Mining Guidelines Group, 2021). These measures can help mitigate the risks associated with truck mobility and ensure the safety of personnel and equipment involved in open-pit mining operations, all these technologies and their description are better explained in the table below.

Table 9 Examples of technologies for improving the safe mobility of trucks in open pit mining operations.

Technology	Description
Real-time monitoring systems	Integrated systems that use sensors, GPS, and telematics to provide real-time information on road conditions and truck location.
Collision avoidance systems	Technologies that warn drivers of 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.
Regular maintenance	Routine checks of brakes, tires, and other critical components to ensure safe truck operation.

2.9. Safe Introduction of Autonomous Trucks in Non-Autonomous Open Pit Mines

The introduction of autonomous trucks in non-autonomous open pit mines can provide several benefits, including increased safety, productivity, and cost-effectiveness. However, it also requires careful planning and risk management to ensure a smooth transition. This subchapter discusses the steps and considerations required to introduce autonomous trucks safely in non-autonomous open pit mines.

One of the initial steps is to conduct a thorough risk assessment to identify potential hazards and develop a plan to mitigate them. This plan should consider the unique risks associated with autonomous technology, such as software malfunctions, equipment failures, and cyber-attacks. Infrastructural requirements, including GPS and telematics equipment, should also be installed, and protocols should be developed for communication between autonomous trucks and other vehicles and personnel in the open pit mine (Sanaa Benlaajili, 2021).

Effective training and certification programs are essential to the safe introduction of autonomous trucks. All personnel involved in the operation of autonomous trucks should be properly trained in the use of the technology, as well as in emergency response and safety protocols. This includes providing clear communication channels for reporting incidents and hazards, as well as regular training and refresher courses to ensure all staff is up to date with the latest procedures (Aleksandr Rakhmangulov, 2021).

Another crucial step is to establish clear guidelines and protocols for the integration process. This includes identifying key performance indicators (KPIs) and metrics for measuring the effectiveness of the technology, as well as developing contingency plans in the event of an emergency or unforeseen circumstance. Simulation models, such as those developed by (John Meech, 2011), can also be used to evaluate the impact of autonomous trucks on open-pit mining operations before their implementation (Both, 2016).

Optimization-based dispatching policies, such as those discussed by (Amanda Smith, 2021), can also be used to ensure the safe and efficient operation of autonomous trucks in open pit mining operations. Additionally, methods for truck dispatching, as discussed (Bastos, 2010), can be adapted for use with autonomous trucks.

Finally, rules of risk management, such as those discussed by (Snezana Kirin, 2020), should be followed, including regular maintenance and inspection of trucks to ensure their safe operation. This includes regular checks of brakes, tires, and other critical components to identify any potential issues before they become safety hazards.

2.10. Risk Management in Open Pit Mining Operations

The identification, assessment, and mitigation of risks are essential to ensure the safety and sustainability of open-pit mining operations. In this subchapter, we discuss the various aspects of risk management in open-pit mining operations, based on the research papers listed above.

Risk identification is the first step in risk management, which involves identifying potential hazards and risks associated with the mining operation. (Matsimbe Jabulani, 2020) suggests conducting safety audits and inspections regularly to identify hazards, while Kirin and Limbic (2020) emphasize the importance of conducting a risk assessment using a systematic approach. Risks can be categorized as safety, environmental, and economic risks, and identifying these risks is crucial to developing effective mitigation strategies.

Risk assessment involves evaluating the identified risks based on their likelihood of occurrence and the potential impact they could have. This assessment can be based on qualitative or quantitative methods. According to Rakhmangulov and Kosyachenko (2021), the risk assessment should be an ongoing process, with regular reviews to ensure the effectiveness of the mitigation measures. In addition, the use of simulation models, such as discrete event simulation, can be an effective tool for evaluating risks and identifying potential areas for improvement (Both, 2016; Fahl, 2019; Tabesh et al., 2016).

Risk mitigation is the process of developing and implementing measures to minimize or eliminate the risks identified in the risk assessment. According to the Global Mining Guidelines Group (2021), risk mitigation strategies can include implementing safety protocols and procedures, using protective equipment, and providing proper training and education to personnel. Liu et al. (2019) suggest optimizing truck routes to minimize transport energy consumption, while (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023) proposes a fuzzy DEMATEL approach to evaluate the risks associated with truck accidents and develop an alternative transportation system.

Effective risk management also requires a strong safety culture within the organization, where safety is seen as a core value and integrated into all aspects of the operation. This includes regular safety training for personnel and ensuring that safety protocols and procedures are followed consistently. Mahdevari and Shahriar (2014) suggest using fuzzy TOPSIS to manage human health and safety risks in underground coal mines.

Regular safety audits, risk assessments, and the use of simulation models can help identify potential risks and areas for improvement. Mitigation strategies should be developed based on the identified risks, and a strong safety culture must be established within the organization to ensure the consistent implementation of safety protocols and procedures for risk management is crucial for ensuring the safe and sustainable operation of open pit mining projects. Risk management in mining operations involves identifying potential hazards and risks, assessing their likelihood and potential consequences, and developing and implementing strategies to mitigate or eliminate those risks as it is shown in Table 10. (Australian Government Department of Industry, Science, Energy and Resources, 2020).

Table 10 Examples of Potential Hazards and Risks in Open Pit Mining Operations

Hazard/Risk	Potential Consequences
Equipment failure	Production delays, worker injuries, equipment damage
Rock falls and slides	Worker injuries, equipment damage, production delays
Weather-related events	Production delays, worker injuries, equipment damage
Explosions and fires	Worker injuries, equipment damage, production shutdowns
Chemical spills	Environmental damage, worker injuries, legal and regulatory compliance issues

3. Research Framework and Simulation Model Development.

3.1 Research design

This study aims to analyze the safety implications of introducing autonomous trucks into an existing non-autonomous open-pit mining operation. The research framework involves creating different automation scenarios using a discrete event simulation model of the open pit mine developed in the simulation software HAULSIM and AnyLogic. The simulation model will be based on the mining automation maturity model designed by the Global Mining Guidelines Group (GMG, 2019), which outlines different levels of autonomy in mining equipment. After creating the different automation scenarios. The simulation will use the scheduling data provided by the mining company to simulate the haulage of open pit trucks, followed by the addition of autonomous trucks to the simulation.

The analysis will focus on evaluating the safety impact of introducing autonomous trucks into the mining operation. Based on the simulation results, the study will compare the safety performance of autonomous and non-autonomous trucks in mining operations. The analysis will consider potential hazards and risks associated with the use of autonomous trucks.

3.2 Development of simulation model inputs and assumptions

The information used for simulating the truck-loader hauling system in this study includes the records of hauling cycle time and the topographic data of a typical mine. These records, along with the details of the mine's roads, were sourced directly from the mining company, making them highly relevant when simulating truck mobility. It was necessary to make several assumptions to carry out the simulation model. These assumptions are related to equipment behavior, material characteristics, operational constraints, and human factors. Based on bibliographic records, technical publications, and international standards mentioned in the previous chapters, these factors are identified as the main variables that will affect the result of the simulation. In this context, the primary importance lies in adopting a comprehensive and proactive approach to risk management in autonomous haulage systems (Saurabh Parakh, 2021; Snezana Kirin, 2020)." Table 11 presents a list of the breakdown topics for the development of the simulation model inputs and Assumptions and the literature references where a similar analysis was made.

Table 11 Breakdown of the "Development of simulation model inputs and Assumptions" topics

Topic	**Approach**	**Literature Reference**
Data sources	Utilize haulage cycle times, topographic data, and road information from the mining company	
Assumptions formulation	Consider the behavior of equipment, material characteristics, and operational constraints	Basu, A. J. (1999); Sturgul, J. (1999)
Estimation of simulation parameters	Combine data analysis from the company with a literature review	Fahl, S. K. (2019); John Meech, J. P. (2011)
Risk management in autonomous systems	Adopt a comprehensive and proactive approach to mitigate risks and ensure safety and operational efficiency	Saurabh Parakh, N. R. (2021); Snezana Kirin, W. L. (2020)

3.3 Selection of simulation software and Tools

3.3.1. Overview of available simulation software and tools

Many simulations software and tools are available in the market, each with its features and capabilities. This section will provide an overview of the simulation software and tools tested for this study: Anylogic, HAULSIM, JaamSim, and Python libraries (Open Simply and SimPy).

Anylogic is a powerful, general-purpose simulation tool that can be used for a wide range of modeling and simulation tasks, including discrete event simulation, system dynamics, and agent-based modeling. It offers a user-friendly interface and supports various programming languages, including Java. Anylogic is known for its flexibility and scalability, making it a popular choice for large-scale simulation projects. (The Anylogic Company, 2023)

HAULSIM is a simulation tool designed specifically for the mining industry. It stimulates the haulage of trucks in open-pit mines and is capable of modeling different types of trucks and equipment. HAULSIM offers features such as real-time graphics, 3D visualization, and the ability to simulate different scenarios, making it a useful tool for evaluating the safety impact of introducing autonomous trucks into a mining operation. (RPMGLOBAL, 2023)

JaamSim is a discrete-event simulation software that allows users to model complex systems using a modular approach. It is open-source software that is widely used in various fields such as healthcare, logistics, and transportation. JaamSim offers a user-friendly interface and a flexible modeling environment that allows users to create custom models and simulations. It also has data analysis and visualization features, making it a powerful tool for decision-making. Some of the capabilities of JaamSim include the ability to model queues, service processes, and complex networks. It also allows for the incorporation of user-defined models, which can be coded in Java. JaamSim has a large online community of users, providing support and resources for those who use the software. (JaamSim, 2023)

Python libraries, including Open Simply and SimPy, are open-source simulation tools that can be used to model and simulate complex systems. They offer a range of simulation techniques, including discrete event simulation and agent-based modeling, and can be used with various programming languages, including Python. Python libraries are known for their flexibility and ease of use, making them a popular choice for researchers who require quick prototyping and testing of their simulation models. (Open SIMPLY, 2023) (SimPy, 2020). Based on the information researched about each software Table 12, was designed:

Table 12 Comparison of the simulation software and tools tested.

Software/Tool	Pros	Con
AnyLogic	-Provides support for multiple modeling methodologies such as discrete event, agent-based, and system dynamics - Has a user-friendly interface - Supports a wide range of industries - Provides extensive data analysis and visualization capabilities	-Can be resource-intensive and require a high-performance computer to run. - Can have a steep learning curve for beginners -Files import limitations.
Haulsim	-Designed specifically for mining operations. -Can simulate both surface and underground mining. -Allows for the creation of realistic mining scenarios. - Can be integrated with other mining software.	-Limited flexibility for modeling other industries. - May not be as user-friendly as other software.
JaamSim	-Has a user-friendly interface. -Supports the creation of complex models -Provides a range of built-in simulation components. -Free and open-source software	-May have limited support and resources compared to commercial software. - Limited documentation and tutorials available.
Python libraries (OpenSim and SimPy)	- Free and open-source software. - Supports a wide range of modeling methodologies. - Can be integrated with other Python libraries for data analysis and visualization.	- May require programming skills to use effectively. -May have limited support and resources compared to commercial software.

Reference: Adaptation of the information found on the following websites: (JaamSim, 2023) (Open SIMPLY, 2023) (RPMGLOBAL, 2023) (SimPy, 2020).

3.3.2. Criteria for selecting the simulation software and tools.

The selection of simulation software and tools was based on several criteria, considering the specific requirements of the study and the limitations of available options. The following criteria were considered:

1. Ease of use and short learning curve: The simulation software needed a user-friendly interface and easy to learn and navigate.

2. Flexibility and adaptability: It was important for the selected software to be flexible and adaptable to different scenarios and mining conditions. This would allow for the simulation of various situations and ensure the applicability of the results.

3. Cost-effectiveness: The development and implementation of the simulation model had to fit within the project's budget. It was essential to consider the cost-effectiveness of the software and tools chosen.

4. Scalability and handling of large datasets: Given the nature of mining operations and the amount of data involved, the selected software needed to be capable of handling large datasets and scaling up as needed.

5. Compatibility with data inputs: The software had to be compatible with the data inputs provided by the mining company to ensure seamless integration and accurate representation of the mining operation.

Considering these criteria, two simulation software tools were chosen for this study: HAULSIM and AnyLogic. HAULSIM was selected for its established use in the mining industry and its haulage simulation and optimization capabilities. It provides a user-friendly interface and allows for easy model development and analysis. HAULSIM is well-suited for visualizing and validating the data and results obtained from the company's haulage records.

However, it was recognized that HAULSIM has limitations when it comes to simulating accidents, collisions, and hazardous situations outside the scope of haulage and mobility. To address this, AnyLogic was also chosen as it offers the ability to simulate accidents, collisions, and other hazardous scenarios. AnyLogic allows for a comprehensive safety assessment analysis, considering a broader range of factors. While AnyLogic cannot directly import the elevation model of the mine's topography, it provides valuable visualization of possible hazardous scenarios and enables the safety assessment analysis.

By combining the strengths of HAULSIM and AnyLogic, the research benefits from both software tools, utilizing HAULSIM for visualization and validation of data and results obtained from the mining company, and AnyLogic for simulating and assessing potential hazardous scenarios beyond the scope of haulage.

This combined approach allows for a more comprehensive evaluation of safety aspects in the implementation of autonomous trucks in a non-autonomous mine, considering both mobility-related factors and potential accidents or collisions.

3.4. Description of the software and tools

3.3.1. HAULSIM

HAULSIM is a commercial simulation software developed by Runge Pincock Minarco (RPM) that allows for the modeling and analysis of surface mining operations, including open pit mines. HAULSIM offers a range of features and functionalities that enable the simulation of different mining scenarios, including the haulage of materials by trucks, the scheduling of mining activities, and the optimization of mine layouts. (RPMGLOBAL, 2023)

One of the main features of HAULSIM is its ability to model and simulate the haulage of materials by trucks, which is essential for the analysis of the safety impact of introducing autonomous trucks into an open pit mine. The software allows users to model different types of trucks, their capacity and performance, and the roads and paths they follow within the mine. This information can then be used to evaluate the impact of different automation scenarios on the safety of the operation. (RPMGLOBAL, 2023)

Another important feature of HAULSIM is its scheduling module, which allows users to model and optimize the scheduling of mining activities based on different criteria, such as production targets, equipment availability, and maintenance requirements. This module is crucial for the analysis of the safety impact of introducing autonomous trucks, as it allows for the evaluation of the impact of different automation scenarios on the overall productivity and efficiency of the mining operation. (RPMGLOBAL, 2023)

HAULSIM also offers a range of reporting and visualization tools, which allow users to analyze and interpret the simulation results in a user-friendly and intuitive way. The software is designed to be user-friendly and accessible, even for users with little or no previous experience in simulation modeling. (RPMGLOBAL, 2023)

However, HAULSIM also has some limitations that need to be considered when using it for simulation modeling. One of the main limitations is its cost, which may be prohibitive for some users. Another limitation is its scalability, as the software may not be suitable for very large or complex mining operations. Additionally, HAULSIM may not be compatible with all types of data inputs and may require significant data preparation and cleaning before it can be used effectively. (RPMGLOBAL, 2023)

3.3.2. AnyLogic

AnyLogic is a powerful simulation software that offers extensive capabilities for modeling complex systems and analyzing various scenarios. It provides a wide range of modeling approaches, including agent-based, discrete event, and system dynamics, allowing for a comprehensive simulation of different processes and interactions. (The AnyLogic Company, 2023)

In the context of this research, AnyLogic offers unique advantages for safety assessment and analysis of autonomous truck implementation in a non-autonomous mine. Its ability to simulate accidents, collisions, and hazardous scenarios sets it apart from HAULSIM, which primarily focuses on haulage and mobility within the mine. (The AnyLogic Company, 2023)

AnyLogic allows users to create dynamic models that consider the behavior and interactions of various elements in the mining operation, such as trucks, equipment, personnel, and the environment. By incorporating factors such as human behavior, traffic patterns, and potential hazards, it provides a more comprehensive understanding of safety implications.

3.5. Limitations of the selected simulation software and tools

The limitations of the selected simulation software and tools include the following:

- Limited customizability: The software has a limited capability for customization, especially using the "Professional - Evaluation" license Figure 3, which may limit the number of blocks and the ability to simulate specific mining scenarios or processes that are unique to a particular mine.

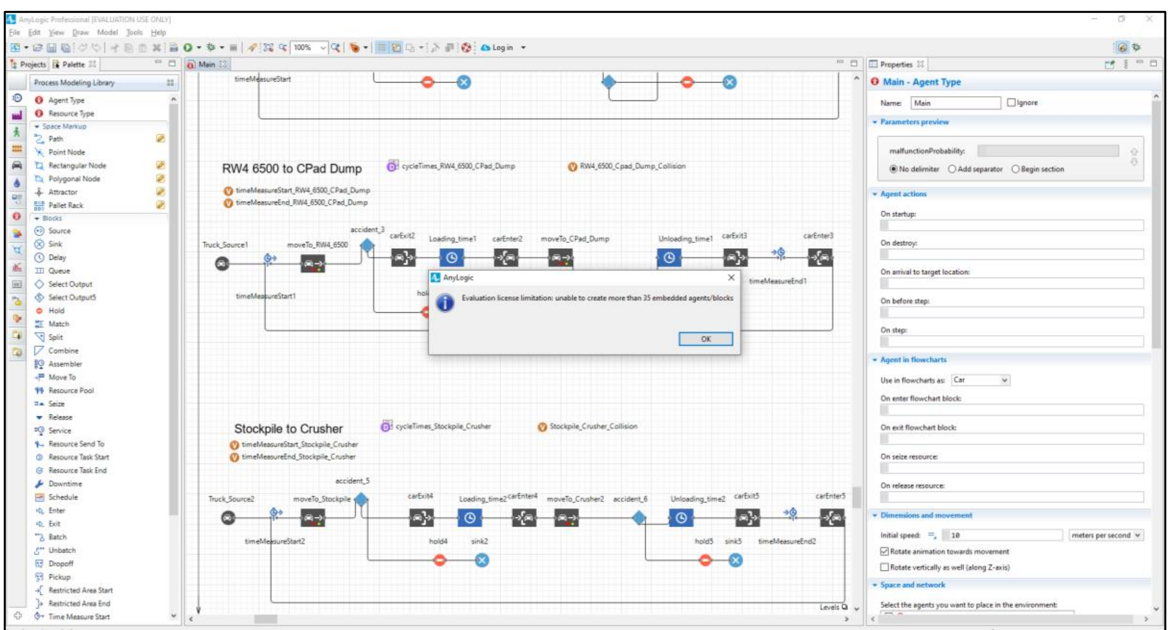

Figure 2 License limitations

- Data requirements: The software requires a large amount of data to generate an accurate simulation, including detailed information on the mine layout, equipment specifications, and material properties. This can be a limitation if the required data is not available or is of low quality.
- Model complexity: The simulation model can become complex and difficult to manage as the number of components and interactions increase. This can make it challenging to modify the model or identify errors or issues.

These limitations may impact the results of the simulation by affecting the accuracy, comprehensiveness, and feasibility of the model, Table 13 shows the comparison between the limitations and the impact of the simulation results:

Table 13 Compare the features and limitations of the simulation software HAULSIM and ANYLOGIC

Limitations	Impact on Simulation Results
Limited ability to model complex haul road geometries	May not accurately represent real-world conditions
Limited ability to model weather conditions	May not accurately represent real-world conditions
Limited ability to model interactions between equipment and personnel	May not accurately represent real-world conditions
Limited ability to model real-time data inputs and outputs	May not accurately represent real-world conditions
Limited ability to model complex maintenance and repair activities	May not provide real-time feedback or response
Limited ability to model complex maintenance and repair activities	May not accurately represent the impact of downtime on the operation

Reference: (RPMGLOBAL, 2023) & (The Anylogic Company, 2023)

3.6. Preparations for the implementation of the selected simulation software and tools

Before implementing the selected simulation software and tools, certain preparations must be made. These preparations are necessary to ensure that the simulation reflects as accurately as possible the real-world scenarios of an open-pit mine operation.

One of the first steps in the preparation process is to gather data on the open pit mine operation. This includes information such as the size and layout of the mine, the equipment used, and the production schedule. This data is essential for accurately modeling the open pit mine operation in the simulation software. (Fishwick, 1995)

Once the data has been collected, it is important to clean and preprocess it to ensure that it is accurate and ready for use in the simulation software. This process may involve removing duplicates, correcting errors, and standardizing the format of the data.

Another important aspect of preparing for the implementation of the selected simulation software and tools is the creation of input models. Input models are used to describe the behavior of the equipment and processes in the open pit mine operation. These models are necessary for the simulation software to accurately model the mine operation. (Tayfur Altiok, 2007). In addition to creating input models, defining the simulation parameters is important. This includes setting up the simulation time frame, defining the simulation scenarios, and selecting the appropriate simulation outputs. (Tayfur Altiok, 2007)

The data preparation process for this study primarily utilized HAULSIM due to its superior flexibility in handling the data files provided by the mining company, a feature that Anylogic lacks. However, once the data was processed and exported through HAULSIM, Anylogic was employed for further analysis and modeling.

By adopting this two-step approach, we were able to leverage the strengths of both software tools: HAULSIM's robust data importing and preprocessing capabilities and Anylogic's advanced analysis and simulation modeling features. This strategic combination allowed for a comprehensive and effective data processing workflow that thoroughly addressed the research needs.

3.7 Hazard Associated with autonomous trucks.

3.7.1. Definition of hazards and risks

According to the Code of Practice for Safe Autonomous Mining in Western Australia, some of the hazards associated with autonomous trucks include equipment failure, software malfunctions, and collisions with other vehicles or objects (Department of Mines and Petroleum, 2015). (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023) also identifies hazards such as cyber-attacks, loss of communication, and sensor malfunction that can affect the safe operation of autonomous trucks in a mining environment.

These hazards can lead to various consequences, such as production delays, equipment damage, worker injuries, and even fatalities (Department of Mines and Petroleum, 2015); (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023)). To effectively manage these hazards and prevent adverse consequences, it is important to identify their causes.

Some of the causes of hazards associated with autonomous trucks include inadequate maintenance, inadequate training and supervision of personnel, and inadequate communication between vehicles and personnel (Department of Mines and Petroleum, 2015). Real-world events have demonstrated the potential consequences of these hazards, such as the Uber self-driving car accident in 2018, where a pedestrian was killed due to a software malfunction (Smiley, 2022).

International standards such as ISO 26262 guide unctional safety for road vehicles, including autonomous vehicles, while ISO 12100 guides risk assessment and risk reduction for machinery in general (International Organization for Standardization, 2018); (International Organization for Standardization, 2010). These standards can provide a framework for identifying hazards and mitigating risks associated with autonomous trucks in a mining environment.

3.7.2. Autonomous Trucks' Hazards

Autonomous Haulage systems bring various hazards and risks that must be identified and mitigated to ensure safe operations. These hazards include software malfunctions, equipment failures, and cyber-attacks (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023); (Department of Mines and Petroleum, 2015).

Software malfunctions can occur due to various reasons, such as errors in programming or insufficient testing (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023). Equipment failures can occur due to inadequate maintenance or component failure (Department of Mines and Petroleum, 2015). Cyber-attacks are also a growing concern, as autonomous trucks rely on networked systems that can be vulnerable to hacking and other malicious activities (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023).

It is essential to identify the causes of these hazards to avoid adverse consequences, good research explaining the best ways to identify the hazards facing the mining industry due to the complex and dynamic nature of the mining environment is: Autonomous Haulage Systems in the Mining Industry: Cybersecurity, Communication, and Safety Issues and Challenges, highlights the importance of effective communication, cybersecurity, and safety measures in autonomous mining operations (Tarek Gaber, 2021). At the same time, international standards such as ISO 26262 and ISO 12100 provide guidelines for functional safety and risk assessment, respectively, which can serve as a framework for identifying hazards and mitigating risks associated with autonomous trucks in a mining environment.

In 2019, an autonomous haul truck at a Western Australian mine experienced a brake failure, causing it to collide with another truck and leading to significant damage (Casey, 2019). The incident highlights the importance of regular maintenance and inspection of autonomous trucks to prevent equipment failures that can lead to hazardous situations.

To mitigate the risk of equipment failures, it is essential to establish maintenance and inspection protocols that address the unique needs of autonomous trucks. The Code of Practice for Safe Autonomous Mining in Western Australia provides guidelines for developing and implementing these protocols, including regular equipment inspections, data analysis, and maintenance schedules (Global Mining Guidelines Group, 2019). Regular equipment inspections can help identify potential issues before they lead to failures, while data analysis can provide insights into the performance and reliability of autonomous truck systems. In addition to regular maintenance and inspection, safety protocols and procedures can also mitigate the risk of equipment failures. The implementation of autonomous trucks requires a comprehensive safety management system that includes procedures for responding to equipment failures and malfunctions (Tarek Gaber, 2021). This includes establishing protocols for emergency shutdowns, system resets, and maintenance interventions, as well as establishing lines of communication between autonomous trucks and personnel. Protective equipment can also help mitigate the consequences of equipment failures. For example, the use of proximity detection systems can alert personnel to the presence of autonomous trucks, reducing the risk of collisions (Department of Mines and Petroleum, 2015). Other protective equipment, such as personal protective equipment, can also help reduce the risk of injuries in the event of an equipment failure or collision.

3.7.3. Identification and evaluation of hazards and risks

Autonomous haulage systems (AHS) bring various hazards and risks that must be identified and evaluated to ensure safe operations in the mining industry. According to the "Guideline for the Implementation of Autonomous Systems in Mining," these hazards include equipment failure, software malfunctions, and collisions with other vehicles or objects (Global Mining Guidelines Group, 2019); (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023) also identifies hazards such as cyber-attacks, loss of communication, and sensor malfunction that can affect the safe operation of autonomous trucks in a mining environment.

