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FRAMEWORK FOR IMPLEMENTING UNMANNED HAULAGE TRUCK IN OPEN PIT MINE

Bachelor's Thesis

Written By: **DULGUUN** Battulga

Study program: Mechanical engineering

Student ID: B2100188

1st Supervisor/Examiner: Prof. Sungchil Lee

2nd Supervisor/Examiner: Prof. Young Suk Kim

Ulaanbaatar/Nalaikh

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Statutory Declaration

DULGUUN Battulga B2100188

Last Name, First Name Student ID Number

I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

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I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

May 28,2025

Place, Date Signature

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ABSTRACT

The use of autonomous trucks can significantly enhance the operational efficiency, sustainability, and safety of both small and large open-pit mines. Automation protects workers from accidents and unhealthy environments while also improving their efficiency and productivity. Autonomous trucks offer many advantages over manually operated trucks, providing a more comfortable and safer working environment for workers and creating a more economically efficient for companies in the long term. Although autonomous trucks travel at slightly slower speeds than Manual trucks, they are more productive because they eliminate the need for shift changes and lunch breaks. They also increase fuel efficiency by reducing idle time, saving approximately 0.06 liters of fuel per tonne hauled, and improving utilization rates by 10–13%. While these figures may not seem significant at first glance, they result in substantial savings over the long term. However, implementing an automated system requires time, a large amount of capital cost, and potential challenges such as worker concerns about job security must be carefully managed. For the successful deployment of autonomous dump trucks, several factors must be considered, with infrastructure and safety being the most critical.

For example, mine roads should be designed without sharp turns or steep slopes, as the vehicle's sensor system may misinterpret sharp changes and cause accidents. Additionally, if a person or vehicle without a radio frequency identification (RFID) tag enters the automated zone, there is a heightened risk of collision and serious accidents. Therefore, autonomous vehicle zones must strictly adhere to ISO road standards, and unauthorized persons and vehicles must be strictly prohibited from entering the automated sections of the mine. It also includes information on factors influencing fuel consumption in automotive performance, such as road gradient, adhesion and friction coefficients, wind resistance, and methods for calculating appropriate gear selection on slopes. Additionally, identifying the most relevant data for this type of research proved to be a significant challenge.

INTRODUCTION

Haulage trucks were among the first mining operations selected for automation in open-pit mining. Leading manufacturers such as Komatsu, Caterpillar, Liebherr, Hitachi, and Kenworth pioneered Autonomous Haulage Systems (AHS), accelerating widespread industry adoption. Initially introduced in Chile in 2005, the technology expanded quickly; by 2022, Australia alone had implemented autonomous haulage trucks across 25 mines, surpassing the 19 autonomous mines in all other countries combined. By July 2024, around 2,000 autonomous trucks were operational worldwide, reflecting the technology's growing global acceptance.[1]

AHS replaces human drivers with centralized systems that direct truck movements, thereby improving operational efficiency, reducing labor costs, and facilitating uninterrupted operations. Machine-controlled driving enhances fuel efficiency, extends equipment lifespan, reduces maintenance requirements, and improves safety by precisely monitoring vehicle speed and position to prevent collisions.[2]

Although open-pit mining involves physical constraints such as road width and bench configurations, autonomous trucks considerably reduce the risk of accidents for operators and auxiliary equipment. Advanced technologies—including GPS, wireless communication, obstacle-detection sensors, onboard computing, and artificial intelligence—enable trucks to function autonomously or be remotely controlled from safe locations. Autonomous driving also promotes consistent vehicle operation, minimizing wear on tires, brakes, and mechanical components, thus prolonging their operational life.[3]

Human drivers often experience fatigue during long shifts, causing inconsistent driving behavior and fuel inefficiencies of up to 35%. Additionally, traditional operations include unnecessary idling during driver shift changes, resulting in fuel consumption between 1.6 and 5.5 liters per hour and increasing carbon emissions. Autonomous truck fleets significantly reduce idle time, lowering emissions, decreasing operating costs, and supporting sustainability objectives.[3]

While haulage automation has significantly advanced, fully automating all mining processes—such as drilling, blasting, digging, and loading—remains challenging due to their complexity. However, ongoing data integration and increasing automation continue to reshape the mining industry, making it safer, more efficient, and more sustainable.

2 BACKGROUND

2.1 Performance Measures

A measure is a quantifiable value representing observable performance, while a metric is a numerical expression evaluating how effectively a system, component, or process achieves a specific attribute, often through comparing multiple measures [4]. For example, a mine producing 10,000 tonnes per week uses metrics to capture variability, with daily outputs highlighting deviations from the target.

An indicator is a variable reflecting a condition or outcome based on process results, typically involving a metric's comparison to a baseline or expected standard. In this context, actual weekly production compared to scheduled targets informs managerial decisions.[4] Performance represents the collective outcome of various measures and metrics, supporting informed decision-making to enhance organizational efficiency.