Identification and evaluation of hazards and risks are crucial steps in ensuring safety in autonomous mining operations. The study "Autonomous Haulage Systems in the Mining Industry: Cybersecurity, Communication and Safety Issues and Challenges," (Tarek Gaber, 2021) highlights the importance of effective communication, cybersecurity, and safety measures in autonomous mining operations. They suggest that the identification of hazards and risks should be based on a comprehensive analysis of the mining environment and the AHS technology.

One approach to identifying hazards in the mining environment is through real-time mine road boundary detection and tracking. This approach is described in the study by (Xiaowei Lu, 2020), "Real-Time Mine Road Boundary Detection and Tracking for Autonomous Trucks." The study proposes a system that uses a camera and a lidar sensor to detect and track road boundaries, which can help prevent collisions with other vehicles or objects.

After identifying the hazards, the next step is to evaluate the associated risks. According to the "Guideline for the Implementation of Autonomous Systems in Mining," risk evaluation should be based on a combination of qualitative and quantitative methods (Global Mining Guidelines Group, 2019). Qualitative methods include hazard and operability studies (HAZOP) and failure modes and effects analysis (FMEA).

3.7.4. Importance of communication, training, and education in managing hazards and risks

Effective communication, training, and education are critical for managing hazards and risks associated with autonomous trucks in mining operations. According to the Guideline for the Implementation of Autonomous Systems in Mining, communication is essential for the safe operation of autonomous equipment as it enables personnel to understand how the system operates, what its limitations are, and how to respond to potential malfunctions or hazards (Global Mining Guidelines Group, 2019).

Similarly, the Code of Practice for Safe Mobile Autonomous Mining in Western Australia highlights the importance of training and education in ensuring the safe operation of autonomous equipment. The Code specifies that personnel involved in the operation and maintenance of autonomous equipment must receive appropriate training and education to operate the equipment safely and understand the hazards associated with it (Department of Mines and Petroleum, 2015).

The importance of communication and training is also highlighted in research on autonomous haulage systems. Autonomous Haulage Systems in the Mining Industry: Cybersecurity, Communication and Safety Issues and Challenges, highlights the importance of effective communication, cybersecurity, and safety measures in autonomous mining operations (Tarek Gaber, 2021). The study recommends that personnel should receive training on cybersecurity and communication protocols to ensure that they can recognize and respond to potential threats to the system.

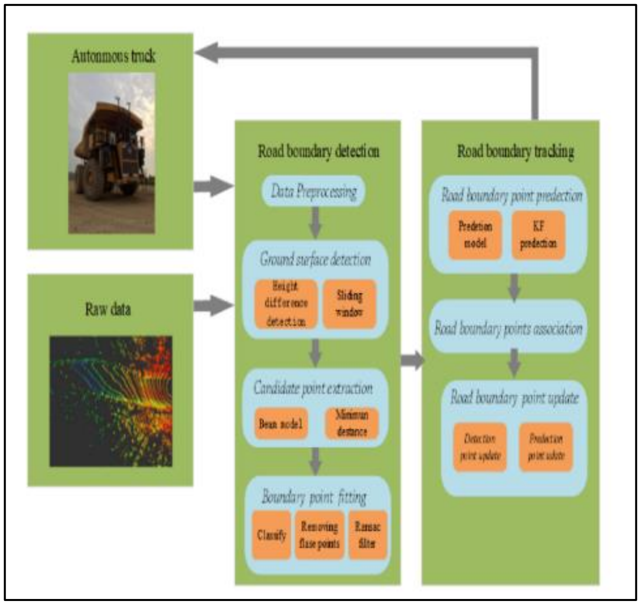

Figure 3 Mine Road detection structure, (Xiaowei Lu, 2020)

To improve the quality of Real-Time Mine Road Boundary Detection and Tracking for Autonomous Trucks, the authors also emphasize the importance of effective communication between autonomous trucks and other vehicles or personnel. The study proposes a real-time road boundary detection and tracking system to enhance the safety of autonomous trucks by enabling them to detect and avoid obstacles and hazards in real-time. Figure 4. shows the main content of the mine road boundary detection and tracking method.

This study proposed the idea of double meshing, due to the particularities of the streets of the mine. This method is not only suitable for the uneven road surface of the mine but also for the slope of the mine road. The road boundary candidate points are extracted at the elevated point, and the false points outside the road are filtered through a series of processes. And then the points are optimized and stabilize the results of road detection through road boundary tracking (Xiaowei Lu, 2020).

3.8 Classification for Risk within international standards

3.8.1. Overview of international standards related to risk management.

Risk management is an essential component of safe and efficient mining operations, especially when it comes to the implementation of autonomous trucks. International standards provide a framework for identifying hazards and mitigating risks associated with autonomous trucks in a mining environment.

ISO 31000:2018 provides principles and guidelines for risk management and can be applied to any type of organization, including mining companies (International Organization for Standardization, 2018).

ISO 12100:2010 guides risk assessment and risk reduction for machinery in general and can be applied to autonomous trucks in a mining environment (International Organization for Standardization, 2010).

ISO 26262:2018 is an international standard that guides functional safety for road vehicles, including autonomous vehicles (International Organization for Standardization, 2018). The standard specifies requirements for the functional safety of electrical and electronic systems in passenger cars, commercial vehicles, and motorcycles.

The implementation of autonomous trucks in a mining environment also involves cybersecurity risks. The International Electrotechnical Commission (IEC) provides standards related to cybersecurity for industrial automation and control systems. IEC 62443 provides a framework for cybersecurity management and specifies requirements for system security, communication security, and product development security (International Electrotechnical Commission, 2021).

At the same time, the Code of Practice for Safe Autonomous Mining in Western Australia also provides guidelines for the safe implementation and operation of autonomous mining systems, including autonomous trucks (Department of Mines and Petroleum, 2015). The code covers various aspects such as risk assessment, communication, training, maintenance, and emergency management.

Table 14, in a very summarized way, presents a list of the different international standards mentioned above and others not mentioned with a brief description of them, that will help to understand the framework for identifying and mitigating risks associated with autonomous trucks in a mining environment. These standards cover various aspects such as risk management, functional safety, cybersecurity, and safe operation. Adherence to these standards can help ensure autonomous trucks' safe and efficient operations in a mining environment.

Table 14 International standards related to risk management.

Standard	Title	Description
ISO 31000	Risk management – Guidelines	Provides principles and generic guidelines on risk management.
ISO 12100	Safety of machinery – General principles for design – Risk assessment and risk reduction	Provides a framework for the risk assessment and risk reduction of machinery.
ISO 26262	Road vehicles – Functional safety	Provides guidance on the functional safety of road vehicles, including autonomous vehicles.
IEC 61508	Functional safety of electrical/electronic/programmable electronic safety-related systems	Provides a framework for the functional safety of electrical/electronic/programmable electronic safety-related systems.
ANSI/ISA-84.00.01	Functional safety: Safety instrumented systems for the process industry sector	Guides the functional safety of instrumented systems for the process industry sector.
IEC 61511	Functional safety – Safety instrumented systems for the process industry sector	Guides the functional safety of instrumented systems for the process industry sector.

3.8.2. Classification of risk associated with autonomous trucks in open pit mines.

According to the literature reviewed, the risks associated with autonomous trucks in open pit mines can be classified into five categories: technical, operational, environmental, health and safety, and security (Tarek Gaber, 2021), 2021; (Pandey & Mishra, Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach, 2023)). Each category is further divided into specific risks, in Table 2 as follows:

Table 15 Classification of risks and their corresponding ranks

Category	Specific Risks	Description
Technical	Software and hardware malfunctions	Risks associated with failures of the technology used by autonomous trucks, such as software and hardware malfunctions.
	Sensor failures	Risks associated with the failure of sensors can impact the safe operation of autonomous trucks.
	Connectivity and communication breakdowns	Risks associated with the breakdown of communication between autonomous trucks and other systems or personnel.
	Cybersecurity threats	Risks associated with the potential for cyber-attacks and other security threats to the autonomous truck system.
Operational	Inadequate maintenance of equipment and software	Risks associated with the failure to properly maintain equipment and software can impact the safe operation of autonomous trucks.
	Lack of proper training and supervision of personnel	Risks associated with inadequate training and supervision of personnel who operate and maintain autonomous trucks.
	Poor design of autonomous systems	Risks associated with the design and implementation of autonomous systems can impact their safe operation.
	Failure to comply with regulations and standards	Risks associated with the failure to comply with regulations and standards related to autonomous trucks.
Environmental	Impacts on the natural environment	Risks associated with the impact of autonomous trucks on the natural environment, such as air and noise pollution.
	Disruption to local communities and ecosystems	Risks associated with the disruption of local communities and ecosystems due to the operation of autonomous trucks.
	Damage to infrastructure and property	Risks associated with damage to infrastructure and property caused by autonomous trucks.
Health and Safety	Worker injuries and fatalities	Risks associated with worker injuries and fatalities due to collisions

ISO 26262 and ISO 12100, provide guidelines and best practices for identifying and mitigating hazards associated with autonomous trucks in mining environments. These standards are crucial for ensuring the safe operation of autonomous haulage systems (AHS) in open pit mines. They provide a framework for risk assessment and reduction, including hazard identification, analysis, evaluation, and control.

ISO 26262 is specifically focused on functional safety for road vehicles, including autonomous vehicles, and provides a comprehensive approach to ensuring safety in the design and development of these vehicles. This standard covers the entire development lifecycle of a vehicle, from concept to decommissioning, and provides a risk-based approach for identifying potential hazards and ensuring their mitigation.

Similarly, **ISO 12100** guides risk assessment and risk reduction for machinery in general, including mining equipment such as autonomous trucks. This standard provides a systematic approach for identifying hazards and assessing their risks, as well as outlining measures for risk reduction, such as engineering controls and administrative controls.

By adhering to these international standards, mining companies can ensure that their AHS are designed, operated, and maintained safely and effectively, minimizing risks to workers, equipment, and the environment. Additionally, compliance with these standards can help companies meet regulatory requirements and demonstrate their commitment to safety and sustainability, As shown in Table 16 which explains the international standards related to Autonomous Haulage Systems (AHS) in mining.

Table 16 International standards related to Autonomous Haulage Systems (AHS) in mining.

Standard Number	Title	Description
ISO 17757:2019	Earth-moving machinery and mining Autonomous and semi-autonomous machine system safety	Provides safety requirements for autonomous and semi-autonomous machine systems used in earth-moving and mining equipment
ISO/TR 23482:2021	Mining Autonomous machinery and equipment Safety requirements	Provides safety requirements for autonomous mining machinery and equipment, including AHS
ISO 19296:2018	Mining Mobile machines working underground Machine safety	Provides safety requirements for mobile underground mining machines, including those equipped with AHS
ISO/TS 50010:2017	Energy management systems Guidelines for the implementation, maintenance, and Improvement of an Energy management system	Provides guidelines for implementing and maintaining an energy management system for AHS and other mining equipment
ISO 50001:2018	Energy management systems Requirements with guidance for use	Specifies requirements for an energy management system for AHS and other mining equipment
IEC 61508:2010	Functional safety of electrical/electronic/programmable electronic safety-related systems	Provides general requirements for functional safety of electrical, electronic, and programmable electronic safety-related systems used in AHS and other mining equipment
IEC 61511:2016	Functional safety instrumented systems for the process industry sector	Specifies requirements for safety instrumented systems (SIS) for AHS and other mining equipment used in the process industry sector

3.9 Causes of hazards and examples of real events.

3.9.1. Causes of autonomous trucks' Hazards

The mining industry has developed safety standards to reduce the impact of potential hazards that are inside the mining activities like the Code of Practice for Safe Autonomous Mining in Western Australia (Department of Mines and Petroleum, 2015) and ISO 17757:2019 to address the risks associated with autonomous systems. While autonomous trucks can eliminate some human-related risks, they are still susceptible to other factors that can increase risk during operation, including ineffective maintenance, system security issues, software bugs, and improper calibration of sensor devices. (Tarek Gaber, 2021) (International Organization of Standardization, 2019)

Maintaining all the components and systems that contribute to safe operation is crucial to ensuring the safety of autonomous trucks. However, human interaction with these systems can also pose challenges, and the safety of autonomous trucks is often dependent on the inputs that drive their performance. (Tarek Gaber, 2021) Despite the potential for safer operation, it is important to note that other risks exist and must be managed to ensure safe mine operations.

One example of how technology is being used to enhance the safety of autonomous trucks is highlighted in the research paper "Real-Time Mine Road Boundary Detection and Tracking for Autonomous Truck," which presents a system for detecting and tracking mine road boundaries in real-time, which could help prevent collisions and improve overall safety. By implementing systems like this and following industry safety standards, it is possible to mitigate the risks associated with autonomous trucks and ensure the safe operation of mining operations. (Xiaowei Lu, 2020)

3.9.2. Case studies and examples of autonomous truck hazards and their consequences

- Fortescue Metals Group's Christmas Creek Iron Ore mine

Two autonomous trucks collided at BHP's Jimblebar mining hub in Western Australia due to heavy rainfall and two driverless trucks collided at Fortescue Metals Group's Christmas Creek iron ore mine, highlighting the potential hazards associated with autonomous trucks. (Casey, 2019)

As previously discussed, the causes of hazards associated with autonomous trucks include inadequate maintenance, system security issues, software bugs, and improper calibration of sensor devices. Additionally, communication issues and loss of connection between the truck and the control center can pose a risk during operation. (Tarek Gaber, 2021) (Xiaowei Lu, 2020)

- BHP's Jimbblebar Western Australia

In the case of the BHP incident, heavy rainfall made the roads slippery, and the two autonomous trucks collided despite operating at different speeds (Jamasmie, 2019). The Department of Mines, Industry Regulation and Safety (DMIRS) of the Western Australian Government issued a code of practice in 2015 for autonomous mining, but it did not provide specific guidance for heavy rainfall situations. DMIRS director of mine safety, Andrew Chaplin, stated that BHP had not limited the trucks' speed due to the unexpected rainfall and issued an improvement notice.

The Fortescue incident, on the other hand, was caused by a Wi-Fi outage that disrupted communication between the truck and the control center. Although Fortescue stated that the crash was not due to any failure in their autonomous haulage systems (AHS), it highlights the importance of effective communication and connectivity in ensuring the safe operation of autonomous trucks. (Tarek Gaber, 2021)

Such incidents demonstrate the need for effective hazard identification and risk management in the development and deployment of autonomous trucks in the mining industry. The safety of autonomous trucks relies on maintaining all the components and systems that contribute to their safe operation. The Code of Practice for Safe Autonomous Mining in Western Australia and international standards like ISO 17757:2019 guide risk assessment and management in autonomous systems. By adhering to these standards and implementing effective maintenance and communication protocols, the mining industry can mitigate the risks associated with autonomous trucks and ensure safe operations. (International Organization of Standardization, 2019)

3.9.3. Analysis of root causes and contributing factors in incidents and accidents

The hazards associated with autonomous trucks include inadequate maintenance, system security issues, software bugs, and improper calibration of sensor devices, among others (Tarek Gaber, 2021; Xiaowei Lu, 2020). Additionally, communication issues and loss of connection between the truck and the control center can pose a risk during operation (Tarek Gaber, 2021; Xiaowei Lu, 2020).

In the case of the Fortescue Metals Group's Christmas Creek iron ore mine, two autonomous trucks collided due to a Wi-Fi outage that disrupted communication between the truck and the control center. While Fortescue stated that the crash was not due to any failure in their autonomous haulage systems (AHS), it highlights the importance of effective communication and connectivity in ensuring the safe operation of autonomous trucks (Tarek Gaber, 2021).

Similarly, in the case of BHP's Jimblebar mining hub in Western Australia, heavy rainfall made the roads slippery, and two autonomous trucks collided despite operating at different speeds (Jamasmie, 2019). The Department of Mines, Industry Regulation and Safety (DMIRS) of the Western Australian

Government issued a code of practice in 2015 for autonomous mining, but it did not provide specific guidance for heavy rainfall situations. DMIRS director of mine safety, Andrew Chaplin, stated that BHP had not limited the trucks' speed due to the unexpected rainfall and issued an improvement notice.

In both incidents, inadequate hazard identification and risk management were the root causes of the accidents. The safety of autonomous trucks relies on maintaining all the components and systems that contribute to their safe operation. Effective hazard identification and risk management are essential in the development and deployment of autonomous trucks in the mining industry. This includes adherence to standards such as ISO 17757:2019, which guides risk assessment and management in autonomous systems, and implementation of effective maintenance and communication protocols to mitigate the risks associated with autonomous trucks (International Organization of Standardization, 2019).

Effective communication, training, and education are also crucial in managing hazards and risks associated with autonomous trucks. It is recommended that operators should have a deep understanding of the capabilities and limitations of autonomous systems and be trained to recognize and respond to malfunctions or hazards. The Code of Practice for Safe Autonomous Mining in Western Australia also emphasizes the importance of training and education in managing risks associated with autonomous systems (Department of Mines and Petroleum, 2015).

3.9.4. Lessons learned and best practices for hazard and risk management in autonomous truck operations.

Lessons learned from past incidents and accidents can inform best practices for hazard and risk management in autonomous truck operations.

1.) Effective Communication and Training Programs: Effective communication and training programs are critical to prevent accidents and fatalities in autonomous truck operations. Operators should have a deep understanding of the capabilities and limitations of autonomous systems and be trained to recognize and respond to malfunctions or hazards. The Code of Practice for Safe Autonomous Mining in Western Australia recommends regular training and assessment of autonomous system operators to ensure their competency in the safe operation of the equipment (Department of Mines, Industry Regulation and Safety, 2021).
2.) Regular Maintenance and Inspection Regular maintenance and inspection of autonomous trucks and their components can prevent equipment failures and reduce the likelihood of accidents. The Code of Practice for Safe Autonomous Mining in Western Australia

recommends regular maintenance and inspection of autonomous equipment, including sensor devices and communication systems (Department of Mines and Petroleum, 2015). Similarly, Autonomous Haulage Systems in the Mining Industry: Cybersecurity, Communication and Safety Issues and Challenges highlights the importance of regular maintenance and inspection of autonomous trucks to ensure their safe and reliable operation (Xiaowei Lu, 2020).

3.) Effective Risk Assessment and Management Effective risk assessment and management are essential for identifying and mitigating hazards and risks associated with autonomous truck operations. The ISO 17757:2019 standard provides guidelines for risk assessment and risk management in autonomous mining equipment (International Organization for Standardization, 2019). Additionally, the Code of Practice for Safe Autonomous Mining in Western Australia recommends a risk management plan that includes a hazard identification process, risk assessment, and risk mitigation strategies (Department of Mines, Industry Regulation and Safety, 2021).

4.) Continuous Improvement and Evaluation Continuous improvement and evaluation of hazard and risk management strategies can help to identify areas for improvement and optimize safety performance. The Code of Practice for Safe Autonomous Mining in Western Australia recommends regular evaluation and improvement of autonomous system safety performance (Department of Mines, Industry Regulation and Safety, 2021). Similarly, Surface Mining: Main Research Issues for Autonomous Operations highlights the need for continuous evaluation and improvement of autonomous mining systems to ensure their safe and efficient operation (Xiaowei Lu, 2020).

3.10 International standards related to the implementation of autonomous trucks.

3.10.1. Overview of international standards related to the implementation of autonomous trucks in open pit mines.

ISO 17757:2019 specifies safety requirements for autonomous machines and semi-autonomous machines (ASAM) used in earth-moving and mining operations, and their autonomous or semi-autonomous machine systems (ASAMS). It guides safe use in their defined functional environments during the machine and system life cycle, specifying safety criteria for machines and their associated systems and infrastructure, including hardware and software. The document applies to autonomous and semi-autonomous versions of the earth-moving machinery defined in ISO 6165 and of mobile mining machines used in either surface or underground applications. It does not apply to remote control capability or function-specific automated features, except when those features are used as part of ASAMS (International Organization of Standardization, 2019).

ISO 21448:2022 guides measure to ensure the safety of the intended functionality (SOTIF) of road vehicles. It specifies applicable design, verification, and validation measures and activities during the operation phase to achieve and maintain SOTIF. The document applies to intended functionalities where proper situational awareness is essential to safety and where such situational awareness is derived from complex sensors and processing algorithms, especially functionalities of emergency intervention systems and systems having levels of driving automation from 1 to 5 (International Organization of Standardization, 2022). ISO 21448:2022 is also applicable to intended functionalities that include one or more E/E systems installed in series production road vehicles, excluding mopeds. However, it does not apply to faults covered by the ISO 26262 series, cybersecurity threats, hazards directly caused by the system technology, and hazards related to electric shock, fire, smoke, heat, radiation, toxicity, flammability, reactivity, the release of energy, and similar hazards, unless directly caused by the intended functionality of E/E systems (International Organization for Standardization, 2018).

IEC 62061:2021 specifies requirements and recommendations for the design, integration, and validation of safety-related control systems (SCS) for machines. It applies to control systems used to carry out safety functions on machines that are not portable by hand while working, including a group of machines working together in a coordinated manner. The document is a machinery sector-specific standard within the framework of IEC 61508 (all parts). It is concerned only with functional safety requirements intended to reduce the risk of hazardous situations, and it is restricted to risks arising directly from the hazards of the machine itself or from a group of machines working together in a coordinated manner (International Electrotechnical Commission, 2021).

AS/NZS 62061:2019 specifies requirements and recommendations for the design, integration, and validation of safety-related electrical, electronic, and programmable electronic control systems (SRECS) for machines. The standard specifies the safety requirements for SRECS that perform safety functions for machines that are not portable by hand while working, including a group of machines working together in a coordinated manner (ANSI, 2019). AS/NZS 62061:2019 is intended to be used in conjunction with ISO 12100:2010, which specifies general principles for the design and risk assessment of machinery and the requirements for technical documentation (International Organization for Standardization, 2010).

These international standards are essential for the implementation of autonomous trucks in open-pit mines. They provide a framework for the design, integration, and validation of safety-related control systems, specifying the safety requirements for autonomous machines and their associated systems and infrastructure, including hardware and software. These standards help to ensure that autonomous trucks are safe and reliable for use in mining operations, reducing the risk of hazards and accidents.

3.10.2. Comparison of international standards across different countries

International standards related to autonomous trucks in open pit mines provide a framework for safe implementation and operation. However, different countries may have different regulations and guidelines in place. This section compares the standards of four different countries: Australia, the United States, Canada, and the European Union.

MSHA Guidelines: The Mine Safety and Health Administration (MSHA) is a US federal agency that is responsible for promoting the health and safety of miners. MSHA has published guidelines for autonomous mining systems that provide recommendations for design, testing, and implementation. These guidelines cover topics such as risk assessment, hazard controls, communication systems, training, and emergency procedures. The guidelines emphasize the importance of ensuring that the system is safe for all workers, including those who are not directly involved in operating the system. (Mine Safety and Health Administration, 2006)

ISO 17757:2019: This is an international standard that provides safety requirements for autonomous and semi-autonomous machines used in earth-moving and mining operations, and their associated systems and infrastructure. It guides safe use in their defined functional environments during the machine and system life cycle. The standard specifies safety criteria for the machines and their associated systems and infrastructure, including hardware and software. It also defines terms and definitions related to autonomous and semi-autonomous machines. (International Organization of Standardization, 2019)

Regulation (EU) 2018/858: This is a European Union regulation that establishes requirements for the type-approval of motor vehicles and their trailers, as well as systems, components, and separate technical units intended for such vehicles. This regulation includes provisions for the approval of automated vehicles, including requirements for functional safety, cybersecurity, and data protection (REGULATION (EU) 2018/858 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2018).

Safety perspective and AHS implementation, all the standards focus on ensuring the safety of workers and the public when implementing autonomous mining systems. They provide guidelines and requirements for risk assessment, hazard controls, and emergency procedures. They also address specific safety concerns related to autonomous systems, such as system security issues, software bugs, and improper calibration of sensor devices. The standards also emphasize the importance of proper maintenance and training for workers who interact with autonomous mining systems.

Table 17 Comparison of some of the key features of the standards

Standard	Scope	Key Requirements/Recommendations
MSHA Guidelines	US-specific	Risk assessment, hazard controls, communication systems, training, emergency procedures
ISO 17757:2019	International	Safety criteria for autonomous and semi-autonomous machines and their associated systems and infrastructure
Regulation (EU) 2018/858	European Union-specific	Type-approval requirements for automated vehicles, including functional safety, cybersecurity, and data protection

The main reason for creation: The main reason for the creation of these standards is to provide a framework for ensuring the safe operation of autonomous mining systems. The use of these systems introduces new risks that are not present in traditional mining operations, and it is essential to ensure that these risks are adequately managed.

Health and safety information: All the standards provide information about health and safety issues related to the machinery used in mining operations. They address specific hazards, such as the risks associated with operating heavy machinery, and guide how to minimize those risks.

Information about the implementation of autonomous vehicles: All the standards provide information about the implementation of autonomous vehicles in mining operations. They provide guidelines for risk assessment, hazard controls, and emergency procedures. They also address specific safety concerns related to autonomous systems, such as system security issues, software bugs, and improper calibration of sensor devices. The standards emphasize the importance of proper maintenance and training for workers who interact with autonomous mining systems.

3.11 Simulation model development

Upon a thorough review of the existing literature on autonomous vehicle implementation in open-pit mines, selection of the appropriate software for discrete event simulation (DES) model development, and identification of its limitations, the project is now set to discuss the process of model development.

This review not only enlightened us on the hazards that come with autonomous vehicle implementation but also outlined international standards to be adhered to during the implementation process. This section will provide a detailed overview of the DES model development process, guided by the insights gathered thus far.

3.11.1. Conceptual model development

The conceptual model developed in this thesis is based on a standard loading and hauling system (Shovel-Truck system) used in most open-pit mining projects in the world. In open pit mining operations, the loading and hauling stage plays a crucial role in the overall production of the mine. This stage determines the production rate that the mining operation can achieve, often serving as a limitation or bottleneck in the open pit mining value chain (Ignacio Andrés Osses Aguayo, 2021). The loading-and-hauling stage involves the movement of previously fragmented materials, following the drilling and blasting process. The first step is to load the material from the bench or working face of the mine into trucks. Subsequently, the material is transported to its destination, such as a stockpile, waste dump, or processing plant, via a specially designed haul road that spirals up the pit walls (Ignacio Andrés Osses Aguayo, 2021).