Three primary types of indicators are used for process monitoring:

- **Key Result Indicators (KRIs):** Show achieved outcomes but do not indicate improvement actions.
- **Performance Indicators (PIs):** Identify necessary actions to reach targets.
- **Key Performance Indicators (KPIs):** A critical subset of PIs used to proactively address issues before impacting performance [3].

Key monitoring areas include:

Payload / Production / Productivity

- Tonnes per cycle (variance)
- Tonnes per unit time

Cycle Performance

- Number of cycles per day
- Cycle time per day
- Queuing time per cycle
- Human breaks per day
- Process delays per day

Fuel Consumption

- Liters per hour (L/h)
- Liters per cycle (L/cycle)
- Liters per tonne (L/tonne)

Utilization

- Percentage of time trucks are operational

Mechanical Availability

- Percentage of time trucks are mechanically available

Maintenance

- Mean Time Between Failure (MTBF)
- Mean Time To Repair (MTTR) [5]

Accurate KPI interpretation is crucial. For instance, an increase in fuel consumption per hour (L/h) in Autonomous Haulage Systems (AHS) does not necessarily imply reduced efficiency, as trucks operate continuously without rest periods. Therefore, indicators like liters per cycle (L/cycle) or liters per tonne (L/tonne) offer a clearer picture of true efficiency gains, with decreases confirming improved fuel performance [5].

2.2 Automation

Original equipment manufacturers today face growing challenges, including rising customer demands, intensified global competition, environmental pressures, and fluctuations in currency markets. To stay competitive, mining companies increasingly adopt automation to boost efficiency, enhance product quality, improve safety, cut operational costs, and ensure timely deliveries. Automation is particularly vital in mining, given the shortage of skilled labor and the necessity to access remote or challenging ore deposits. Its primary goal is to replicate human decision-making and capabilities through controlled systems.[6] Automation encompasses various operational levels, from supervised and semi-automatic to fully autonomous systems, with each step requiring progressively reduced human involvement. In mining, automation commonly includes equipment such as autonomous haulage trucks controlled by sensors and onboard computer systems. Nevertheless, human oversight remains essential, especially for maintenance tasks or during emergencies such as power outages. Although automation minimizes human exposure to hazardous or repetitive tasks, improving safety, it also necessitates developing new workforce competencies. Workers must be trained in software operations and system management to accommodate evolving roles resulting from automated technologies [**7**].

2.3 Application of Automation in Mining

Automation in mining first emerged during the late 1990s and early 2000s, driven by the need to enhance worker safety and boost productivity. Automated systems help reduce human errors, particularly fatigue-related mistakes arising during long shifts. Today, automation is widely implemented across mining operations of all scales, using equipment ranging from small water sprayers to massive 300-ton haul trucks [5]. Common automation technologies include tracking systems, telemetry, remote-controlled equipment, and robotics. In drilling operations, wireless networks and GPS enable remote control of machinery, reducing worker exposure to hazards such as dust, noise, and physical danger, although injuries still occasionally occur, particularly in exploration and petroleum drilling.

In open-pit mining, systems such as Caterpillar's MineStar demonstrate the advantages of semi- and fully autonomous technologies. MineStar utilizes high-precision GPS, radar, and obstacle-detection systems, enabling trucks to navigate constrained spaces with minimal human intervention. First implemented at Fortescue Metals Group’s Solomon Hub in 2013, MineStar enabled real-time route optimization, reduced vehicle idling, and improved fuel efficiency. Trucks operating at speeds up to 55 km/h (34 mph) increased productivity by reducing cycle times up to 15%, lowered fuel usage, and minimized tire wear. Additionally, eliminating driver fatigue substantially improved operational safety [8]. Although automation initially focused on underground mining, its underground implementation remains complex and expensive. Autonomous underground operations necessitate expanded access tunnels, enhanced ventilation systems, drainage, and temperature regulation. While future innovations might revolutionize underground mining methods, deep mining operational costs continue to increase. In contrast, open-pit mining has realized quicker and clearer benefits from automation. Despite road width and bench limitations affecting equipment size, autonomous trucks equipped with GPS, sensors, wireless communication, and AI safely navigate without human drivers. Real-time tracking of vehicle positions and speeds significantly reduces collision risks and maintenance demands. Although breakdowns may still occur, predictive maintenance effectively prolongs vehicle lifespan and minimizes downtime. Overall, mining automation continues to enhance safety, efficiency, and supports sustainable long-term operations [9].