The most common system for the loading and hauling stage in open pit mining is the Shovel-Truck system (ST). This system involves a shovel that loads blasted material into a truck, which then transports the material to its destination for unloading. The truck then returns to the shovel, and the cycle repeats as is shown in Figure 5. The Shovel-Truck system has been widely implemented in mining operations due to its simplicity, reliability, flexibility, and effectiveness (Ignacio Andrés Osses Aguayo, 2021).

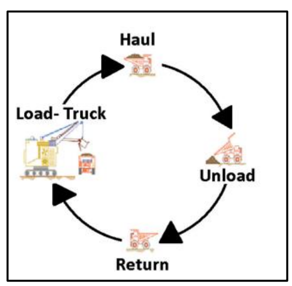

Figure 4 Cycle of Shovel-Truck System (Ignacio Andrés Osses Aguayo, 2021)

Regarding the simulation, the conceptual model will include a comprehensive representation of the truck haulage system. This model will consist of a main model with several interconnected sub-models that are activated by a percentage of chances that could happen in a regular haulage schedule cycle. The main model contains the logical process that the trucks will apply in the mine, as can be seen in Figure 6.

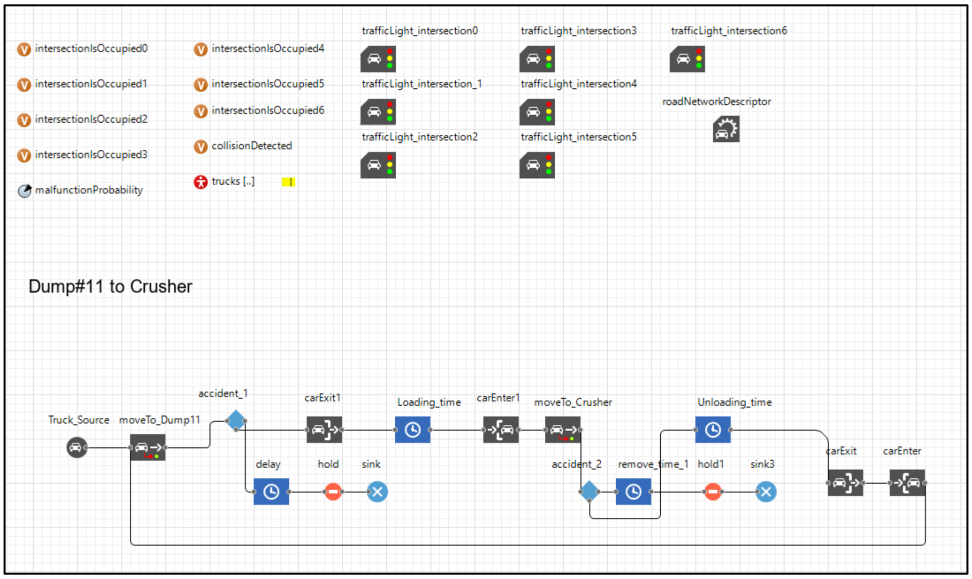

Figure 5 Main flowchart dumping and loading system in Anylogic.

- The logic flowchart begins with the "Truck Source" block, which generates a predetermined number of trucks for each mining cycle. To simulate realistic conditions, the production rate of trucks is regulated to maintain a safe distance between each vehicle. Additionally, each truck is assigned a specific initial speed, maximum acceleration, and maximum deceleration parameters.
- The "Move To" block, within the "Car Move to" section, represents the movement of trucks towards their designated locations. This block contains various actions that each truck will perform, which will be further explained in subsequent chapters of the thesis.
- Following the movement logic, the simulation evaluates accident conditions using the "Select Output" block. This block determines the outcome based on whether the accident condition is true or false. If a collision occurs, trucks near the intersection will reduce their speed and eventually come to a stop, while the trucks involved in the collision will be removed from the simulation.
- If no accidents occur, the trucks proceed to the loading and unloading bays. The "Car Exit" and "Car Enter" blocks are responsible for animating the trucks as they transition between different lanes.
- The loading and unloading processes are represented by the "Delay" blocks, which simulate the estimated time required for these operations to be completed.

This entire process is then repeated for the unloading cycle, continuing until the simulation time reaches its designated end.

3.11.2. Model structure development

The primary focus of the simulation model is to accurately capture the truck-shovel interaction and the interaction between trucks themselves.

The truck-shovel interaction will be simulated by modeling the loading and unloading process, where the shovel loads material into the trucks from the bench or from one of the stockpiles, then the truck will travel to the crusher or directly to one of the dump areas designates by the company. This process will consider factors such as loading and unloading time, loading capacity, and the availability of the shovel. Additionally, the simulation will incorporate variations and uncertainties that can affect the loading processing process, such as the impact of irregular stops because of trucks and shovel failures or breakdowns, and regular stops as shift change and lunchtime.

At the same time, the model will simulate the interaction of trucks with each other and another auxiliary vehicle during the haulage process. This includes modeling factors like travel time, speed, traffic rules, and the capacity of the trucks. Interactions such as overtaking, queuing, and coordination between trucks will be considered in the simulation to capture the dynamics and performance of the overall haulage system.

Develop data from the mining company that will be utilized to accurately represent the truck-shovel and truck-truck interaction will include cycle time, haulage string, and topographic information. By integrating this data into the simulation model, a realistic and reliable representation of the haulage cycle can be achieved.

The HAULSIM software, chosen for this study, provides advanced modeling capabilities specifically designed for simulating open-pit mining operations. Its features enable modeling various entities, processes, and interactions within the haulage system, allowing for a detailed representation of the truck-shovel and truck-truck interactions. By leveraging the capabilities of HAULSIM, the simulation model can accurately capture the complexities and dynamics of the haulage cycle.

3.11.3. Data input in HAULSIM

The data provided by the company includes specific information necessary for the simulation. This includes the cycle time data for the months of June and July, which represents the planned and actual haulage times for the trucks as shown in Table 18 and Table 19. These cycle time data points are essential for modeling the performance of the haulage system and evaluating its efficiency and productivity.

Table 18 June Haulage

June					
Cycle Time	Sources				
Sinks	#11 Dump	RW4 6500	RW5 6550	Stockpile	Grand Total
#11 Dump			29.90		29.90
16_MF Stockpile			22.20		22.20
7_Liberty MF Stockpile			45.46		42.09
Crusher	20.87		36.26	15.15	22.67
RE 6700 Dump		29.28	23.54		23.55
Stockpile			35.35		35.13
Keystone Dump			30.26		30.26
CPad Dump		31.72	29.88		29.88
Grand Total	20.87	31.09	28.47	15.15	27.17

Table 19 July Haulage

July								
Cycle Time	Sources							
Sinks	#11 Dump	7_Liberty MF Stockpile	7B_Stockpile	RW4 6500	RW5 6500	RW5 6550	Stockpile	Grand Total
#11 Dump					29.83	30.79		30.28
7_Liberty MF Stockpile					45.45	50.53		47.99
7B_Stockpile					47.33			47.33
Crusher	23.87	13.51	17.22		38.41	36.54	15.25	22.23
RE 6700 Dump				22.59	23.61	24.19		23.93
Stockpile					33.95	37.63		34.42
CPad Dump				28.28	30.06	31.26		30.37
Keystone Dump		29.35	42.82		34.50	34.18		34.45
Grand Total	23.87	13.61	18.24	23.59	29.77	28.21	15.25	27.75

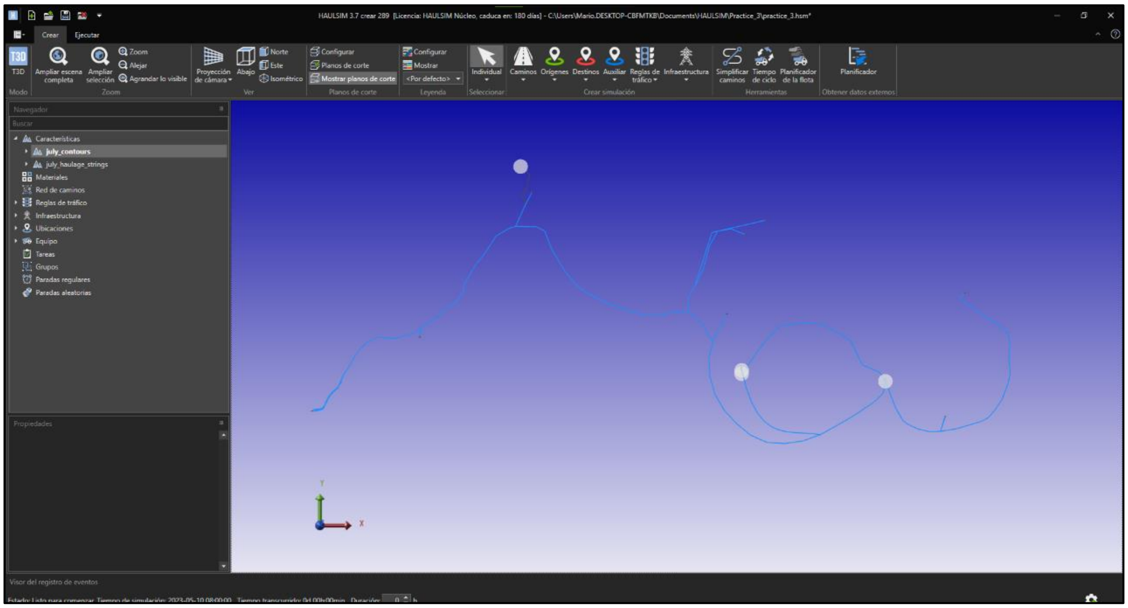

Figure 6 June haulage string file

The simulation leverages a string file obtained from the mining company, which serves as a digital representation of the roads or haulage routes utilized by the trucks within the mine during the months of June and July, as depicted in Figure 7. This string file offers valuable insights into the layout and connectivity of the road network, enabling the simulation model to faithfully replicate the movements and interactions of the trucks.

In addition to the string file, an elevation model in the form of a topographic file is integrated into the simulation. This topographic file accurately captures the mine's terrain and layout during the specified period of June and July, as illustrated in Figure 8. By incorporating this topographic information, the simulation model gains a spatial reference that facilitates the precise placement of various entities, such as the loading and dumping locations, within the virtual mine environment.

The utilization of these data files, namely the string file for road representation and the topographic file for terrain mapping, enhances the realism and accuracy of the simulation. By faithfully replicating the actual road network and mine layout, the simulation model can provide valuable insights into the behavior and performance of autonomous trucks operating in the real-world mining context.

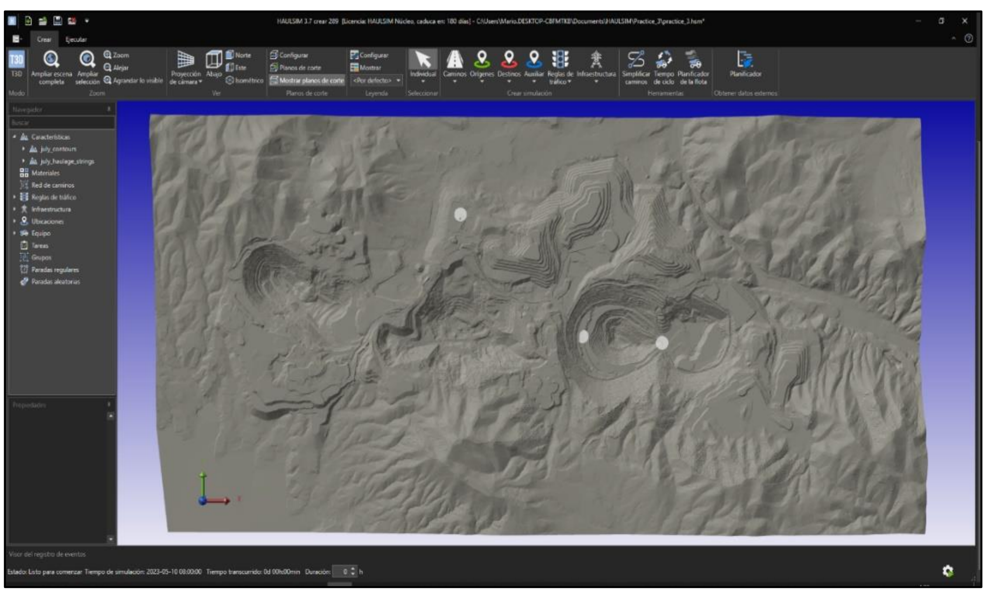

Figure 7 Topography of the mine

Merging both files for the month of June, with the sources information of dump, stockpile, and crushers it will look like it's shown in Figure 9.

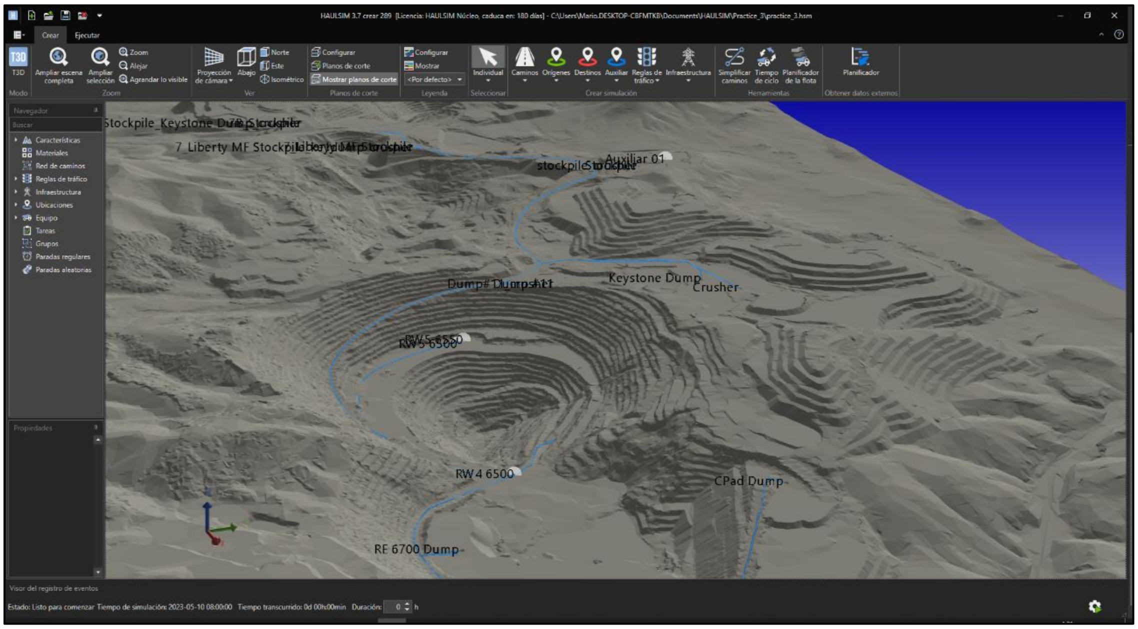

Figure 8 Mine layout

In terms of fleet and equipment information, data on the fleet of trucks (Komatsu 930 E-4SE) and loading equipment

(Komatsu P&H 2800) was assume. This information includes specifications, capabilities, and performance characteristics of the equipment, which are critical for the accurate representation of their behavior in the simulation model. The shift schedule for the mining operation was assumed to be a 3-shift schedule with 30 minutes allocated for breaks and 30 minutes for shift changes. This information is important for modeling the timing and availability of the trucks and operators during the simulation.

The mine production target was defined based on the available fleet size of 20 Komatsu 930 E-4SE trucks. The average cycle time of 33.19 minutes and a productivity rate of 87.5% were considered in setting the production target, which equates to 21 productive hours.

3.11.4. Calculations for the simulation Haulsim

To conduct the simulation, several calculations and parameters need to be determined to establish the baseline for the mine simulation. These calculations and parameters will serve as the foundation for modeling the open pit mine operations using the selected simulation software, as it is shown in Table 20. The following key factors will be considered in the simulation:

Table 20 Factors for the Simulation

	Value	Unit
Fleet information:	20	
Loading Equipment:	3	
Equipment productivity:	87.5	**%**
Average Cycle Time:	0.55	**hr**
Bucket Capacity:	290	**Tons**
Number of Journeys:	38	
Tons transported	11,009	**tons / cycle**
Goal production:	220,187	**tons/day**

- Fleet Information: The number of trucks in the fleet will be a crucial parameter for the simulation. It will determine the availability and capacity of the trucks for the haulage operations.
- Loading Equipment: The number of shovels or loading equipment will also be considered in the simulation. This parameter determines the availability and capacity of the loading equipment for loading the trucks.
- Equipment Productivity: The number of working hours per day for the equipment will be a significant factor in the simulation. It represents the operational time available for loading and hauling operations, considering 3 shifts of 7 hours then the productivity calculation will be the following:

$$Equipment\ productivity = \left(\frac{number\ of\ working\ hours\ in\ a\ day}{number\ of\ hours\ in\ a\ day}\right) * 100\% \qquad 1$$

$$Equipment\ productivity = \left(\frac{21\ hr}{24\ hr}\right) * 100$$

- Average Time per Cycle: This parameter represents the time it takes for a truck to complete one full cycle, including loading, transportation, and unloading. The average time per cycle is derived from the total provided by the mining company. It accounts for factors such as travel distance, rolling resistance, ground structure, maximum speed (full and empty), and loading/unloading time.

$$Average\ Cycle\ time = \left(\frac{Averga\ time\ of\ the\ grand\ total\ (min)}{60\ hr}\right) \qquad 1$$

$$Average\ Cycle\ time = \left(\frac{33.19\ min}{60\ min}\right)$$

- Bucket Capacity: The capacity of the truck's bucket, which determines the amount of material it can carry in one cycle, will be considered in the simulation. This parameter is an essential characteristic of the trucks and will be obtained from the manufacturer's specifications or mine records.

- Number of Trips: The number of trips a truck can make during the working hours of the day will be calculated based on the average time per cycle and equipment productivity. This calculation considers the available working hours and the time required for each cycle.

$$Number\ of\ Journeys = \left(\frac{productivity\ working\ hours}{Average\ Cycle\ time}\right) \quad 2$$

$$Number\ of\ Journeys = \left(\frac{21\ hr}{0.55}\right)$$

- Tons Transported: This calculation determines the amount of material transported by each truck in one cycle, considering the bucket capacity and the material density. It helps in evaluating the efficiency and productivity of the haulage operations.

$$Tons\ transported = \left((number\ of\ journeys) * (bucket\ capacity)\right) \quad 3$$

$$Tons\ transported = \left((38) * (290\ tons)\right)$$

Goal Production: The goal production represents the target amount of material that is expected to be produced per day in the open pit mine. This value is derived from the mine production plan and serves as a reference for evaluating the performance of the simulated operations.

$$Goal\ Production = \left((number\ of\ trucks) * (tons\ transported)\right) \quad 4$$

$$Goal\ Production = \left((20) * (11{,}009\ tons/cycle)\right)$$

These calculations and parameters serve as the initial inputs for the simulation model. Other variables or parameters that may influence the simulation results, such as road conditions, traffic congestion, or system failures, will be set to default values provided by the simulation software unless specific data or historical records are available for accurate representation.

3.11.5. Parameters for AnyLogic

To ensure accurate visualization and calculations in the simulation, several parameters need to be defined in AnyLogic. These parameters are specifically tailored for an open pit mine located in a

Table 21 Parameters for Anylogic

	Value	unit
Initial Speed	8	**km/hr**
Preferred Speed	25	**km/hr**
Max acceleration	1	**m/s^2**
Max deacelaration	1.5	**m/s^2**
Loading time	240	**seconds**
Unloading time	60	**seconds**

desert environment, where safe truck driving, effective dust control, and clear signage are crucial. These considerations are essential for the development of a realistic and reliable simulation. The following table presents the key parameters for the simulation:

These parameter values are based on typical mining operations in desert conditions, which is where the mine is located. However, it is important to note that these values should be further refined and adjusted according to the specific characteristics and requirements of your mine.

3.11.6. Data input in AnyLogic

In the AnyLogic model, the professional version offers advanced capabilities, including the ability to utilize the CAD Drawing option. This functionality allows for the importation of a string file from HAULSIM, which contains the necessary information about the haulage routes in the mine. The imported file includes nodes located at the end of each line, which represent the specific destinations for the mine haulage.

Figure. 10 showcases the main working area within the AnyLogic software, providing a visual representation of the interface used for model development and analysis.

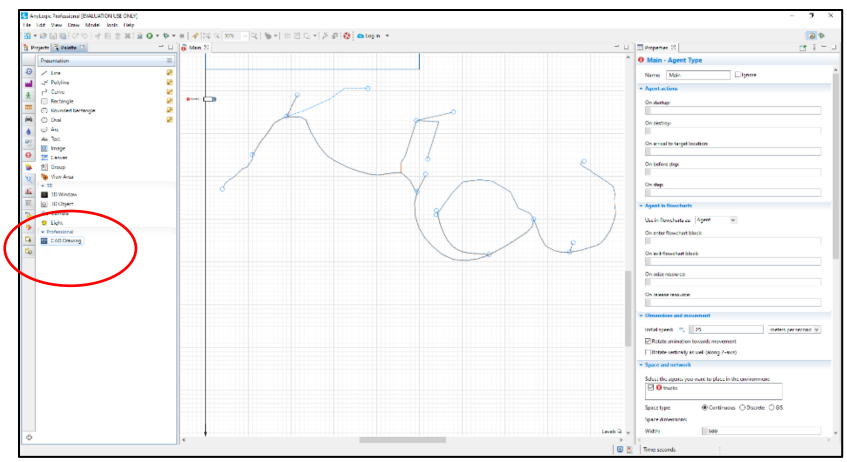

Figure 9 Mine haulage string file

Following the data import from the mining company, the next step involved incorporating the nodes that signify the destinations to which the trucks are required to reach within the simulation. Subsequently, the agent data to be transported throughout the simulation was integrated. Once the preliminary logic was designed as outlined previously, the simulation was deemed ready to commence its execution.

Another input used for the development of the simulation in Anylogic was the times in each cycle in the month of June, as shown in Table 18.

3.11.7. Model development HAULSIM

After importing the input data as described in the previous sections, the simulation model was developed step by step in HAULSIM software. The following key steps were taken to configure and create the model:

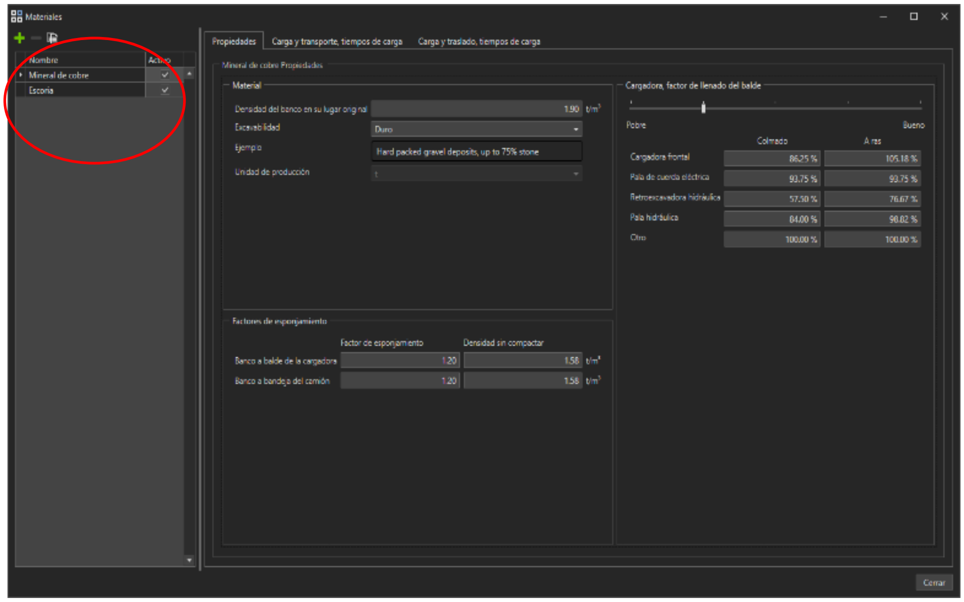

Figure 10 Material selection

1. Definition of Transported Materials: The materials transported in the open pit mine, including blasted ore and waste, were defined in the simulation model, as it is shown in Figure 11. These materials are essential for accurately representing haulage operations. The properties of the minerals, such as density and other characteristics, were configured based on default values provided by the software, ensuring a realistic representation of the materials.

2. Configuration of Road Network: The imported string format file representing the road network was edited to create a connected network of nodes. This step involved importing the string file into the software and then exporting it in CSV format to obtain the coordinates of the loading and unloading points, as it is shown in Figure 12. These loading and unloading points are crucial for the simulation, as they represent the key locations in the haulage cycle. Additionally, characteristics such as rolling

StringId	X	Y	Z	Rolling Resistance	Ground Structure	Maximum Speed Full (Fwd)	Maximum Speed Empty (Fwd)	Maximum Speed Full (Rev)	Maximum Speed Empty (Rev)
1	112542.324	100951.652	6700	2	0	100	100	100	100
1	112952.727	101020.854	6740	2	0	100	100	100	100
2	112542.324	100951.652	6700	2	0	100	100	100	100
2	112244.123	100940.428	6670	2	0	100	100	100	100
3	112542.324	100951.652	6700	2	0	100	100	100	100
3	112647.844	101320.615	6700	2	0	100	100	100	100
4	112542.324	100951.652	6700	2	0	100	100	100	100
4	112647.844	101320.448	6740	2	0	100	100	100	100
5	112542.324	100951.652	6700	2	0	100	100	100	100
5	112952.727	101020.854	6740	2	0	100	100	100	100

Figure 11 Road network output file

resistance, ground structure, and maximum speed (full and empty) were assigned to each road segment, ensuring an accurate representation of the road conditions.

3. Placement of Loading and Unloading Points: The location of the loading points within the pit and the unloading points (dump, stockpile, or crusher) was specified in the simulation model, as it is shown in Figures 13 and 14. These points define the destinations for the trucks and play a vital role in the overall haulage operations. Proper placement of these points ensures realistic routing and movement of the trucks in the model.

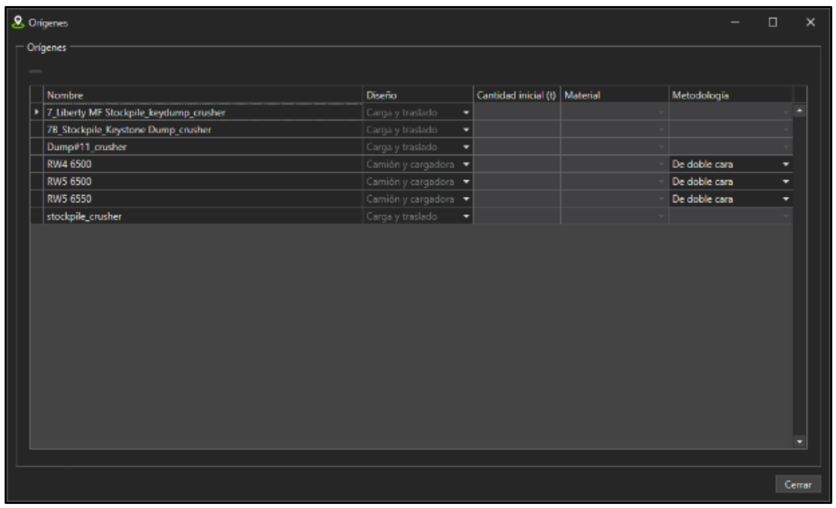

Figure 12 Loading point setup

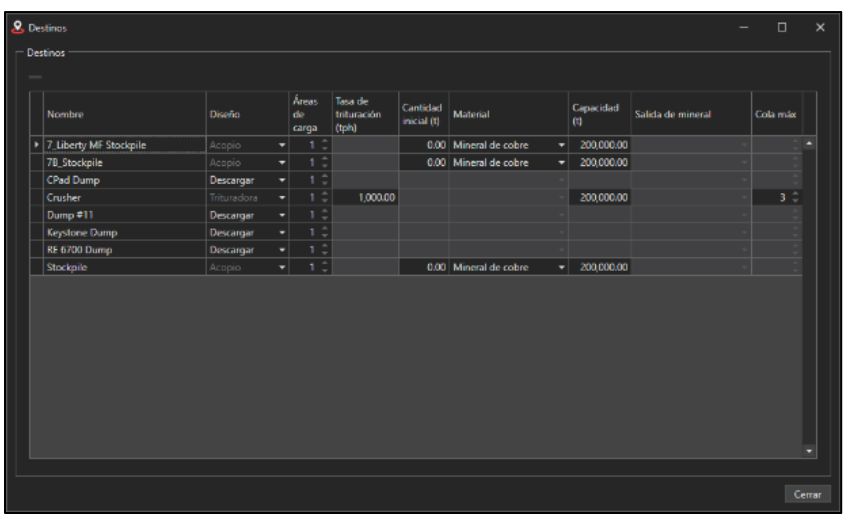

Figure 13 Unloading point setup.

4. Task Assignment: The simulation model required the assignment of tasks to the trucks. This

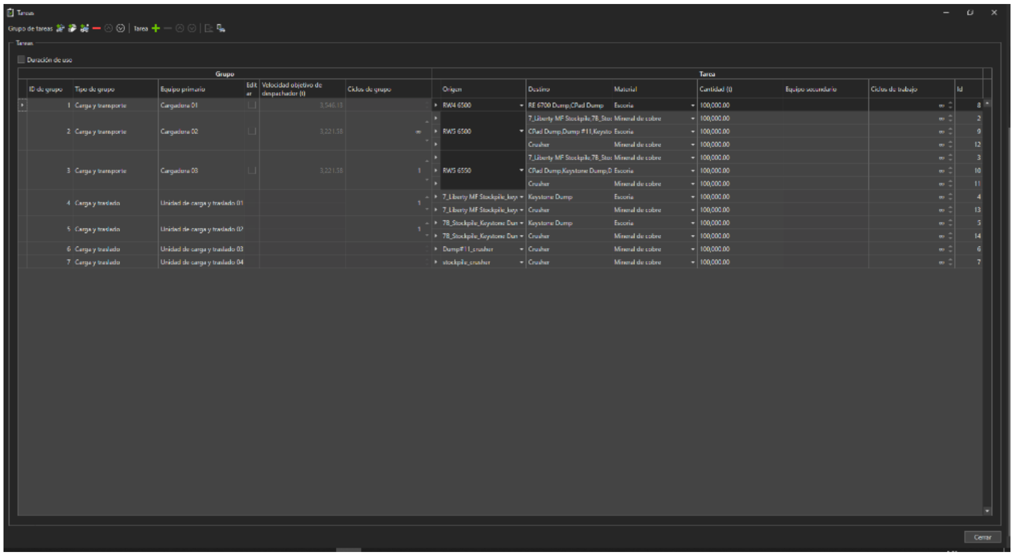

Figure 14 Task assignment

involved specifying the sequence of actions for the trucks, including their origin, loading points, destinations, materials to be carried, and the corresponding quantities. The work cycles, which represent the activities performed by the trucks in each shift, were also defined. These task assignments ensure that the trucks follow the designated routes and perform the required actions during the simulation, as it is shown in Figure 15.

5. Incorporation of Regular Stops: Regular stops, such as lunch breaks and shift changes, were incorporated into the model. The lunch break was assigned a duration of 30 minutes, allowing for a realistic representation of the work schedule. Similarly, the shift change was also allocated 30 minutes to account for the necessary transition between shifts, as it is shown in Figure 16.

By following these steps, the simulation model in HAULSIM was successfully developed, incorporating the essential elements of the haulage cycle, road network, loading and unloading points,

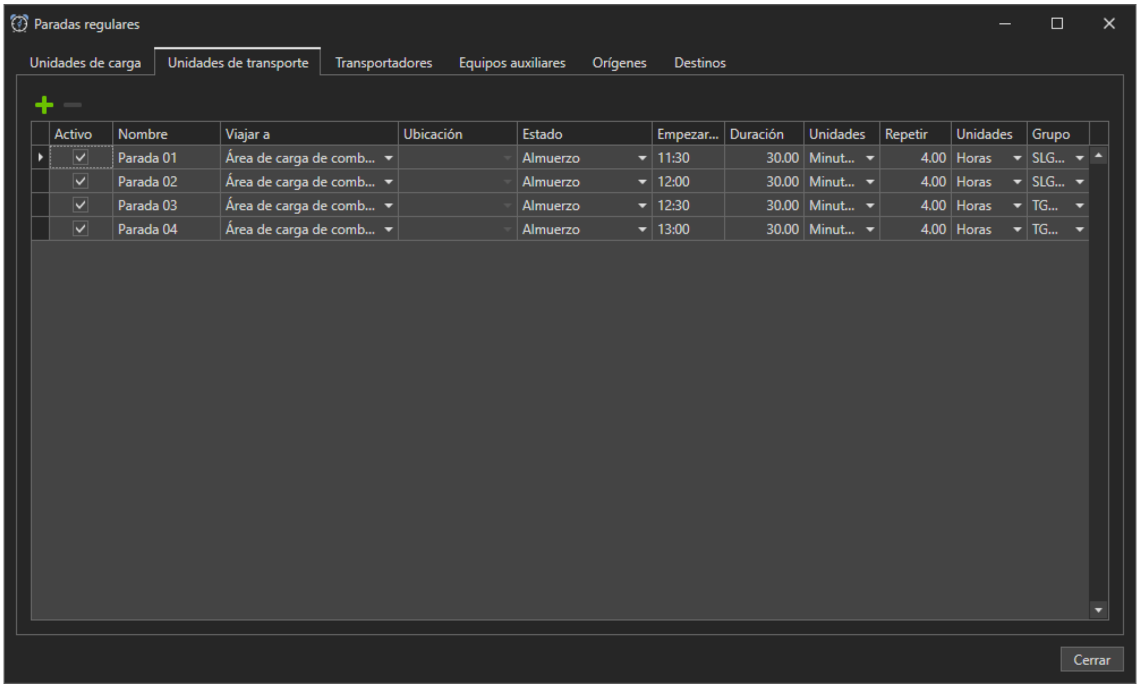

Figure 15 Regular Stops

task assignments, and regular stops. This comprehensive model enables a detailed analysis of haulage operations and provides valuable insights into the performance and efficiency of the autonomous haulage system.

3.11.8. Model development AnyLogic

The model developed in AnyLogic involved the creation of a simulation model that accurately represents the haulage system in the non-autonomous mine. AnyLogic was chosen for its capabilities to simulate accidents, collisions, and other hazardous scenarios, complementing the functionalities of HAULSIM. The development process can be summarized as follows:

Data Import and Node Integration: The initial step was to import the relevant data provided by the mining company. This included information on haulage routes, destinations, and agent characteristics. The nodes representing the destinations to which the trucks must arrive were added to the model, ensuring an accurate representation of the mining operation, Figure 17.

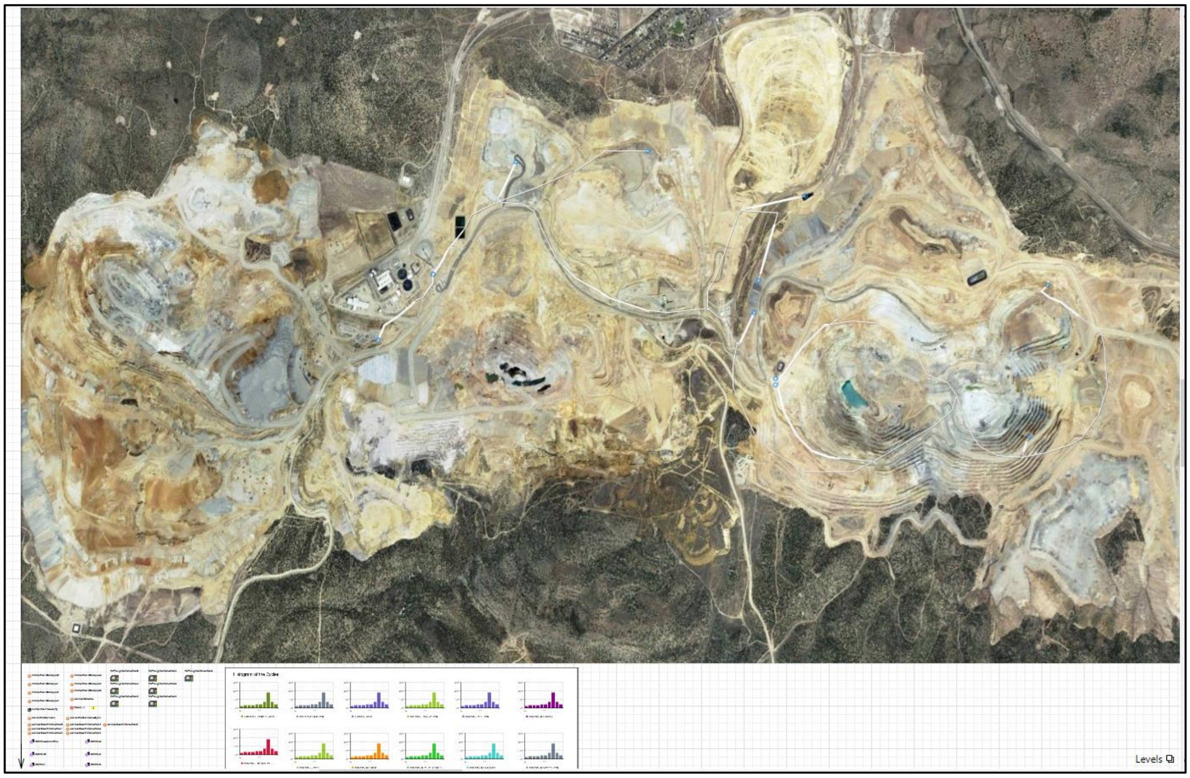

Figure 16 Satellite Image from Google, merged with the string file imported from HAULSIM.

Logic Design: The logic of the simulation model was carefully designed to capture the key aspects of the haulage system. This involved considering factors such as truck movement, delays, accident probabilities, statistical data recollection of collisions per intersection, cycle time measurement, statistical data recollection, and queue management at loading and unloading areas. The model was developed with a focus on replicating the operational dynamics and challenges of the non-autonomous mine, Figure 17.

In the logical cycle (outlined in Chapter 3.10.4), there exist variables named "IntersectionIsOccupied". These boolean variables serve as a marker, indicating whether or not a vehicle occupies an intersection. Initially, at the start of the simulation, these variables are set to "false", denoting that the intersections are free of vehicles, as it is shown in Figure 18.

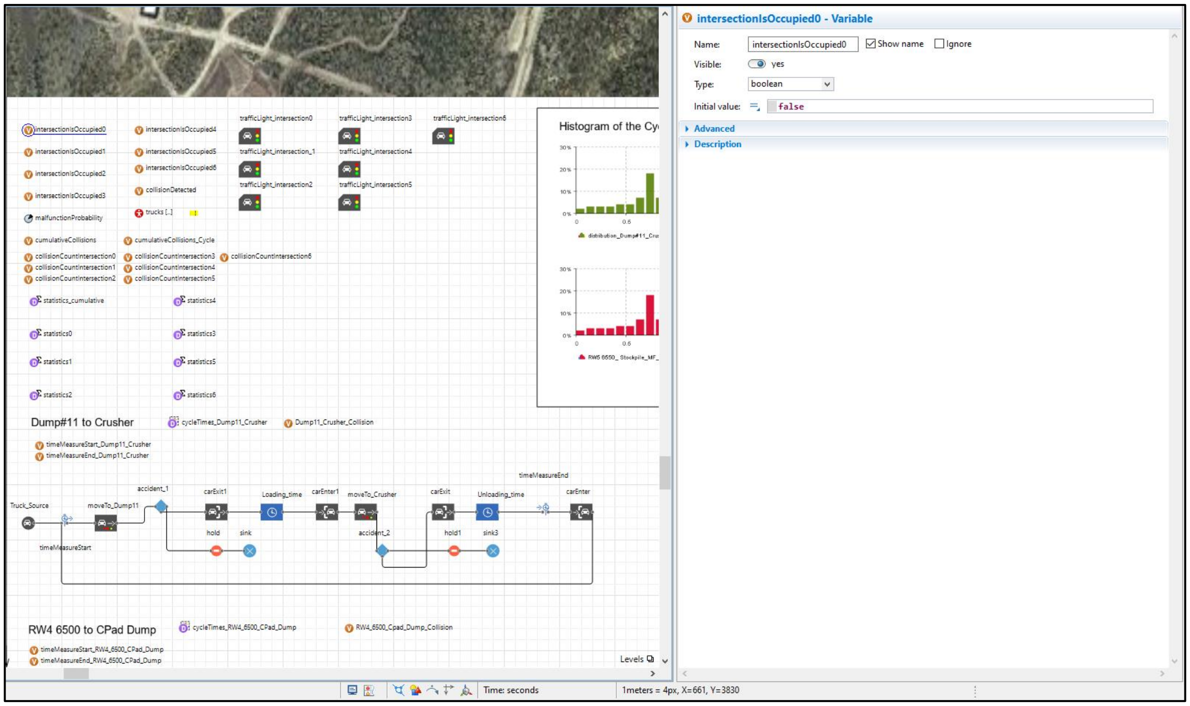

Figure 17 Variables and the logic flowchart in Anylogic

After establishing the main parameters to control the flow of interactions between vehicles at intersections, the production of trucks (agents) begins at the "source." The trucks are generated at specific times to maintain a safe distance between each vehicle. Additionally, their production order is determined by their predetermined cycle. All trucks share common characteristics such as initial speed, preferred speed, maximum acceleration, and maximum deceleration. These parameters can also be customized based on specific requirements.

In the simulation, the trucks produced at the source are initially not associated with any intersection. To represent this, the variable "intersectionIsOccupied" is defined with “false” as the initial value, as it is shown in Figure 19 Each truck is assigned a code for the intersection it will interact with during each cycle. These variables and codes are embedded within the actions performed by the trucks (agents) to regulate their behavior within the simulation.

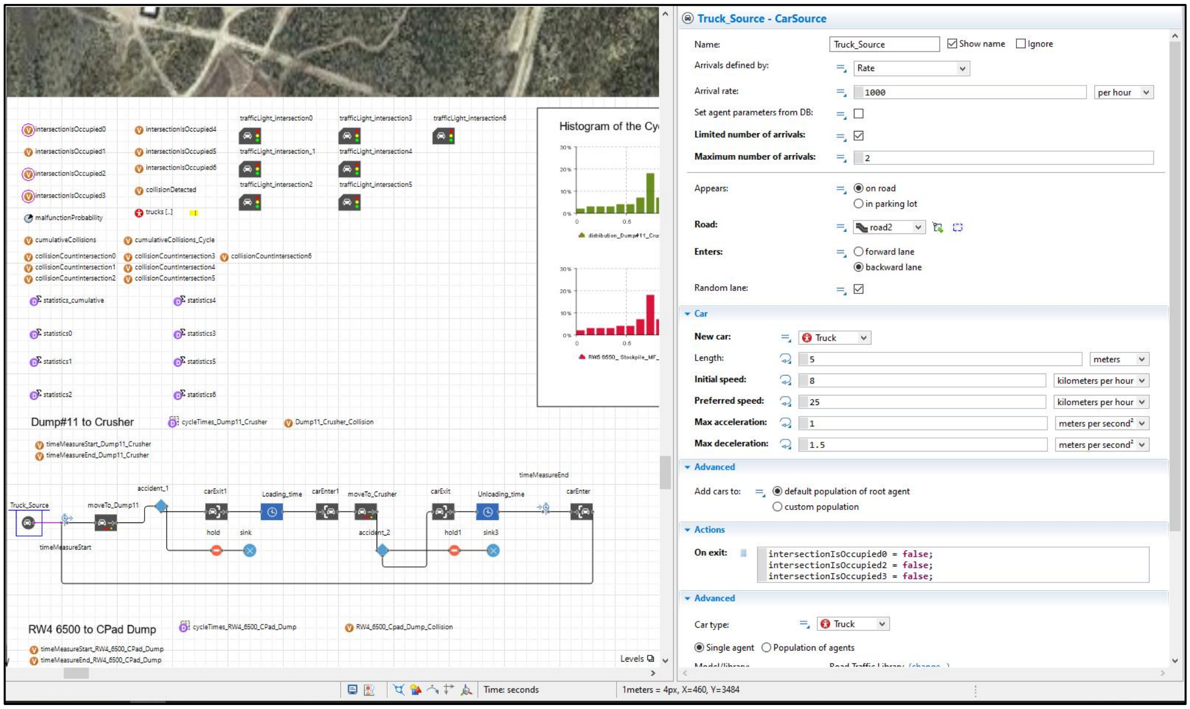

Figure 18 Truck source logic with the codes

It is visible that when the truck source block is selected the variables that will be affected by conditions in the code have a purple circle around them.

To accurately measure the number of loading and unloading cycles during a typical working day, the simulation incorporates "time measurement" blocks. These blocks function as counters that start and

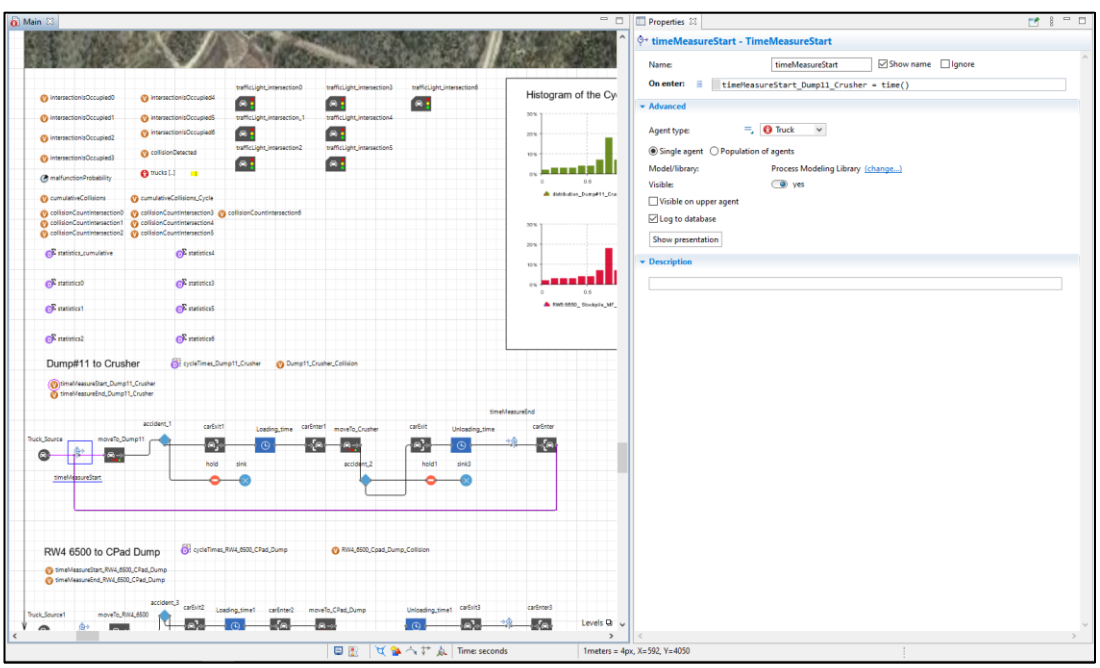

Figure 19 Time measurement blocks, and their relationship with the code for the cycle counter

stop at the beginning and end of each haulage cycle within the mine. By assigning these counters to specific variables, the simulation can effectively keep track of the completed cycles.

In terms of truck movement, the "moveTo" block plays a crucial role by issuing commands that direct the trucks to their intended destinations Figure 20. This block ensures that the trucks follow a predetermined path and adhere to the desired sequence of actions. By coordinating the movement of trucks through the simulation, the "moveTo" block contributes to the realistic representation of the mining operation.

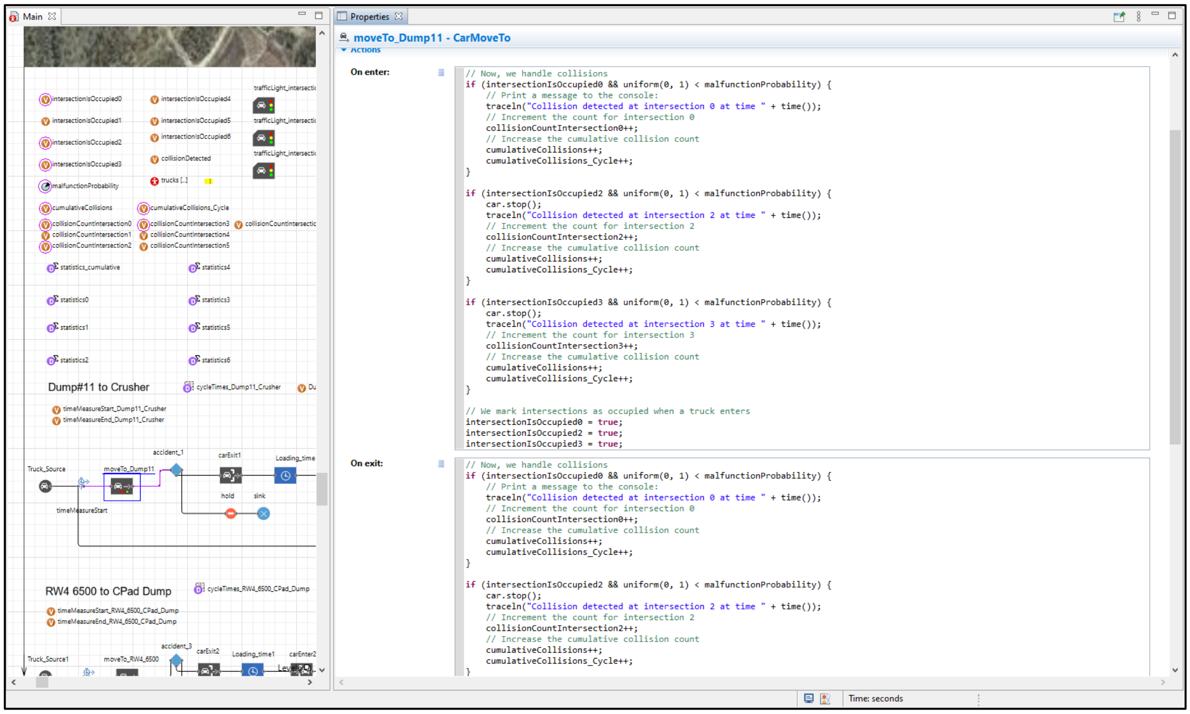

Figure 20 Move to block with the collision restriction codes.

The provided code inside the “Move To” block is responsible for handling collisions in the simulation and tracking collision-related information. The code first checks if an intersection (0, 2, or 3) is occupied by a truck. If the condition is met and a random number generated is less than the malfunction probability, it indicates a collision has occurred at the respective intersection. The simulation prints a message to the console indicating the time on the simulation when the collision and increments the collision count for that specific intersection. It also increments the cumulative collision count for overall statistics. Following that, the code marks the intersections as occupied when a truck enters them by assigning a value of "true" to the corresponding “intersectionIsOccupied” variable. By monitoring and detecting collisions, the simulation can gather data on the frequency and timing of collisions at different intersections. Figure 21. This information is essential for assessing the safety performance of the system and evaluating potential risk factors.

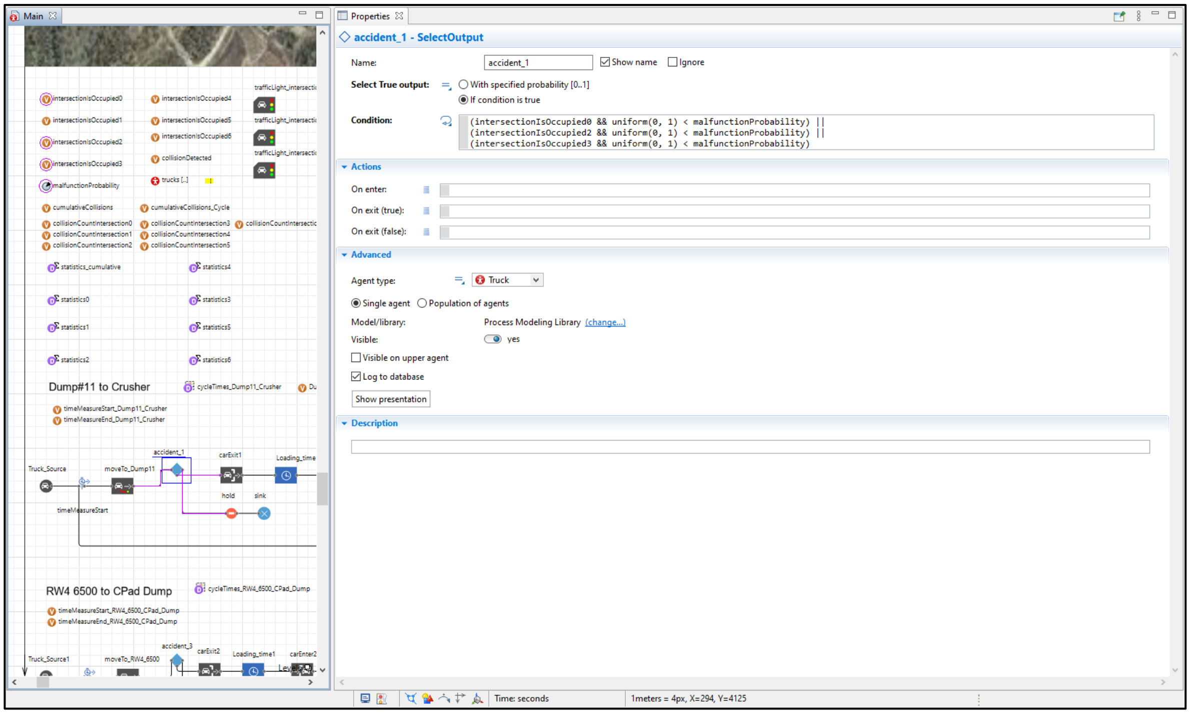

Figure 21 Select Output with the collision condition.

Following a collision event, the logic flowchart diverges into two distinct paths. Firstly, during the journey towards the loading point, there remains a possibility of encountering a collision. Similarly, the journey toward the unloading point also carries the risk of collision Figure 22. The code responsible for triggering the collision and subsequently removing the affected truck from the simulation is contained within the "Select Output" block. The code within this block functions as follows:

When the condition `(intersectionIsOccupied0 && uniform(0, 1) < malfunction Probability) || (intersectionIsOccupied2 && uniform(0, 1) < malfunction Probability) || (intersectionIsOccupied3 && uniform(0, 1) < malfunction Probability)` evaluates to true, it signifies that a collision has occurred at one of the intersections. The logic within this code block handles the response to a collision event.

In the case of a collision, the truck's movement is halted using the `stop()` function and a message indicating the collision and the specific intersection is printed on the console. Additionally, the collision count for the corresponding intersection is incremented, and the cumulative collision count is increased.

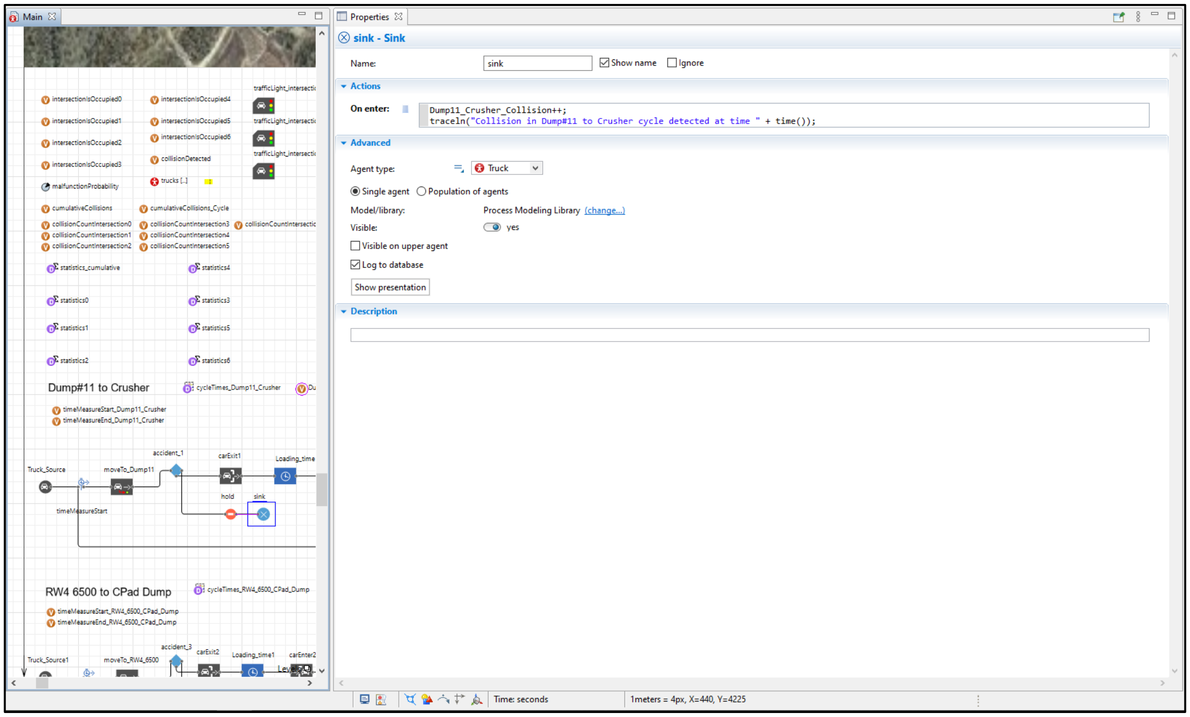

Figure 22 Sink code that registers trucks elimination.

On the other hand, if the condition evaluates to false, indicating that no collision has occurred, the truck continues its journey toward the destination without any interruptions.

In the event of a collision, apart from stopping the movement of the trucks and removing them from the simulation, it is crucial to capture and record relevant information regarding the collision. This information includes the destination of the truck and the timestamp at which the collision occurred. To accomplish this, a "Sink" block is utilized within the system.

The "Sink" block serves as a repository for collecting and storing data related to the collided trucks. It captures the destination of each truck involved in the collision and records the specific simulation time at which the collision took place. This information is then stored and can be later accessed for analysis and evaluation purposes.

Incorporating the "Sink" block into the simulation model, enables the collection of important data points associated with collisions, facilitating further analysis and assessment of the safety performance within the system. Figure 23 visually represents the integration of the "Sink" block and its role in capturing and documenting collision-related information.

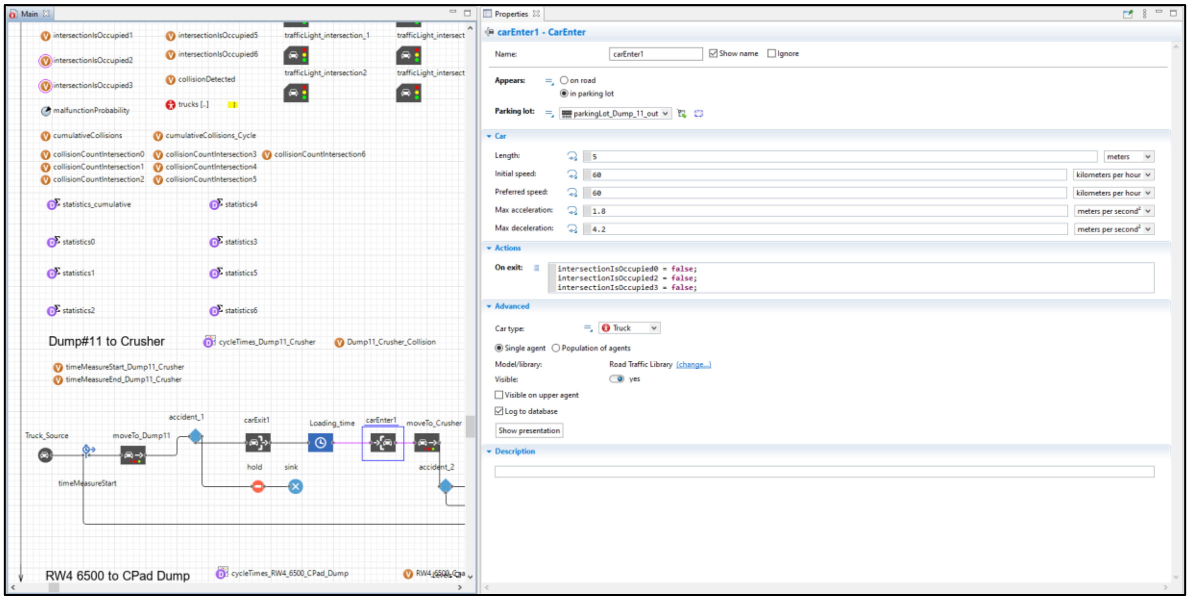

Figure 23 Block that represents the re-starting of the trucks to go for the next point

The loading process of the trucks is managed by the "Delay" block, which simulates the duration of time required for the trucks to be loaded. During this loading period, the "car enter" block as it is shown in Figure 24 represents the trucks transitioning from the road to the loading bay. Additionally, the block contains code that interacts with the intersection variables.

Within the code, the intersection variables are assigned a value of "false." This indicates that while the trucks are being loaded, they are not considered to be occupying the intersection. Similarly, when the trucks depart from the loading area, they are still not classified as being at the intersection. This interaction with the intersection variables ensures that the simulation accurately reflects the trucks' movements and positions throughout the loading process.

Upon completion of the loading phase, the "moveTo" block is once again activated. This time, it directs the trucks to proceed to the unloading area using the same code structure as the previous "moveTo" block. The process is essentially repeated, with the trucks following the designated path and interacting with the relevant intersection variables.

By coordinating the "Delay," "carEnter," and "moveTo" blocks in this manner, the simulation effectively simulates the loading and unloading operations of the trucks, considering their movement, interactions with intersections, and the overall flow of the mining operation.

Simulation Execution: The Anylogic software provides comprehensive visualization capabilities, enabling accurate representation of the simulation in both 2D and 3D environments. Through the software, users can review the recorded data from the logic flowchart, gaining insights into various aspects of the simulation. One of the key features is the ability to generate histograms that illustrate the distribution of haulage cycles for different processes within the mine. These histograms offer a visual representation of the frequency and duration of each cycle, providing valuable information for analysis and evaluation. Furthermore, Anylogic allows for the printing of detailed records that capture important collision-related data. This includes the specific cycle and time at which a collision occurred, as well as the corresponding intersection involved. The software also tracks the individual and cumulative number of collisions per intersection and per cycle, allowing for a thorough examination and assessment of safety performance. This functionality enhances the overall simulation experience and facilitates informed decision-making and optimization efforts within the mining operation. Figures 25 to 28.

Figure 24 Starting of the simulation 2d view.

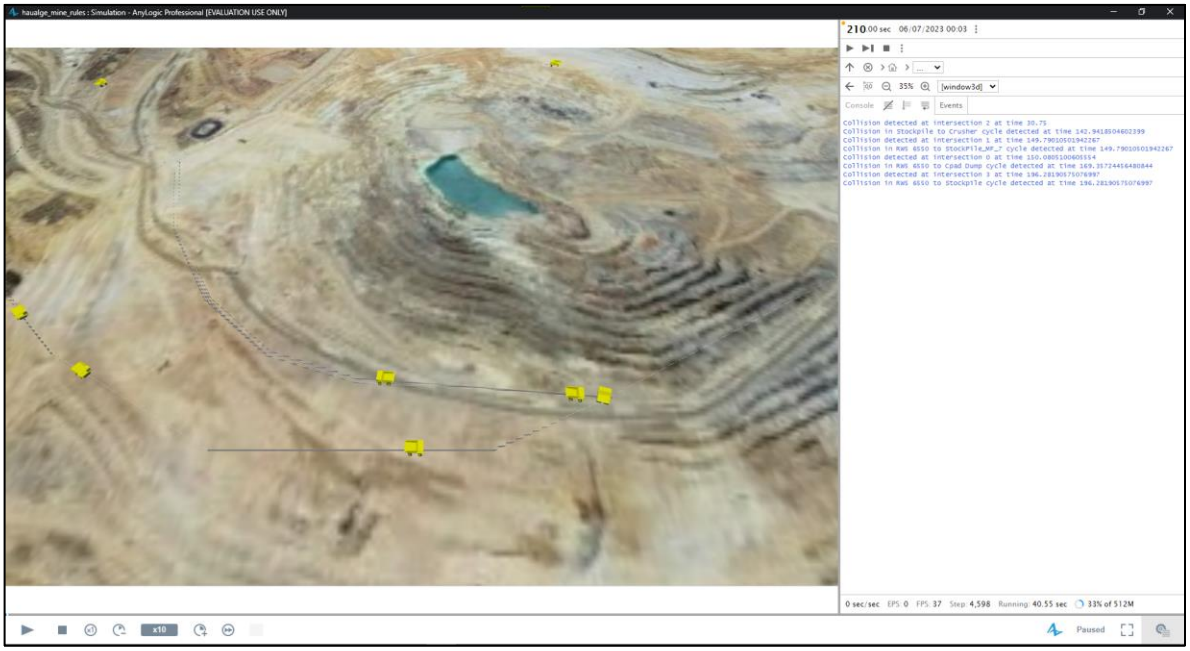

Figure 25 Simulation 3D view

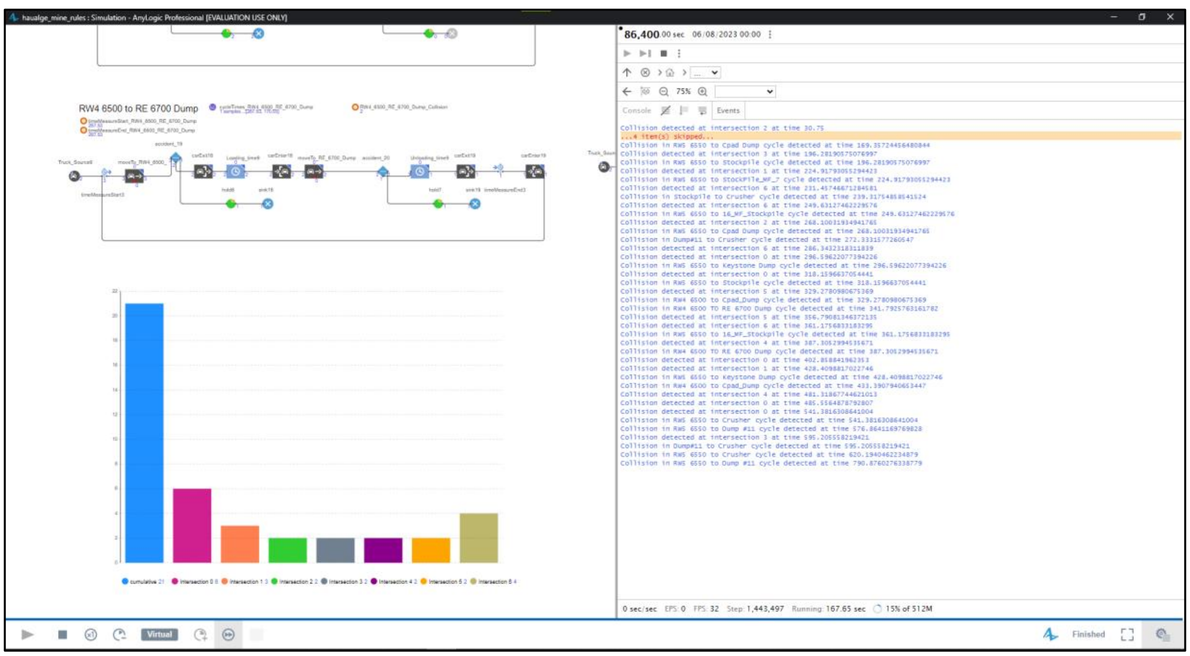

Figure 26 Statistic collected at the end of the simulation/logic flowchart.

Figure 27 Simulation completed with all the collisions and statistical data registered.

3.11.9. Scenario development

The scenario development for accident prediction in mining operations is informed by valuable insights from the literature and analysis of relevant research studies. Notably, Zhang's (2014) master's thesis titled "Analysis of Haul Truck-Related Fatalities and Injuries in Surface Coal Mining in West Virginia" provides a comprehensive understanding of the root causes of haul truck accidents in coal mining operations. Building upon this knowledge, the developed scenarios consider multiple factors that contribute to the probability of accidents in mining operations, including operator experience, time of day, and human error. The parameters considered for the scenarios are presented in Table #, which outlines the specific variables incorporated into the mathematical model. To capture the human error factor, information was extracted from the NIOSH Mining website for the same period, as it serves as a reliable reference (Center for Disease Control and Prevention, 2023). By considering and quantifying these variables, the mathematical model developed provides a comprehensive assessment of accident probabilities in various scenarios.

Table 22 Factors for the Empirical simulation formula, Zhang's (2014)

Years at current mine	%
0 a 5	0.69
6 a 16	0.23
17+	0.08

Injury Time	%
6 am - 2 pm	0.52
2 pm - 10 pm	0.28
10 pm - 6 am	0.2

Table 23 Injury rate, NIOSH

Years	Injury rate per 100 FTE
2011	1.94
2010	2.04
2009	2.22
2008	2.37
2007	2.53
2006	2.65
2005	2.88
2004	3
2003	3.24
2002	3.56
2001	3.54
2000	3.85
1999	3.81
1998	4.1
1997	4.01
1996	4.18
1995	4.63

The scenario development process involved creating three distinct scenarios to simulate different mining conditions and evaluate their respective accident probabilities. The aim was to demonstrate the logic behind the scenarios' development, provide a rationale for the chosen approach, and showcase the potential of the simulation method. The following paragraphs outline each scenario in detail:

1. Mine Human Operated:

In this scenario, it is developed an empirical equation that considers several factors: years of experience, working shifts, and human error. To ensure the equation's reliability, the human error calculation is based on historical accident data registered by NIOSH, which is the Injury rate per 100 FTE. By assigning weighted values to each factor, the resulting accident risk estimation is grounded in actual accident records rather than mere assumptions. The equation for this scenario is as follows:

$$Risk\ simulation = (Years\ of\ experience) \times (Shift\ hours) \times (Injury\ rate) \qquad 5$$

2. Hybrid-operated mine (20% Autonomous - 80% Non-Autonomous):

The hybrid scenario combines the use of autonomous and non-autonomous trucks. To accurately model the accident probabilities, it is incorporated an additional factor, which is based on the 2013 research finding that attributed 69% of truck accidents in mines to fatigue or lack of rest (Goodbody, 2013), it is introduced a correction factor for human error into the calculations. The equations for this scenario are the followings:

$$New\ Injury\ rate = (80\%) \times (Injury\ rate) + \big((20\%) \times (Injury\ rate) \times (1 - 0.7)\big) \qquad 6$$

$$Risk\ (Hybrid) simulation = (Years\ of\ experience) \times (Shift\ hours) \times (New\ Injury\ rate\ ) \qquad 7$$

By combining the results obtained from the previous equations, considering the 20% autonomous and 80% non-autonomous truck ratio, a final weighted risk value is derived.

3. Fully Autonomous Mine:

In the fully autonomous scenario, it was assumed that the implementation of autonomous trucks would significantly reduce the accident rate by 99%. This reduction indicates that only 1% of the accidents are attributed to the remaining human error, as the majority of accidents are expected to be eliminated through autonomous operations.

For this scenario, the focus is primarily on estimating the number of collisions based on the historical rate of injury for each year. Since autonomous trucks operate without human intervention, the equation for this scenario simplifies to:

$$Fully\ autonomous\ Mine\ simulation = (Injury\ rate) \times (1 - 0.99) \qquad 8$$

The equation calculates the expected number of collisions by multiplying the annual injury rate by 0.01, representing the 1% of accidents that can still occur due to human error. This approach allows for an estimation of the collision count while assuming that other factors and risks associated with human-operated trucks are no longer present in the fully autonomous scenario.

Additionally, to enhance the reliability and provide insights into the most critical areas within the mine, a feature was implemented in the software to track the specific intersections where collisions occurred. This option was designed to increase the robustness of the data and identify the intersections that pose the highest risk.

As part of the simulation analysis, the total number of collisions in each scenario was recorded. Moreover, in each iteration of the simulation, the exact location of each collision was captured. This valuable information is presented in Table 24, which showcases the specific intersections where collisions took place throughout the simulation runs.

Table 24 Collisions per intersection

(Injury rate)*(17+ years)*(10-6 shift)	
Intersections	***#collision***
0	17
1	5
2	1
3	5
4	14
5	4
6	2

By identifying the intersections with a higher frequency of collisions, the mining operation can prioritize safety improvements and implement targeted mitigation strategies to minimize the risk of accidents. The detailed data obtained from the simulations provide valuable insights into the areas that require particular attention and enable informed decision-making for enhancing safety measures within the mine.

4. Simulation Results and Discussion

4.1 Analysis and Interpretation of Simulation Model Results

The analysis and interpretation of simulation model results play a crucial role in understanding the implications and outcomes of the proposed implementation of autonomous trucks in the mining operation. In this subchapter, we will delve into the details of the simulation results, considering the data sources and methodologies utilized during the research.

The foundation of our simulation model results is rooted in a combination of various sources of information. Firstly, we drew insights from the study conducted by Zhang (2014) titled "Analysis of Haul Truck-Related Fatalities and Injuries in Surface Coal Mining in West Virginia." This comprehensive study provided valuable insights into the factors contributing to accidents in open pit mining environments, particularly focusing on the role of human error.

To maintain consistency and ensure comparability, the same number of years studied by Zhang (2014) was adopted as the timeframe for our analysis. Additionally, to quantify the human error factor and evaluate the probabilities of collisions and other accidents, we referenced the "Number and rate of nonfatal lost-time injuries, 1995 - 2011" dataset available from the National Institute for Occupational

Safety and Health (NIOSH, 2023). Specifically, we utilized the "Injury rate per 100 FTE" metric from this dataset.

Building upon this foundation, a total of 323 simulations were conducted using the AnyLogic Software, incorporating the equations derived from the empirical research and data analysis. The results obtained from these simulations will be comprehensively presented and analyzed in the subsequent sections.

By drawing from reputable studies and utilizing relevant data sources, our analysis aims to provide meaningful insights into the potential impact of autonomous truck implementation on the safety and accident rates within the mining operation. By meticulously examining the simulation results, we can gain a deeper understanding of the projected outcomes and evaluate the feasibility and effectiveness of this proposed solution.

In analyzing and interpreting the simulation model results, we explore three distinct scenarios that represent different levels of autonomy in the mining operation. Each scenario considers various factors that contribute to the probability of accidents and collisions, providing valuable insights into the safety implications of different implementation approaches.

The first scenario represents the base scenario, simulating a purely human-operated mine. In this scenario, we take into account factors such as years of experience, work shift schedules, and the human error factor, which is particularly influenced by fatigue and wear. We explore the range of possible outcomes through extensive simulations by considering different combinations of these factors. It is worth noting that the input data used in the simulation reflects a gradual decrease in risk as the years progresses, illustrating the industry's continuous focus on prioritizing safety. The results obtained in each scenario shed light on the impact of these factors and provide valuable insights into the safety performance of the mine.

The second scenario focuses on a semi-autonomous or hybrid implementation plan. In this scenario, the number of human operators is reduced to 80%, with the remaining 20% replaced by autonomous trucks. To account for the interaction between human and autonomous elements, a correction factor is introduced to mitigate the risk of accidents caused by human factors such as fatigue. However, it is crucial to acknowledge that this interaction still poses certain risks, warranting the consideration of factors like years of experience and work shift hours to define the overall risk element associated with this scenario. Through simulations, we examine the specific risk profiles and safety outcomes resulting from this hybrid approach, providing valuable insights for decision-making.

The third scenario explores a fully autonomous mining operation, where 99% of the haulage is carried out by autonomous trucks. In this scenario, the correction factor is reduced to allow for a 1% margin of error, signifying that no project can be entirely devoid of risk. The emphasis in this scenario is on the continuous pursuit of information and training to ensure the safety of workers in the mine. Factors considered in the previous scenarios become less relevant with the fleet predominantly consisting of autonomous equipment. Consequently, the simulation is performed 17 times, representing the analysis for each year based on the corrected injury rate. This analysis provides insights into the safety implications and potential benefits of a fully autonomous mine.

By systematically analyzing these scenarios, we aim to uncover the relationships between various parameters, identify potential risks, and evaluate the safety performance of different implementation approaches. The simulation results obtained from each scenario contribute to a comprehensive understanding of the accident probabilities and collision risks associated with different levels of autonomy in the mining operation. This analysis enables us to make informed decisions and develop strategies to enhance safety in mining operations while leveraging the advantages of autonomous technologies.

Furthermore, the software used for the simulation provides a valuable tool to analyze the specific intersections where the highest number of collisions occur. This analysis considers factors such as the frequency of occupancy and the number of cycles each intersection experiences. By leveraging this information, we can create a comprehensive heat map that visualizes the collision hotspots for each scenario.

The heat map will provide a visual representation of the areas within the mine that pose the highest collision risks. By identifying these high-risk intersections, mine operators and safety managers can prioritize safety measures and implement targeted interventions to mitigate the risks in those specific areas. This heat map will serve as a valuable resource for designing effective traffic management strategies, optimizing haulage routes, and implementing additional safety measures to minimize the occurrence of accidents and collisions.

Through the analysis of collision data and the development of a heat map, we aim to provide actionable insights and recommendations for improving safety in the mining operation. By identifying the critical areas and intersections prone to collisions, mine operators can proactively implement measures to enhance safety and reduce the likelihood of accidents. This comprehensive analysis will contribute to the overall understanding of the safety implications of different scenarios and guide decision-making processes to create a safer working environment in the mining operation.

It is important to note that the heat map analysis is based on the simulation results obtained from the AnyLogic software, which provides accurate and reliable data for analyzing collision patterns.

4.1.1. Scenario 1

As mentioned earlier, one of the key scenarios analyzed in this study focuses on the purely human-operated mine. This scenario aims to evaluate the potential risks and accident probabilities associated with human factors in the mining operation.

The following table is an example of a situation where the workers have just recently been hired and work the morning shift (6 a.m. to 2 p.m.):

Table 25 Results scenario 1shift 6. a.m. to 2 p.m.

Years	**(Injury rate) *(Exp.years) *(shift)**	**#collisions**
2011	0.70	16
2010	0.73	17
2009	0.80	17
2008	0.85	18
2007	0.91	20
2006	0.95	20
2005	1.03	21
2004	1.08	21
2003	1.16	22
2002	1.28	22
2001	1.27	22
2000	1.38	24
1999	1.37	23
1998	1.47	25
1997	1.44	25
1996	1.50	25
1995	1.66	25

And for that same situation, the collision per intersection was also obtained, the following table present which intersection present the greatest number of collisions:

Table 26 Collisions Scenario 1

Intersection	# Collisions
0	131
1	36
2	7
3	36
4	105
5	33
6	15

The next situation to be analyzed focuses on drivers with the same range of experience as the previous analysis but the focus it's to target workers who are assigned to the afternoon shift from 2 p.m. to 10 p.m. This scenario aims to assess the influence of specific working hours on accident probabilities within the mining operation.

Table 27. Results scenario 1 2 p.m. to 10 p.m.

Years	(Injury rate) *(Exp.years) *(shift)	#collisions
2011	0.37	13
2010	0.39	13
2009	0.43	14
2008	0.46	14
2007	0.49	15
2006	0.51	15
2005	0.56	15
2004	0.58	15
2003	0.63	15
2002	0.69	15
2001	0.68	16
2000	0.74	17
1999	0.74	17
1998	0.79	17
1997	0.77	18
1996	0.81	18
1995	0.89	20

The intersections affected by this simulation are the following:

Table 28 Collisions Scenario 1

Intersections	#collision
0	96
1	27
2	5
3	27
4	77
5	24
6	11

The next situation to be analyzed focuses on drivers with the same range of experience and specifically targets workers who are assigned to the night shift from 10 p.m. to 6 a.m. This scenario aims to assess the influence of the operator at a specific working hour on accident probabilities within the mining operation.

Table 29 Results scenario 1 shift 10 p.m. to 6 a.m.

Years	(Injury rate)*(Exp.years)*(shift)	#collisions
2011	0.27	11
2010	0.28	11
2009	0.31	13
2008	0.33	13
2007	0.35	13
2006	0.37	13
2005	0.40	13
2004	0.41	14
2003	0.45	14
2002	0.49	15
2001	0.49	15
2000	0.53	15
1999	0.53	15
1998	0.57	15
1997	0.55	15
1996	0.58	15
1995	0.64	15

The number of collisions per intersection is the following:

Table 30 Collisions Scenario 1

Intersections	#collision
0	85
1	24
2	5
3	24
4	68
5	21
6	9

Looking at these tables, it appears that injury rates and the number of collisions is consistently higher in earlier shifts (6 a.m. – 2 p.m.), compared to the later shifts (2 p.m. – 10 p.m. and 10 p.m. – 6 a.m.). The injury rate is highest in the 6 a.m. – 2 p.m. shift, slightly lower in the 2 p.m. – 10 p.m. shift, and lowest in the 10 p.m. – 6 a.m. shift, Figures 28 & 29. This is interesting as one might expect that fatigue would increase over the course of the day, resulting in higher injury rates in later shifts, the following may be the reasons why the results are the opposite of the expected:

1. Reduced Personnel: If there are fewer personnel working in later shifts, it could result in lower chances of human-related errors leading to accidents. With fewer workers, the workspace might be less crowded, resulting in less chaotic situations that could lead to collisions.

2. Reduced Volume of Transported Material: If there is less material being transported during these shifts due to low visibility or other reasons, it could also result in fewer collisions. With fewer vehicles moving around, there is less likelihood of a collision occurring.

3. Increased Levels of Caution: If workers tend to be more cautious during these shifts, it could also contribute to the lower rate of collisions. This could be due to increased awareness of the risks associated with working in low visibility conditions, or a result of specific safety procedures implemented for these shifts.

To validate these hypotheses, it would be necessary to collect additional data related to these variables, such as the number of workers per shift, the volume of material transported, and the safety procedures in place.

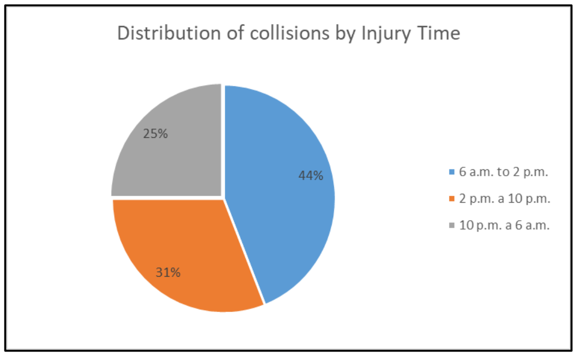

Figure 28 Distribution of collisions by shift scenario 1

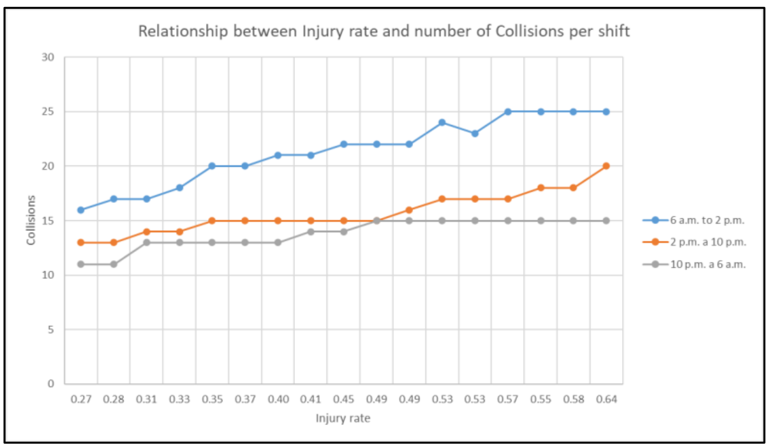

Figure 29 Collisions and Injury rate per shift scenario 1

As Figures 29 and 30 show during the day shift, there may be more activity, including more personnel present, more operations occurring, and possibly higher volumes of materials being transported. This increased activity could inherently present more opportunities for incidents to occur.

Further, during the day shift, visibility might be better than during the other shifts. While better visibility might seem like it would decrease accidents, it could potentially have the opposite effect if it leads to overconfidence, less cautious behavior, or if it obscures the fact that visibility varies throughout the day and the year.

While this figure provides a useful visual representation of your data and observations, it would be beneficial to conduct a statistical analysis to quantify the relationship between the injury rate and shift collisions. This could provide stronger evidence to support your observations. It would also be useful to investigate the factors discussed above to identify their specific contributions to this trend. For instance, data on worker alertness, volume of activity, and visibility conditions during each shift could help to clarify their roles in these trends.

Figure 31 presents the chart with the relation between intersection and collisions and from an initial view, it's clear that Intersection 0 has the highest number of collisions across all three tables. This suggests that Intersection 0 is the most dangerous or highest-risk intersection, regardless of the specific scenario.

Intersection 4 also appears to be significantly more dangerous than the other intersections, with it having the second-highest number of collisions in all three scenarios.

In contrast, Intersection 2 consistently has the fewest collisions, which may suggest it is the least hazardous intersection.

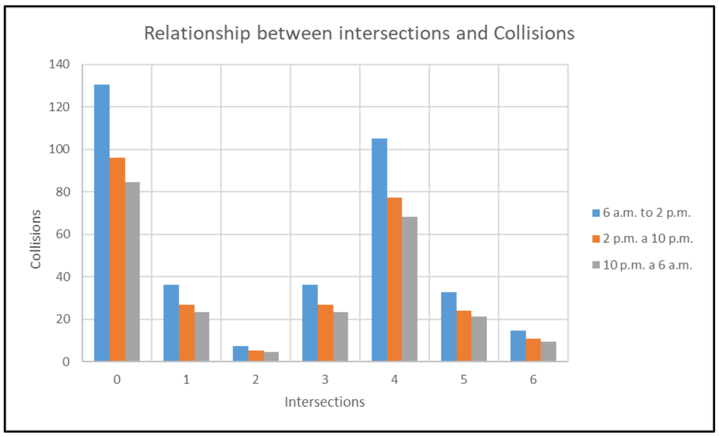

Figure 30 Collisions by intersections scenario 1

Table 26 shows Intersection 0 having a significantly higher collision count (131) than the other intersections. Intersection 4 also shows a high count with 105 collisions. The remaining intersections (1, 3, 5, 6) exhibit relatively similar collision numbers, except for Intersection 2 which only has 7 collisions.

Table 28 maintains the same general pattern as Table 1, with Intersection 0 (96 collisions) and Intersection 4 (77 collisions) experiencing the most collisions. Again, Intersection 2 has the fewest collisions.

Table 30 follows a similar pattern as well, with Intersection 0 (85 collisions) and Intersection 4 (68 collisions) having the most collisions, and Intersection 2 having the fewest.

When comparing the tables, we can observe a decreasing trend in the number of collisions at each intersection across the three tables. This could suggest that safety measures implemented over time are having a positive effect, reducing the overall number of collisions.

In a real mining environment, these intersection collision statistics could be used to focus resources and safety interventions at the intersections with the highest collision rates. For example, Intersection 0 and Intersection 4 may benefit from additional signage, altered traffic flow, enhanced lighting, or other safety improvements.

On the other hand, Intersection 2 shows a very low number of collisions which after checking the whole haulage systems of the mine shows is because of the few circulations of trucks it has per cycle, but at the same time it could also serve as a model for safer intersections design. It would be beneficial to deeply study the difference and why this intersection presents such a small number of collisions at every shift.

4.1.2. Scenario 2

In this scenario, we're introducing a significant change into the equation: the implementation of autonomous vehicles. However, to ensure consistency in our analysis, the variables we've been assessing will remain largely the same. That is, while we're integrating autonomous vehicles into our operations, we're maintaining the same shift times and worker experience ranges as the other scenarios. This allows us to isolate the impact of autonomous vehicle introduction on safety and efficiency outcomes within the mining operation.

Table 31 Results scenario 2 shift 6. a.m. to 2 p.m.

Years	(Injury rate)*(years)*(shift)	#collisions
2011	0.60	15
2010	0.63	15
2009	0.69	16
2008	0.73	17
2007	0.78	17
2006	0.82	18
2005	0.89	20
2004	0.93	20
2003	1.00	21
2002	1.10	21
2001	1.09	21
2000	1.19	22
1999	1.18	22
1998	1.27	22
1997	1.24	22
1996	1.29	22
1995	1.43	25

Although in this scenario the number of human workers decreased there are still collisions because of the injury rate and the other factors that lead the human error for accidents, the intersections that present collisions in this simulation are the following:

Table 32 Collisions Scenario 2

Intersections	#Collisions
0	121
1	34
2	7
3	34
4	97
5	30
6	13

The next situation to be analyzed focuses on drivers with the same range of experience as the previous analysis but the focus it's to target workers who are assigned to the afternoon shift from 2 p.m. to 10 p.m. This scenario aims to assess the influence of specific working hours on accident probabilities within the mining operation.

Table 33 Results scenario 2shift 2. p.m. to 10 p.m.

Years	(Injury rate) * (Exp. years) * (shift)	#collisions
2011	0.32	12
2010	0.34	12
2009	0.37	13
2008	0.39	13
2007	0.42	14
2006	0.44	14
2005	0.48	15
2004	0.50	15
2003	0.54	15
2002	0.59	15
2001	0.59	15
2000	0.64	15
1999	0.63	15
1998	0.68	16
1997	0.67	16
1996	0.69	16
1995	0.77	17

The collisions registered per intersection are the following:

Table 34 Collisions Scenario 2

Intersections	#Collisions
0	89
1	25
2	5
3	25
4	72
5	22
6	10

The next situation to be analyzed focuses on drivers with the same range of experience and specifically targets workers who are assigned to the night shift from 10 p.m. to 6 a.m. This scenario aims to assess the influence of the operator at a specific working hour on accident probabilities within the mining operation and the collisions per intersection.

Table 35 Collisions Scenario 2

Intersections	#collision
0	80
1	22
2	4
3	22
4	64
5	20
6	9

Table 36 Results scenario 2 shift 10. p.m. to 6 a.m.

Years	(Injury rate) *(Exp. years) *(shift)	#collisions
2011	0.23	10
2010	0.24	10
2009	0.26	10
2008	0.28	11
2007	0.30	12
2006	0.31	12
2005	0.34	12
2004	0.36	13
2003	0.38	13
2002	0.42	14
2001	0.42	14
2000	0.46	15
1999	0.45	15
1998	0.49	15
1997	0.48	15
1996	0.50	15
1995	0.55	15

Examining the three tables, it's clear that implementing autonomous vehicles in a hybrid approach (80% non-autonomous, 20% autonomous) has indeed impacted the number of collisions in each shift, albeit to varying degrees, Figures 32 & 33

Table 1: Shift from 6 AM - 2 PM

The first shift (6 AM - 2 PM) experienced a slight reduction in the number of collisions compared to the previous scenario where all the trucks were non-autonomous. The collision rate appears to be slightly decreased from 2011 to 1995, which suggests that the integration of autonomous vehicles had a positive effect on reducing collisions. This is likely because autonomous trucks are less prone to human error, especially during this high-activity shift.

Table 2: Shift from 2 PM - 10 PM

Like the first shift, the second shift (2 PM - 10 PM) has also seen a reduction in the number of collisions. However, the rate of decrease is slightly less compared to the first shift, which might be due to less vehicle activity during this shift or the autonomous trucks coping better with the reduced light conditions.

Table 3: Shift from 10 PM - 6 AM

For the third shift (10 PM - 6 AM), the reduction in collisions is the most consistent of all the shifts. This is likely due to the autonomous trucks' capabilities to operate efficiently even in lower light and visibility conditions, where human operators might struggle.

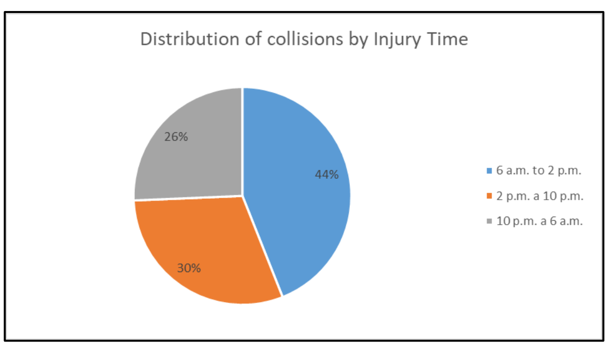

Figure 31 Distribution of collisions by shift scenario 2

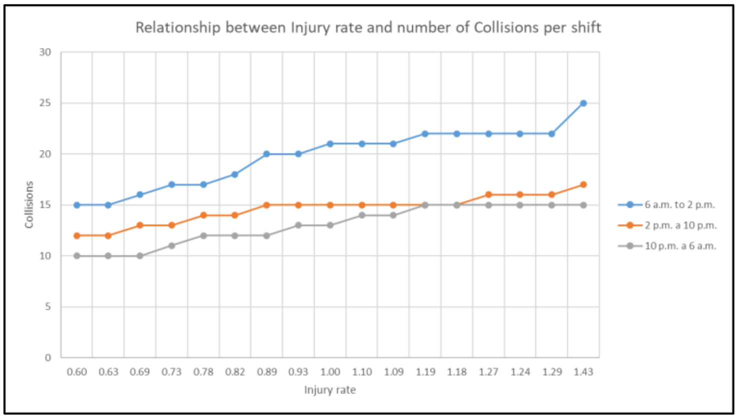

Figure 32 Collisions and Injury rate per shift scenario 2

Indeed, as observed in Figure 32, there is a noteworthy transformation in the distribution of collisions about injury time. A noticeable decline in collisions is evident in the interval from 2 PM to 10 PM. However, in contrast, an uptick in collisions can be seen between the hours of 10 PM to 6 AM. This highlights that while the implementation of autonomous vehicles has improved safety conditions in the mine, the predominance of non-autonomous vehicles implies human error continues to play a significant role. This aspect will be delved into in greater depth later when we draw comparisons between the different scenarios.

Figure 33 effectively encapsulates the relationship between injury rate and the number of collisions. There is a significant reduction in collisions, and strikingly, the interval from 2 PM to 10 PM intersects

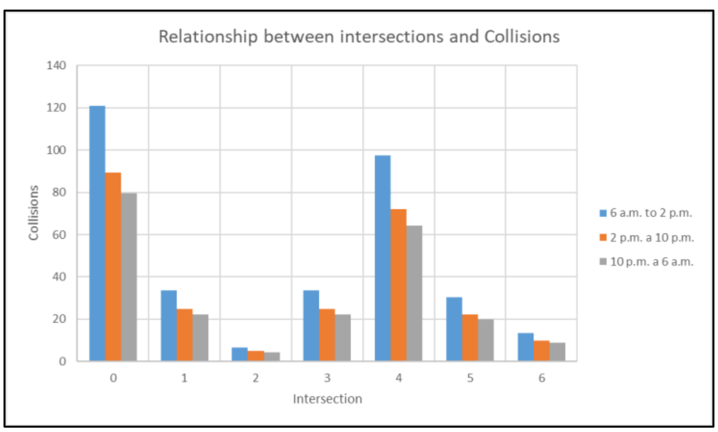

Figure 33 Collisions by intersections scenario 2

and surpasses several injury rate intervals on the graph corresponding to the interval from 10 PM to 6 AM. This indicates that as the injury rate escalates, the trend of collisions is inclined to decrease, showcasing the positive impact of implementing autonomous vehicles.

Analyzing the data presented in the tables and reflected in Figure 34, there's an interesting pattern that comes to light.

In Table 32, Intersections 0 and 4 record the highest number of collisions, which is consistent with the pattern observed in previous scenarios. Intersections 1 and 3 also have a significant number of collisions, more than the rest of the intersections. This reveals a potential risk hotspot and indicates the need for safety measures at these intersections. A comparison with the previous scenarios shows a reduction in the number of collisions, which might be an outcome of the partial integration of autonomous vehicles.

Table 34 exhibits a similar pattern, with Intersections 0 and 4 continuing to have the highest number of collisions. Again, the number of collisions has reduced compared to Table 32, further underscoring the positive impact of the implementation of autonomous vehicles in reducing collisions. The reduction of collisions across all intersections is an encouraging sign.

Table 35 shows a continuation of this downward trend in collision numbers. This may well be the result of an increasing adaptation and effective utilization of autonomous vehicles, coupled with continuous learning and improvement in autonomous technology.

From the author’s perspective, while the implementation of autonomous vehicles has shown a promising impact in reducing collisions, the fact that Intersections 0 and 4 continue to have the highest number of collisions implies a persistent challenge. This could be due to factors like complex traffic dynamics, ineffective intersection design, or insufficient signage. Therefore, in addition to implementing autonomous vehicles, it's recommended that further safety measures should be introduced, including improving visibility, updating intersection designs, providing clear signage, and integrating smart traffic management systems.

Furthermore, the data suggest that longer shift times tend to correlate with a higher number of collisions, indicating that factors such as worker fatigue or decreased visibility could be playing a role. Consequently, these aspects should also be addressed in any comprehensive safety improvement strategy.

4.1.3. Scenario 3

In this fully automated scenario, the human element is completely removed from the equation, which presumably leads to a significant reduction in the risk of accidents. Autonomous vehicles, with their consistent performance, lack of fatigue, and advanced safety systems, are expected to reduce the number of accidents dramatically. The decision to reduce the injury rate to 1% reflects this assumption, implying that the vast majority of previous accidents were due to human factors.

Nevertheless, the introduction of a correction factor adds an element of realism to this scenario, acknowledging that no system is infallible and that there may still be some risk of accidents, even with fully autonomous vehicles. This could arise from mechanical failures, software bugs, or unforeseen operational circumstances.

In the 17 simulations performed based on the years of study, any observed fluctuations or trends will solely reflect changes in operational conditions or autonomous vehicle technology, as the human factor has been removed. This should provide valuable insights into the relative safety of a fully automated mine and highlight any potential areas for further improvement.

It's important to note, however, that while removing the human factor can reduce the risk of accidents, it can also introduce new challenges. For example, in a fully automated environment, issues like system failures, cyber-attacks, or unforeseen environmental conditions may pose new risks that need to be carefully managed. Consequently, a comprehensive safety management plan for a fully automated mine should address these potential issues, in addition to aiming to minimize the risk of collisions.

Table 37 Results Scenario 3

Years	Injury rate per 100 FTE	Correction Factor (99%)	Collisions
2011	1.94	0.02	1
2010	2.04	0.02	1
2009	2.22	0.02	1
2008	2.37	0.02	1
2007	2.53	0.03	2
2006	2.65	0.03	2
2005	2.88	0.03	2
2004	3	0.03	2
2003	3.24	0.03	2
2002	3.56	0.04	2
2001	3.54	0.04	2
2000	3.85	0.04	2
1999	3.81	0.04	2
1998	4.1	0.04	2
1997	4.01	0.04	2
1996	4.18	0.04	2
1995	4.63	0.05	3

Upon examining the data and the associated graph (Figure 35), the impact of full automation with the implementation of the correction factor is apparent. In Table 37, the injury rate per 100 Full-Time Equivalents (FTE) increases steadily over the years. However, once the 99% correction factor is applied to reflect the introduction of autonomous vehicles, the corresponding injury rate becomes negligible, remaining between 0.02 and 0.05.

Consequently, the number of collisions is significantly reduced to either 1, 2, or 3 per year, representing a dramatic decrease compared to the figures seen in previous scenarios. It's worth mentioning that this data implies that the remaining collisions might have occurred due to reasons beyond human error, such as mechanical failures, software bugs, or unforeseen environmental conditions.

Examining the graph, the injury rate and the number of collisions demonstrate a flat correlation, showing that even with the increasing injury rate per 100 FTE, the number of collisions remains consistently low. This indicates that autonomous vehicles have effectively managed the risks associated with human factors.

This result is encouraging from a safety perspective as it shows the substantial positive impact that autonomous vehicles can have in reducing the risk of collisions. It suggests that the adoption of this technology could lead to a much safer working environment in mines. However, it's important to bear in mind that while autonomous vehicles can minimize some risks, they may introduce new ones, like system failures or cyber threats, which need to be actively managed.

It should also be noted that even with a 99% correction factor, some risk of accidents persists, emphasizing the importance of robust vehicle maintenance protocols, regular system checks, and continuous improvement of safety systems even in a fully automated environment.

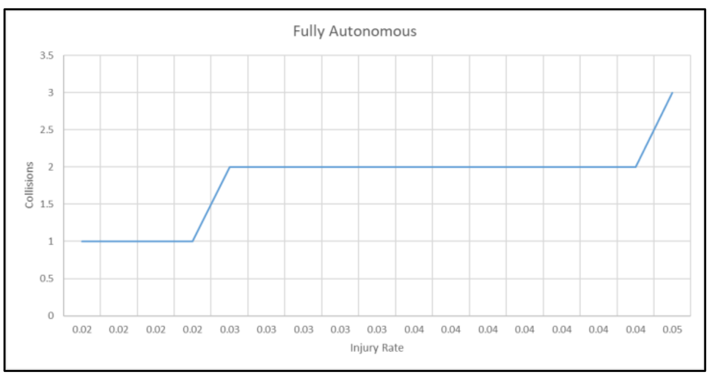

Figure 34 Collisions and Injury rate for (AHS)

Table 38 Collisions Scenario 3

Intersections	**#collisions**
0	11
1	3
2	1
3	3
4	9
5	3
6	1

Examining the intersection and collisions table, it's evident that even in a fully autonomous setting over 17 years of simulation, some collisions still occur. However, it's critical to understand that the data provided here is cumulative over nearly two decades, so the yearly average is quite low. The total of 31 collisions spread across 17 years equates to fewer than 2 collisions per year on average.

From Table 38, it can be seen that intersections 0 and 4 have the highest frequency of collisions, with 11 and 9 collisions respectively over the entire simulation period. In contrast, the other intersections have experienced significantly fewer collisions, ranging from 1 to 3 collisions.

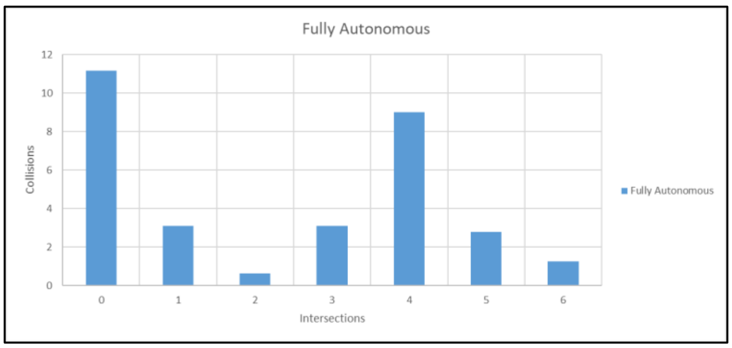

Figure 35 Collisions by intersections scenario 3

Looking at the graph in Figure 36, this trend becomes even clearer. The bar chart visually reinforces that intersections 0 and 4 are areas of concern when it comes to collision frequency.

This information suggests that despite automation, there may be underlying structural or design issues at these intersections that contribute to the higher collision rate. These areas should be a focus for further study and possibly for the implementation of additional safety measures or design modifications.

For instance, it may be helpful to conduct a detailed analysis of the specific circumstances of each collision event at these intersections, to identify any common factors. Possible issues could range from physical layout constraints, software glitches in handling these junctions, or environmental conditions affecting sensor performance.

As safety recommendations, while the overall safety performance in this fully autonomous scenario is commendable, the persistence of some collisions underscores the need for ongoing vigilance, regular system checks, software updates, and continuous improvement of safety systems. Furthermore, special attention should be given to high-risk intersections to understand and mitigate the risks they pose.

4.1.4. Comparison of simulation results

This section is dedicated to a comprehensive comparison and discussion of the simulation results obtained under the different scenarios considered. The evolution from a fully manual to a fully automated mining environment was systematically investigated, with a particular focus on the implications for safety performance.

The objective of this comparative analysis is to highlight the trends, patterns, and key differences in safety indicators across the different operational settings. This involves a critical examination of injury rates, collision frequencies, and their relation to variables such as shift timing, the experience level of the workers, and the proportion of autonomous vehicles in the fleet.

In the following sections, we will delve into a detailed comparison of the outcomes derived from the manual, hybrid, and fully autonomous scenarios. The impact of the transition from human-operated to autonomous vehicles on safety performance is explored, providing valuable insights into the potential benefits and challenges of integrating automation in mining operations.

Furthermore, we will identify specific areas of concern, such as intersections with higher collision rates, that need targeted attention for safety improvement. We will conclude the chapter with a discussion of the implications of our findings for future mining safety strategies and practices.

4.1.5. Relationship injury rate and collision for all the scenarios

Analyzing the data in Figure 37, it is possible to observe the clear impact of implementing autonomous vehicles on the probability of collisions. As the proportion of autonomous vehicles in the fleet increases, the rate of collisions significantly decreases. This downward trend is consistent across all shift times and experience levels, highlighting the safety benefits of vehicle automation.

In the manual operation scenario, there's a higher frequency of collisions, which can be attributed to human factors such as operator error, fatigue, and lapses in judgment. These risks are mitigated in the autonomous scenario, leading to fewer accidents.

Upon transitioning to a hybrid scenario (80% non-autonomous and 20% autonomous vehicles), there is a noticeable reduction in collisions. This suggests that even a partial introduction of autonomous vehicles can have a meaningful impact on safety performance.

However, the most striking change is observed in the fully autonomous scenario, where the collision rate drops significantly. The implementation of autonomous vehicles, designed to adhere strictly to safety protocols and unaffected by human limitations, has led to a drastically safer working environment.

It's important to note that this reduction in collisions directly correlates to a decrease in the injury rate, demonstrating a clear advantage of automation in improving worker safety in the mining industry. However, the adoption of autonomous vehicles is not without its challenges, which will be further discussed in later sections.

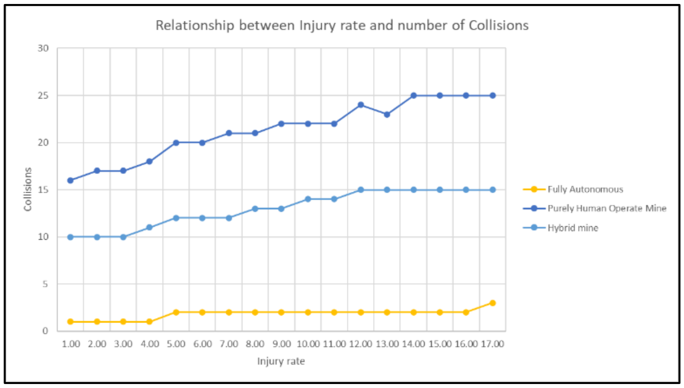

Figure 36 Three scenarios together comparison

Understanding the scenario comparisons is crucial to this study. The simulation data used for this research indeed represents a high-risk scenario, specifically considered because of the importance of driver health and safety. By evaluating the worst-case scenarios, we can ensure the reliability of the study's results. Consequently, the high injury rate and associated collision numbers may seem unusually high when compared to recent trends in mining safety, but this approach exceeds the average risk levels observed in many contemporary mining operations.

Despite this, it is essential to note that the comparative results obtained from the different scenarios are still representative and relevant to real-world mining operations. This relevance is supported by the thorough consideration of key factors such as equipment behavior, material characteristics, operational constraints, and especially human factors, which mirror real-world conditions. Every mining project has its unique set of risks and challenges, and the meticulous design of the simulation ensures that these findings are potentially applicable to a wide range of situations.

Of particular interest is the noticeable improvement in safety observed even in the hybrid mine scenario, where the majority (80%) of the fleet is still human-operated. Despite the predominance of non-autonomous vehicles, the highest collision count in the hybrid scenario is still lower than the lowest collision count recorded in the fully human-operated scenario.

This finding is significant as it highlights the potential safety benefits that can be realized even during the initial stages of transitioning toward autonomous operations. It provides a strong argument for integrating autonomous vehicles into mining operations, emphasizing that tangible safety improvements can be achieved long before full automation is realized.

4.1.6. Relationship collision and years of experience for scenarios 1 and 2

Worker experience within a mine is an invaluable asset, serving not only to foster familiarity with mine-specific safety regulations but also to gain in-depth knowledge about the mine's routes and the equipment being utilized. More importantly, experience often becomes a pivotal factor during decision-making in unpredictable risk situations that are an inherent part of daily operations in a mining project.

When the workers experience exceeds 5 years, the beneficial impact on safety becomes even more evident. Within the purely human-operated mine, the number of collisions witnessed a substantial reduction of 58% once the workers had amassed more than 5 years of experience. This indicates that seasoned workers, with their knowledge and instinct honed by years on the job, significantly contribute to the reduction of accidents.

In the hybrid mine scenario, the experience effect is still prominent, although slightly less drastic. A reduction of 56% was observed, which, while slightly less than in the fully human-operated environment, is still significant. This slightly smaller reduction in the hybrid scenario may be attributable to the interplay between human operators and autonomous vehicles, which could pose new challenges that seasoned operators need time to fully adapt to.

Regardless, these results underscore the vital role that experience plays in ensuring the safety of mine workers. Whether in a fully human-operated environment or a transitional phase towards automation, seasoned workers prove to be a key factor in mitigating risks and enhancing overall safety.

4.1.7. Relationship collision and intersections per scenarios

Understanding the likelihood of collisions within a mining environment is not solely about calculating the sheer probability of such events. It's equally, if not more, essential to discern where these incidents are likely to occur and with what frequency. It's this holistic perspective—considering not just the 'if' but also the 'where' and 'how often'—that can provide the most comprehensive insight into mine safety and enable effective preventative measures. It's with this objective in mind that we embark on this chapter, delving deep into the relationship between collisions and intersections across various operational scenarios.

Indeed, a critical examination of the collision data from all the scenarios distinctly points out that intersections 0 and 4 are consistent hotspots for collisions. These intersections act as pivotal points within the mine's logistics Figure 38, bearing a considerable load of the truck traffic, which precipitates a higher incidence of collisions.

Intersection 0 serves as the initial crossing point for trucks entering the mine and a gateway to the "crusher." Consequently, it faces heavy traffic flow, inflating the risk and incidence of collisions. Similarly, intersection 4 is the conduit to the "source" or the "extraction front." Given its integral role in material flow, it witnesses substantial truck volumes, which likewise elevates collision probability.

In stark contrast, intersections 2 and 6 appear to be less prone to collisions due to their connections to the "dumps". These intersections generally see a lower flux of vehicles, and accordingly, the chances of collisions plummet at these points.

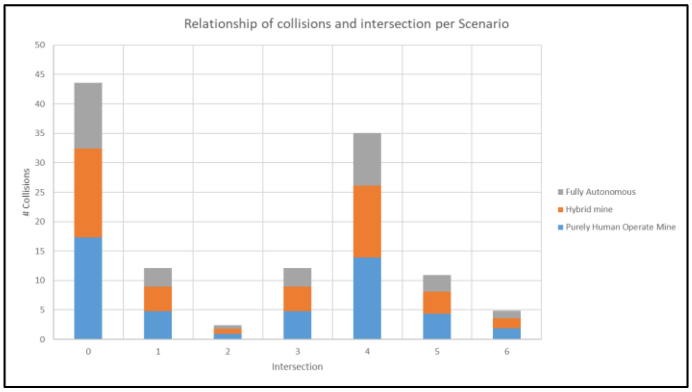

Figure 37 Collisions by intersection for all scenarios

The most intuitive way to comprehend and visualize this data is through heat maps Figure 39, Figure 40 & Figure 41, which have been crafted for all three scenarios. The heat maps depict collision frequency across the intersections using a color gradient: a translucent hue denotes lower ranges (0-5), while a vibrant red signals high collision numbers (17+). These heat maps serve as vivid illustrations of collision hotspots, guiding where precautionary measures need to be concentrated.

Given these findings, safety recommendations would include intensive monitoring and control at intersections 0 and 4, possibly enhanced by technologies such as proximity detection systems. Additionally, reevaluating traffic patterns and logistical flow through these intersections could help alleviate the congestion and subsequently reduce collision occurrences.

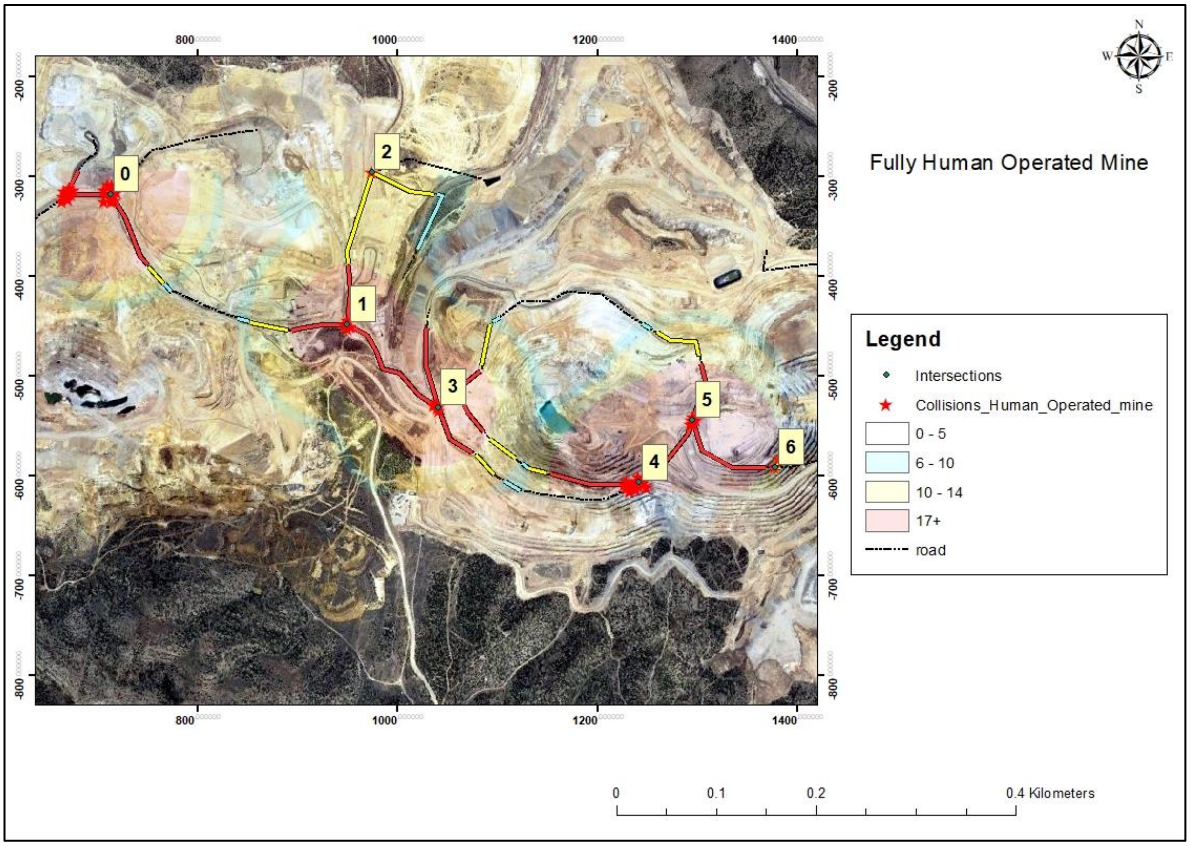

Figure 38 Fully Human Operated Mine

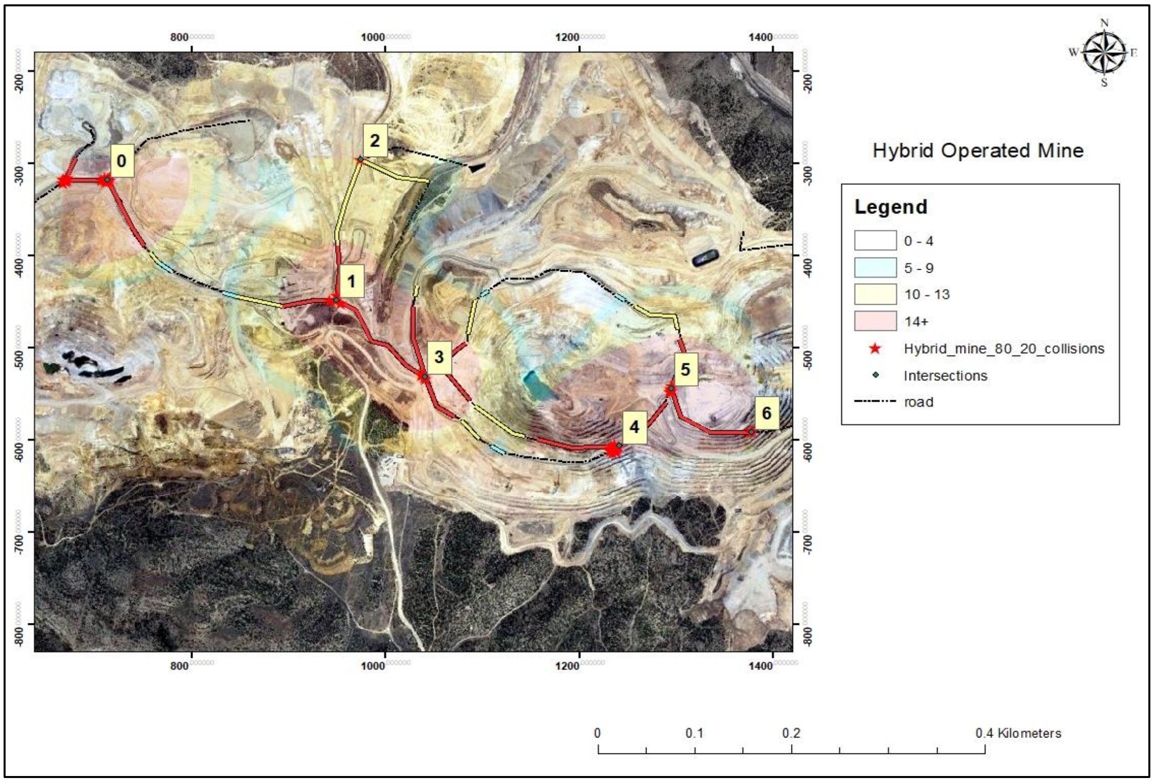

Figure 39 Fully Hybrid Operated Mine

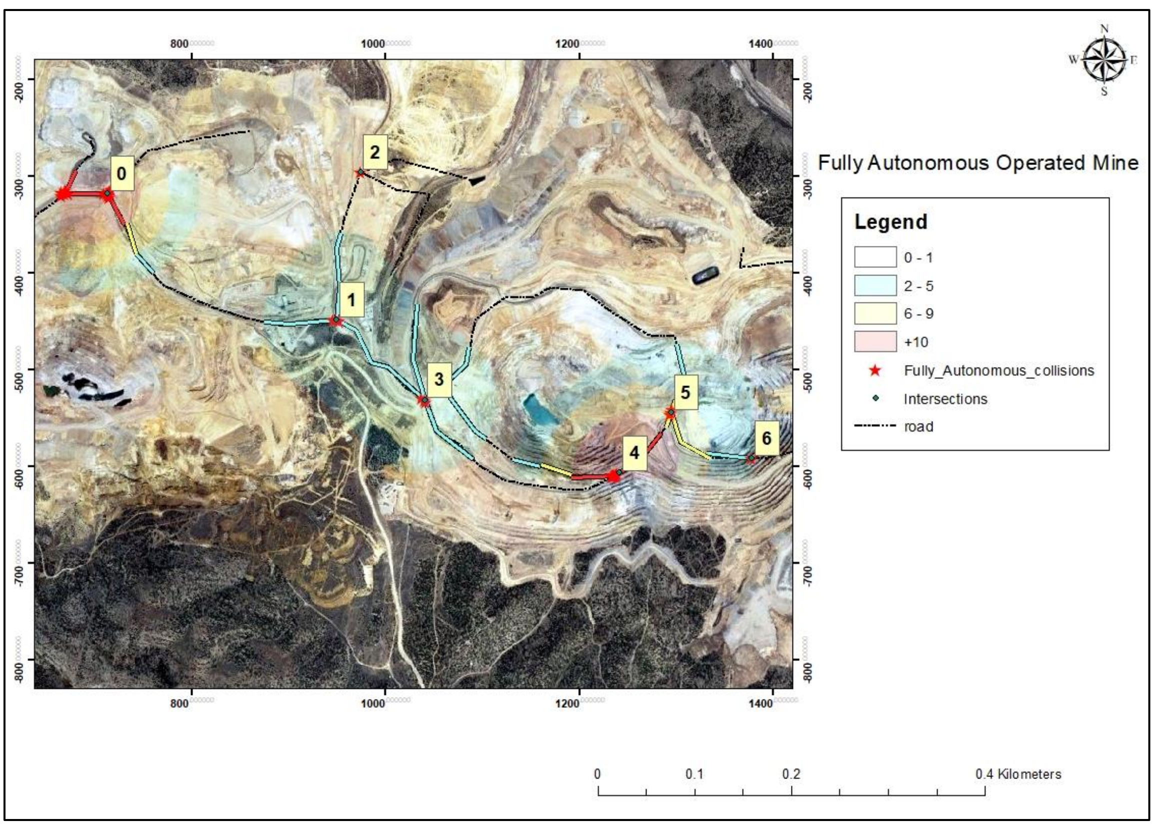

Figure 40 Fully Autonomous Operated Mine

The intersection and collision relationship analysis reveals intersections 0 and 4 as collision-prone hotspots across all scenarios. These intersections are integral to the mining operations, thereby handling a significant proportion of truck traffic, which leads to a higher incidence of collisions.

The heat maps corroborate this observation with the most collision-prone intersections - 0 and 4, registering prominently in red, indicating high collision numbers, and it decreases as much as far from these intersections the trucks are, with the “coolest” areas in the intersections 2 and 6, primarily leading to "dumps" and experiencing less vehicular flux, display a comparatively lower collision frequency.

It's essential to recognize that these findings aren't merely random patterns but indicate deeply embedded operational dynamics. The disproportionate burden of traffic at certain intersections magnifies the collision risk, an issue that needs critical attention. This disparity underlines the need for strategic interventions, including comprehensive risk management and traffic flow reorganization at intersections 0 and 4, to mitigate these collision hotspots and enhance overall safety within the mine.

4.2 Safety Assessment

In this chapter, we focus on the critical assessment of safety within the mining operations as depicted by our simulation results. The goal is to examine the effectiveness of current safety measures in place and discern potential areas requiring further enhancements. It uses various safety metrics and indicators identified in numerous studies to aid in the analysis.

Through an extensive review of the literature, key insights are incorporated from research focusing on the safety analysis of surface haulage accidents, hazards related to autonomous haulage systems, and the impact of factors such as employee age, experience, and daytime shift on the likelihood of accidents.

Through this analysis, we aim to understand how the Anylogic simulations align with real-world scenarios, and how we can use this information to bolster safety measures, reduce the risk of accidents at the implementation of autonomous trucks, and ultimately contribute to the health and well-being of mine workers.

In the next sections, it will delve deeper into these elements, breaking down the complexities of our safety assessment and shedding light on our findings.

4.2.1. Risk identification

In the analysis of the mining operations through the various simulated scenarios, several risks were identified that could impact the safety of autonomous haulage systems in open-pit mining operations. The examination of these risks provides not only a better understanding of potential hazards but also offers a foundation for strategies to mitigate them.

1. Traffic Risk: The simulation results demonstrate a higher number of collisions occurring at intersections 0 and 4. This is due to the high traffic volume at these points, as they provide key access to the crusher and the extraction front, respectively. Mitigation strategies might include improving traffic management at these intersections, possibly by implementing automated traffic control systems or exploring alternative routes to balance traffic flow.

2. Inexperience drivers: The simulation results indicate a noticeable reduction in collisions when experience levels exceed five years, highlighting the importance of experience in mining safety. Therefore, ensuring comprehensive training programs for employees, both for those operating the equipment and those in supervisory roles, can contribute to the mitigation of this risk.

3. Transition Risk: The shift from a purely human-operated mine to a hybrid mine introduces new risk factors. These risks may arise from a lack of familiarity with autonomous systems, potential communication issues between human-operated and autonomous vehicles, and changes in operational routines. Providing thorough training on the operation and expectations of autonomous systems, establishing clear communication protocols, and gradually transitioning operational routines can all help mitigate these risks.

4. Maintenance Risk: Autonomous vehicles, while reducing human error, introduce new forms of risks related to mechanical failure. Regular preventative maintenance, automated diagnostic systems, and emergency protocols for breakdowns can help reduce these risks.

5. Risk of Reduced Vigilance: With autonomous systems, there may be a risk of reduced vigilance due to over-reliance on automation. Regular safety audits, reinforced safety culture, and the implementation of advanced monitoring systems can counteract this risk.

These identified risks underline the complexity of safety considerations within mining operations, especially in the context of introducing autonomous systems. However, through careful attention to these factors and proactive safety measures, these risks can be managed and mitigated to create a safer working environment.

4.2.2 Risk Profile

In the analysis of the risk profile, the results obtained from the simulations play a vital role. These outcomes were meticulously evaluated and compared across different scenarios, culminating in a synthesized matrix that embodies the underlying complexity of the system. The matrix, as depicted in Table number 39, not only characterizes each simulated scenario with its respective number of collisions but also provides an intuitive risk categorization using color coding.

The color scheme employed offers a visual representation of the observed risk levels and is defined as follows:

- Red (D): High Risk - Scenarios with frequent collisions or other grave safety issues, necessitating immediate attention and intervention.

- Orange (C): Moderate Risk - Scenarios where collisions are less frequent but still present notable safety concerns that require monitoring and potential action.

- Yellow (B): Low Risk - Scenarios that are generally safe but may have minor issues or occasional collisions, suggesting room for further optimization.

- Green (A): Safe Condition - Scenarios that indicate optimal safety conditions with minimal or no collisions, reflecting a well-managed and controlled environment.

Table 39 Risk Profile Analysis:

Scenarios	**Number of Collisions**	**Experience 0-5 years**	**Experience 6-16 years**	**Experience 17+ years**	**Morning Shift**	**Afternoon Shift**	**Night Shift**
Scenario 1	1602	(D)	(C)	(B)	(D)	(C)	(B)
Scenario 2	1469	(C)	(B)	(B)	(C)	(B)	(A)
Scenario 3	31	(A)	(A)	(A)	(A)	(A)	(A)

4.3 Risk Mitigation Strategies

The simulation results, underpinning the risk analysis, allow us to identify several key areas where interventions could meaningfully reduce risk and improve overall safety in autonomous and hybrid mining operations. This chapter will detail several mitigation strategies, evaluating their effectiveness in response to the identified risks.

1. Autonomous Vehicle Implementation: One of the most significant risk mitigation strategies that the simulation data supports are the increased implementation of autonomous vehicles in mining

operations. The simulation data showed a drastic reduction in collisions in fully autonomous scenarios compared to those with a mix of autonomous and human-operated vehicles or human-only operations (Figure 43). This strategy directly reduces the risk of injuries and fatalities among mine workers.

2. Improving Operational Efficiency at Intersections: The results have shown a higher risk of collisions at intersections 0 and 4. Therefore, operational efficiency at these intersections could be improved by deploying advanced traffic management systems, including intelligent traffic signals or designated pathways for autonomous vehicles. In addition, traffic flow could be further improved by increasing road widths at these intersections, allowing for better vehicle maneuverability and reduced collision risk.

3. Robust Training Programs: For hybrid mining operations, a robust training program that focuses on improving human-automation interaction is crucial. This program could entail educating human drivers about the operational characteristics of autonomous vehicles and how to efficiently and safely interact with them. It could also cover general safety procedures and awareness.

4. Continuous Monitoring and Emergency Response Measures: Continuous monitoring of the mining operations, including vehicle health, traffic congestion, and weather conditions, is necessary to identify potential risk factors in real time. The monitoring data should inform a rapid response system capable of mitigating risks as they emerge.

5. Regular Maintenance and Inspection of Vehicles: Regular and thorough inspections of all vehicles, especially autonomous ones, are critical. Early detection of technical issues can prevent vehicle failures that may lead to accidents.

6. Road Maintenance and Proper Construction: Following the recommendations by MSHA (2008), maintaining roads in good condition, ensuring proper construction, and improving visibility can significantly reduce accidents. This includes the construction of adequate berms and effective drainage systems to manage water runoff, especially during the rainy season.

In implementing these strategies, evaluating their efficacy continuously and adjusting as necessary is important. This adaptive approach ensures that safety protocols evolve alongside advancements in autonomous technologies, operational practices, and our understanding of human-machine interactions in this context.

4.4. Mitigation strategy hazards associated with autonomous trucks.

The implementation of autonomous trucks in open pit mines brings with it a range of hazards and risks Figure 43. To mitigate these risks and ensure safe operations, it is essential to have effective mitigation strategies in place. Some of the mitigation strategies that can be employed include regular maintenance and inspections, safety protocols and procedures, and protective equipment. Table 40 will provide an overview of these strategies and how they can be implemented to manage risks associated with autonomous trucks in open pit mines.

Table 40 Mitigation strategies

Identification of Risk	Mitigation Plan	Category
Equipment failure	Regular maintenance and inspections of trucks and equipment	Maintenance
Cybersecurity threats	Implementing network security protocols and regular system updates	Security
Loss of communication	Regular checks and maintenance of communication equipment	Communication
Improper calibration of sensor devices	Regular calibration and maintenance of sensors	Maintenance
Slippery roads due to weather conditions	Reduce truck speed and/or pause operations until conditions improve	Weather-related
Collision with other vehicles or objects	Implementing collision avoidance systems and regular safety training	Safety

The main ideas from this table came from an adaptation of the following research:

- The Department of Mines, Industry Regulation and Safety of Western Australia (2021) emphasizes the importance of regular maintenance and inspection in identifying and mitigating hazards associated with autonomous trucks.
- Mishra (2023) highlights the importance of implementing network security protocols and regular system updates to manage cybersecurity threats.
- The Code of Practice for Safe Autonomous Mining in Western Australia recommends regular checks and maintenance of communication equipment to prevent loss of communication (Department of Mines, Industry Regulation and Safety, 2021). Proper calibration of sensor devices is also emphasized by the guidelines for the implementation of autonomous systems in mining (Palmer & Daneshmend, 2017).
- The need for reducing truck speed or pausing operations during adverse weather conditions is also highlighted in the Surface Mining: Main Research Issues for Autonomous Operations research (Jiang et al., 2017).
- Collision avoidance systems and regular safety training are also emphasized as important mitigation strategies by the International Organization for Standardization (2019).

To effectively manage hazards and risks associated with autonomous trucks in open pit mines, it is crucial to integrate them into an overall safety management system that includes a comprehensive risk assessment process (Department of Mines, Industry Regulation and Safety, 2021). This involves identifying potential hazards and developing appropriate controls to mitigate those hazards, such as regular maintenance, inspections, safety protocols and procedures, and protective equipment (Mishra, 2023). Risk assessments should be conducted at regular intervals and updated as needed to ensure that the system remains effective in preventing accidents and fatalities (Department of Mines, Industry Regulation and Safety, 2021).

Starting the implementation of a "hybrid" autonomous truck system by designating a restricted area exclusively for autonomous vehicles is a strategic approach to ensure a controlled and safe rollout. Intersection #6, for instance, could serve as an ideal testbed for this introduction. By confining the initial deployment to a specific intersection or zone, it allows for close monitoring and evaluation of the autonomous system's performance in real-world mining operations without overwhelming disruptions. Furthermore, it provides a controlled environment to identify any potential hazards or issues that might arise, thereby enabling timely interventions. This phased approach not only ensures the safety and efficiency of the operation but also helps in gradually building confidence and trust among the workforce and stakeholders. Over time, as the system proves its reliability and safety in this restricted area, expansions into broader zones can be considered, always keeping safety and efficiency as primary concerns. The restricted area idea for autonomous trucks could be an effective mitigation strategy to reduce the risk of collisions with other vehicles and objects in the mine (Tarek Gaber, 2021).

However, it is important to gradually introduce autonomous trucks to interact with regular trucks and other vehicles to ensure a smooth transition and minimize disruption to the mining operation (Department of Mines, Industry Regulation and Safety, 2021). Additionally, effective communication protocols and procedures must be in place to ensure the safe interaction of autonomous and regular vehicles (Jiang et al., 2017).

The Global Mining Guidelines Group (GMG) suggests a maturity model for autonomous mining operations, which assigns levels of autonomy to specific equipment and stages of maturity that reflect the overall operation's level of autonomy (GMG, 2019). This model is based on the SAE International (2018) taxonomy of driving automation terms and adapted to apply to mining automation using standard terminology from ISO 17757:2019 (International Organization of Standardization, 2019). The model defines six levels of autonomy, ranging from no automation (Level 0) to fully autonomous (Level 5) as shown in Figure 44. The model can be used to assess the maturity of a mine's autonomous operations, from manual operation to hybrid operation, and highly autonomous operation (GMG, 2019).

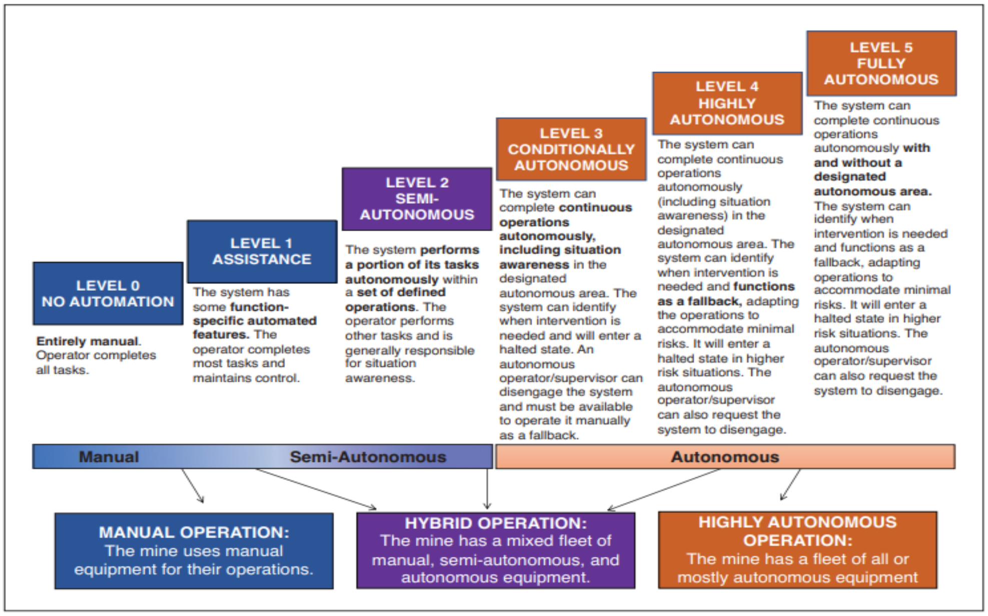

Figure 41 Mining Automation Maturity Model (Figure Design by (Global Mining Guidelines Group, 2019))

4.4.1. Investigation of ways to reduce the probability of accidents in autonomous trucks.

The evolution from a solely human-operated mining environment to a hybrid model, where both autonomous trucks and human personnel share the same space, undeniably introduces complexities in managing safety. As evidenced in Figure 43, even with advancements in autonomous technologies, there remains a notable probability of collisions. This underscores the imperative need to stringently minimize all potential accidents.

The literature teems with a plethora of strategies aimed at curtailing the risks associated with the integration of autonomous trucks in mines. These strategies range from technological solutions, and infrastructural modifications, to operational shifts and training. Such proposed strategies underline the collective acknowledgment of the industry and academia regarding the significance of safety in these transformative times for the mining sector. The ultimate goal remains consistent: to harness the benefits of autonomous technologies while ensuring the safety and well-being of every individual on-site. In the following sections, we will delve deeper into these proposed strategies, critically analyzing their feasibility, advantages, and potential shortcomings in the context of our study.

One of the ways to reduce the probability of accidents is to ensure proper training and education for the operators and maintenance personnel. This will help them to have a better understanding of the capabilities and limitations of autonomous trucks and identify potential hazards. The Global Mining Guidelines Group recommends training operators on safe interaction with autonomous vehicles and how to identify and report issues (Global Mining Guidelines Group, 2019).

Another way to reduce the probability of accidents is through regular maintenance and inspection of autonomous trucks. This can help to detect any malfunctions or component failures before they cause an accident. The Code of Practice for Safe Autonomous Mining in Western Australia recommends that autonomous vehicles be regularly inspected and maintained (Department of Mines, Industry Regulation and Safety, 2015).

Furthermore, the use of protective equipment such as proximity detection systems and collision avoidance technologies can help to reduce the probability of accidents involving autonomous trucks. Proximity detection systems can alert the operator and the autonomous system when there is a risk of collision with other vehicles or objects in the mine. Collision avoidance technologies can automatically stop or slow down the truck when it detects a potential collision (Tarek Gaber, 2021).

A summary of the ways to reduce the probability of accidents with autonomous trucks in open pit mines is presented in Table 41.

Table 41 Ways to reduce the probability of accidents with autonomous trucks in open pit mines.

Identification of Risk	**Mitigation Plan**	**Category**	**Reference**
Insufficient training of personnel	Provide proper training and education for operators	Training	Global Mining Guidelines Group (2019)
	and maintenance personnel		
Inadequate maintenance and inspection	Regularly inspect and maintain autonomous vehicles	Maintenance	Department of Mines, Industry Regulation and Safety (2015)
Risk of collision with other vehicles or objects in the mine	Use proximity detection systems and collision avoidance technologies	Protective Equipment	Tarek Gaber (2021)

References: Department of Mines, Industry Regulation and Safety. (2015). Code of Practice for Safe Autonomous Mining in Western Australia. Government of Western Australia. Global Mining Guidelines Group. (2019). Guideline for the implementation of autonomous systems in mining. Global Mining Guidelines Group. Tarek Gaber. (2021). Autonomous Mining Trucks: Risks, Hazards and Safety Measures. Journal of Loss Prevention in the Process Industries, 71, 104484.

4.5 Limitations and Future Research

The simulation conducted in this study, while instrumental in shedding light on the impacts of varying degrees of autonomous haulage system implementation in open-pit mining operations, is subject to certain limitations that warrant discussion. Furthermore, acknowledging these limitations paves the way for future research directions to refine our findings and contribute to a more nuanced understanding of the subject matter.

- Data Availability: One of the key constraints of this study is the limited availability of detailed data from the mine. Information about specific mine layouts and haulage operations for June and July were available, but numerous operational parameters such as loading and unloading times, fleet sizes, vehicle speed, acceleration and deceleration, inter-vehicle distances, shift times, production goals, and working days were not. These parameters were, therefore, estimated based on averages from the industry. Future research should aim to utilize detailed, mine-specific data to improve the precision of the simulation outcomes.
- Model Simplifications: To facilitate the simulation process using HAULSIM software, a certain degree of model simplification was inevitable. While these simplifications were necessary and commonly accepted within the simulation community, they may not fully capture the complexity of real-world mining operations. Future studies should consider incorporating more detailed aspects of mine operations into the simulation model.
- Assumptions: The simulation model was developed based on a series of assumptions. This approach, while feasible and efficient, may lead to deviations between the simulation results and real-world scenarios. Future research should seek to substantiate these assumptions with empirical data wherever possible.
- Collision Data: The data sourced from Zhang (2014) and NIOSH (2023) provided critical insights into collision incidences. However, the reported values were exceptionally high compared to a typical mining operation, potentially skewing the analysis of collision risks and safety measures.

Future research in this area should aim to address these limitations. Greater collaboration with mining companies to access more comprehensive data would enhance the simulation's realism and applicability. Additionally, further advancements in simulation technology and methodologies may allow for more complex and accurate modeling of mining operations. By building on the work presented in this study, future research can continue to explore and enhance the safety benefits of autonomous haulage systems in open-pit mining.

5. Conclusion and Recommendations

The essential objective of this research was to develop a discrete event simulation model for an open-pit mining operation. The simulation aimed to identify, analyze, and evaluate the risks associated with the introduction of autonomous haulage systems. It also endeavored to create a realistic representation of the mine environment, providing essential safety information for the implementation of autonomous in a non-autonomous mining operation.

The development of this safety assessment necessitated the use of two simulation software applications - HAULSIM and AnyLogic. The initial stage of simulation planning and conceptual design was conducted with HAULSIM, establishing a solid foundation for the simulation model. However, due to certain limitations in HAULSIM, it became necessary to complement and enhance it with AnyLogic, which facilitated the development of a comprehensive discrete event simulation model.

AnyLogic was employed to construct the full-fledged simulation model, integrating various components of the mining operation. These components included the mine layout, haulage operations, and different scenarios of fleet compositions (fully autonomous, hybrid, and non-autonomous). This provided a comprehensive platform to analyze collision risks - a critical area of concern highlighted in mining safety literature (Zhang, 2014; NIOSH, 2023).

The ensuing analysis of the simulation results revealed a direct, inverse relationship between the number of collisions and the proportion of autonomous vehicles in operation. Through the empirical equation created in the study, it was shown that the fully autonomous scenario presented the lowest risk, manifesting significantly fewer collisions than the hybrid and non-autonomous scenarios. Further examination of the model highlighted the pivotal role of intersections in the mine, identifying Intersection 0 and Intersection 4 as high-risk areas due to their dense traffic. The results elucidated the potential impact of the different scenarios on safety outcomes, substantiating the purpose and significance of the simulation model.

From a safety perspective, the introduction of autonomous haulage systems can lead to a significant reduction in collision risks. This aligns with studies by Santos et al. (2010) and Kecojevic & Md-Nor (2009), which emphasize the potential of autonomous systems in reducing equipment-related injuries and fatalities. However, the safety evaluation should not overlook the potential risks associated with autonomous operations. These include unforeseen technical failures or malfunctions, which can lead to accidents or disruptions in mine operations.

Considering the simulation results and safety literature, we recommend adopting a gradual approach to implementing autonomous haulage systems in mining operations. Start with pilot programs in low-risk areas (intersection 6) before expanding to high-risk zones such as Intersection 0 and Intersection 4. Regular safety audits and assessments should be conducted to evaluate the effectiveness of these systems, as suggested by Drury et al. (2012) and MSHA (2008).

In conclusion, the study has met its intended objectives by providing a realistic simulation of a mining operation and enabling critical analysis of safety risks associated with various fleet compositions. The use of discrete event simulation in this study has demonstrated its potential as a powerful tool for safety evaluation and decision-making in mining operations. However, the results should be interpreted with caution due to the high values of collision data from the literature and certain assumptions made in the simulation model.

5.1 Recommendations

The completion of this study does not mark the end of research in this area, but rather, it opens new avenues for exploration. The results gleaned from the simulation, albeit insightful, were limited by the assumptions made and the generic nature of the operational data. To enhance the accuracy and applicability of the simulation model, future research should seek to incorporate more detailed, mine-specific data. This includes parameters such as exact haulage distances, operational schedules, specific loading and unloading times, and precise truck specifications. A greater depth of data would permit more nuanced simulations, accurately reflecting the complex realities of a mining operation.

Considering the licensing constraints of the Analogic software, our exploration of its expansive capabilities was inevitably limited, particularly when designing the logic flowchart and integrating elements such as "action blocks," "agents," and "variables". As depicted in Figure 3, this led to a restrained number of actionable constructs within the program. Nevertheless, despite these limitations, the software proved instrumental in quantifying the collisions observed during the hauling simulation. Future endeavors might benefit from securing a more comprehensive license or alternative software solutions to fully harness the potential of such simulation tools.

As autonomous technology continues to evolve, it will become increasingly crucial to test the latest equipment and scenarios within the simulation framework. Future studies could benefit significantly from trialing recently developed autonomous vehicles, algorithms, and dispatch systems, and analyzing their safety performance in a controlled environment before on-site implementation.

Moreover, future research could investigate collecting empirical data from mining operations that have already implemented autonomous haulage systems. Such first-hand information could provide invaluable insights into the actual safety performance of these systems, which could then be contrasted and validated with the simulation results. Learning from the experiences of these pioneering projects could provide a more robust understanding of the real-world challenges and risks of implementing autonomous haulage systems.

Furthermore, as the nature of mining operations is continually evolving with technological advancements, the simulation models should evolve concurrently. This includes integrating new safety measures and protocols, reflecting changes in regulatory standards, and incorporating technological advancements in related sectors, such as AI-driven analytics, real-time tracking systems, or advanced vehicle safety features. This evolution in the model will ensure that it remains relevant and valuable as a tool for safety evaluation and decision-making in the mining industry.

Finally, the development and promotion of best practice guidelines for implementing autonomous technology in mining operations is strongly recommended. Based on the insights gained from this study and future research, these guidelines should emphasize rigorous safety evaluations and risk mitigation measures before, during, and after implementation. They should also highlight the need for regular monitoring and evaluation of the safety performance of autonomous systems, enabling continuous learning and improvement. In this way, the implementation of autonomous technology can contribute to enhancing both safety and productivity in the mining environment.

References

Aleksandr Rakhmangulov, K. B. (2021). Sustainable Open Pit Mining and Technical Systems: Concept, Principles, and Indicators. *Sustainability*.

Amanda Smith, J. L. (2021). Optimization-based dispatching policies for open-pit. *Springer Science+Business Media, LLC, part of Springer Nature*.

ANSI. (2019). *AS/NZS 62061:2019 Safety Of Machinery - Functional Safety Of Safety-Related Electrical, Electronic, And Programmable Electronic Control Systems.*

Baafi, A. J. (1999). Discrete event simulation of mining systems: Current practice in Australia. *International Journal of Surface Mining, Reclamation and Environment*.

Bastos, G. S. (2010). METHODS FOR TRUCK DISPATCHING IN OPEN-PIT MINING. *Research Gate*.

BBC UK. (2023). *BITESIZE*. Obtenido de https://www.bbc.co.uk/bitesize/guides/z6scbdm/revision/1

Both, C. (2016). Review of the Applicability of Discrete Event Simulation for Process Optimization in Mining.

Casey, J. (20 de March de 2019). *Mining Technology*. Obtenido de https://www.mining-technology.com/news/two-autonomous-trucks-collide-in-heavy-rain-at-bhps-jimblebar-hub/

Center for Disease Control and Prevention. (2023). *NIOSH mining*. Obtenido de https://wwwn.cdc.gov/NIOSH-Mining/MMWC/Injuries/NumberAndRate?StartYear=1995&EndYear=2011&SelectedOperatorType=&SelectedMineType=

David Valis, M. K. (2009). SELECTED OVERVIEW OF RISK ASSESSMENT TECHNIQUES. *Probl. Eksploat*, 19-32.

Department of Mines and Petroleum. (2015). *code of practice: Resources Safety, Department of Mines and Petroleum, Western Australia, 30 pp.*

European Technology and Innovation Platform. (2018). Batteries Europe. *European Commission under Tender*, 33-36.

Evrin, V. (2019). Risk Assessment and Analysis Methods: Qualitative and Quantitative. *ISACA*.

Fahl, S. K. (2019). Benefits of Discrete Event Simulation in Modeling Mining Processes. *Procedia Manufacturing*.

Fishwick, P. A. (1995). *Simulation Model Design and Execution: Building Digital Worlds.* Prentice Hall.

Global Mining Guidelines Group. (2019). *GUIDELINE FOR THE IMPLEMENTATION OF AUTONOMOUS SYSTEMS IN MINING.*

Global Mining Guidelines Group. (2021). *System Safety for Autonomous Mining (White Paper).* Canadian Institute of Mining, Metallurgy, and Petroleum.

Goodbody, A. (31 de May de 2013). Feeling tired? *Mining Magazine. 7*, págs. 38-48.

Guangwei Liu, S. C. (2019). Optimizing Open-Pit Truck Route Based on Minimization of Time-Varying Transport Energy Consumption. *Hindawi, Mathematical Problems in Engineering*.

Guohua (Annie) Wu and Yingnan (Jason) Li, J. T. (01 de March de 2021). *Mining in China: an overview.* Obtenido de Thomson Reuters Practical Law: https://uk.practicallaw.thomsonreuters.com/w-011-1348?transitionType=Default&contextData=(sc.Default)&firstPage=true#co_pageContainer

Hanna Ziady. (13 de 03 de 2023). *CNN BUSINESS.* Obtenido de https://edition.cnn.com/2023/03/13/investing/silicon-valley-bank-collapse-explained/index.html

Ignacio Andrés Osses Aguayo, M. N. (2021). Optimizing Productivity and Safety of the Open Pit Loading and Haulage System with a Surge Loader. *mining*.

International Electrotechnical Commission. (2021). *IEC 62061:2021 Security for industrial automation and control systems.*

International Organization for Standardization. (2010). *ISO 12100:2010.*

International Organization for Standardization. (2018). *ISO 26262-1:2018.*

International Organization for Standardization. (2018). *ISO 31000:2018.*

International Organization of Standardization. (2019). *ISO 17757:2019 Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety*.

International Organization of Standardization. (2022). *ISO 21448:2022 Road vehicles — Safety of the intended functionality.*

JaamSim. (2023). Obtenido de https://jaamsim.com/index.html

Jamasmie, C. (15 de February de 2019). *Mning.com*. Obtenido de https://www.mining.com/driverless-trucks-not-flawless-two-crash-fortescue-mine-australia/

Jeong Dahee, J. B.-s. (2020). Open-pit mining truck-loader transportation system using Anylogic. *Korean Society of Resources Engineering Journal of The Korean Society of Mineral and Energy Resources*.

JinPeng. (Junio de 2006). *World-class EPCM Supplier-JinPeng*. Obtenido de https://www.jinpengmining.com/solution/content/Graphite-mineral-processing-flowsheet-21.html?tracking=search&device=c&campaign=0111_search_edge&keyword=graphite%20mining&matchtype=e&adposition=&gclid=Cj0KCQiA47GNBhDrARIsAKfZ2rCkuqTQBKFXttbHCfh4YN4W6FhX97J

John Meech, J. P. (2011). An interactive simulation model of human drivers to study autonomous haulage trucks. *Elsevier B.V.*

Matsimbe Jabulani, G. S. (2020). Assessment of Safety Culture and Maturity in Mining Environments: Case of Njuli Quarry. *The Asian Institute of Research*.

Michelle Blom, A. R. (2018). Short-Term Planning for Open Pit Mines: A Review. *n International Journal of Mining, Reclamation and Environment*.

Mine Safety and Health Administration. (2006).

Mohammad Tabesh, S. P.-N. (2016). Discrete Event Simulation of Truck-Shovel Operations in Open Pit Mines1. *MOL Report Seven*.

Open SIMPLY. (2023). Obtenido de https://opensimply.org/

Panagiotou, G. N. (1999). Discrete mine system simulation in Europe. *International Journal of Surface Mining, Reclamation and Environment, 13:2, 43-46*.

Pandey, B., & Mishra, D. (2023). Developing an Alternate Mineral Transportation System by Evaluating Risk of Truck Accidents in the Mining Industry—A Critical Fuzzy DEMATEL Approach. *Sustainability*.

REGULATION (EU) 2018/858 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. (2018).

Richard A. Brealey, S. C. (2017). *PRINCIPLES OF CORPORATE FINANCE, TWELFTH EDITION.* New York: McGraw-Hill Education.

RPMGLOBAL. (2023). Obtenido de https://rpmglobal.com/es/product/haulsim/

S. Al-Thyabat, T. N. (2013). Adaptation of minerals processing operations for lithium-ion (LiBs) and nickel metal hydride (NiMH) batteries recycling: Critical review. *Science Direct*.

Sanaa Benlaajili, F. M. (2021). Infrastructural requirements for the implementation of autonomous trucks in open-pit mines. *6th International Innovative Mining Symposium.*

Satar Mahdevari, K. S. (2014). Human health and safety risks management in underground coal mines using fuzzy TOPSIS. *Elsevier B.V.*

Saurabh Parakh, N. R. (2021). SIMULATING BACKFILL OPERATIONS FOR UNDERGROUND MINING. *Winter Simulation Conference.*

Schafer, H., Beier, N., & Macciotta, R. (2021). A Failure Modes and Effects Analysis Framework for Assessing Geotechnical Risks of Tailings Dam Closure. *Minerals*.

Shirong Ge, F.-Y. W. (2022). Making Standards for Smart Mining Operations: Intelligent Vehicles for Autonomous Mining Transportation. *IEEE TRANSACTIONS ON INTELLIGENT VEHICLES*.

Simmons, R. (1998). *System Safety and Risk Management.*

SimPy. (2020). Obtenido de https://simpy.readthedocs.io/en/latest/

Smiley, L. (22 de March de 2022). *Wired*. Obtenido de https://www.wired.com/story/uber-self-driving-car-fatal-crash/#:~:text=In%202018%2C%20an%20Uber%20autonomous,behind%20the%20wheel%20finally%20speaks.&text=Rafaela%20Vasquez%20liked%20to%20work,assigned%20her%20the%20Scottsdale%20loop.

Snezana Kirin, W. L. (2020). Rules of Risk Management - Case Study of Open Pit Mine. *Elsevier B.V.*

Sturgul, J. (1999). Discrete mine system simulation in the United States. *International Journal of Surface Mining, Reclamation and Environment, 13:2, 37-41*.

Tarek Gaber, Y. E. (2021). Autonomous Haulage Systems in the Mining Industry: Cybersecurity, Communication and Safety Issues and Challenges. *electronics*.

Tayfur Altiok, B. M. (2007). *Simulation Modeling and Analysis with ARENA.* Academic Press.

The Anylogic Company. (2023). *Anylogic mining*. Obtenido de https://www.anylogic.com/mining/

The International Council on Mining and Metals. (2018). *Health and Safety Critical Control Management-Good Practice Guide.*

Walter Frick. (05 de 2019). *Harvard Business Review*. Obtenido de https://hbr.org/2019/05/how-to-survive-a-recession-and-thrive-afterward

Xiaotong Zhang, A. G. (2022). Real-Time Scheduling of Autonomous Mining Trucks via Flow Allocation-Accelerated Tabu Search. *IEEE TRANSACTIONS ON INTELLIGENT VEHICLES, VOL. 7, NO. 3*.

Xiaowei Lu, Y. A. (2020). Real-Time Mine Road Boundary Detection and Tracking for Autonomous Truck. *Sensors*.

Zhang, M. (2014). Analysis of Haul Truck- Related Fatalities and Injuries in Surface Coal Mining in West Virginia. *Graduate Theses, Dissertations, and Problem Reports. 7031*.