2.4 Autonomous Haulage System

Existing fleets of open-pit haul trucks can be upgraded for autonomous operations by integrating several critical components, including:

- A wireless communication network to enable real-time data transmission
- Navigation and obstacle-avoidance sensors
- Onboard computing units to process sensor inputs and control vehicle functions such as acceleration, steering, and braking
- Controllers for precise regulation of final-control elements
- A central processing unit to manage communication and vehicle coordination
- High-accuracy GPS (with localization within 10 cm) for precise positioning across the mine site
- Software systems for local vehicle control and overarching supervisory management [7].

Leading original equipment manufacturers (OEMs), including Komatsu, Caterpillar, and Hitachi, continue to spearhead advancements in Autonomous Haulage Systems (AHS). Komatsu's Front Runner AHS has been successfully implemented at iron ore and coal mines across Australia, as well as locations in North and South America. Caterpillar's Cat MineStar Command system supports autonomous haul trucks, such as the CAT 793F and 797F, notably at Fortescue's Solomon Hub and BHP's Jimblebar mine in Western Australia. Hitachi, meanwhile, has integrated its AHS capabilities with Wenco's fleet management software to create scalable autonomous systems undergoing trials worldwide. Rio Tinto's "Mine of the Future" initiative has developed one of the world's largest autonomous mining truck fleets, remotely managed from the company's Operations Centre in Perth. Similarly, in 2019, Vale introduced Caterpillar's MineStar Command system at its Minas Gerais mine in Brazil, retrofitting conventional trucks with autonomous technology. Equipped with GPS, LiDAR, radar, and centralized control systems, these trucks operated alongside manually driven vehicles. Vale reported significant operational improvements, including a 26% increase in production, notable reductions in fuel usage, and a remarkable 93% decrease in safety incidents involving human exposure. Additionally, continuous operation without shift changes further enhanced overall productivity and efficiency [10] Despite these substantial advantages—including greater fuel efficiency, extended equipment life, improved safety, and enhanced production accuracy—AHS implementation does present challenges. Communication reliability, particularly network bandwidth and latency, can significantly impact system effectiveness, especially in large-scale operations with extensive autonomous fleets. Therefore, mining companies must thoroughly evaluate both operational benefits and broader organizational impacts when considering autonomous technology adoption [9].

2.5 Economics of Automation

The introduction of autonomous systems in mining operations affects not only the mine's economy and supply chain but also local communities and businesses. However, the full economic impacts remain uncertain, given the relatively recent adoption of these technologies. In discussions on automation and sustainable development, it is essential to highlight positive outcomes for both society and the environment. Companies and governments should prioritize reinvesting automation gains into innovations that support environmental protection and social welfare, rather than merely exploiting natural resources. As mining automation advances, companies are expected to implement these technologies first in controlled environments where benefits can be more readily achieved [5].

2.6 Implementation of a Successful Project

Successfully automating mining equipment requires a clear strategy, strong leadership commitment, and a long-term vision. Mining companies can assess the success of an Autonomous Haulage System (AHS) project by linking specific performance criteria to each project phase, including implementation, start-up, and ongoing operations.

There are three general approaches to implementing autonomous trucks:

- **Slow Implementation:** A low-risk, high-cost strategy involving gradual deployment with multiple checkpoints, allowing time for research and integration of new developments.
- **Phased Implementation:** A medium-risk, medium-cost approach that progresses through several stages, blending mature and emerging technologies with two or three evaluation points.
- **Rapid Implementation:** A high-risk, lower-cost method where traditional operations are quickly replaced with proven commercial autonomous solutions [9][11].

Integrating AHS with Manual Haulage Systems (MHS) introduces safety challenges, particularly when autonomous and manned vehicles share haul routes or loading and dumping zones. Workers may express concerns about job security and operational safety near autonomous trucks. To mitigate these risks, detailed planning, system redundancies, and backup procedures are essential. Key competencies for a successful AHS rollout include:

- Fundamentals of process control
- Understanding control stability
- Supervisory control systems
- Software algorithm development
- Artificial intelligence techniques
- Large database management
- Sensor operation and maintenance
- Remote equipment operation [9].

Strong interdepartmental communication is critical during the automation transition. Sharing KPI reports across teams can highlight operational improvements and reveal additional performance indicators, such as sensor efficiency and data quality. Organizational changes, such as centralizing mine management, must prioritize the needs of field workers. Additionally, managing large volumes of operational data is a significant challenge—without proper organization and analysis, raw data provides limited value. Effective data management is vital for ensuring a smooth and successful automation process.

2.7 Managing Workforce and Community Transitions in the Era of Mining Automation

The mining industry is rapidly embracing automation to improve safety, sustainability, and operational efficiency. However, the transition to autonomous technologies significantly affects workers, organizations, and communities, particularly in terms of job security. As machines take over tasks traditionally performed by humans, redefining roles becomes essential to ensure a fair and equitable transition . Automation is especially effective in replacing repetitive and hazardous work, enabling operators to oversee multiple machines while improving overall system reliability [12]. Simultaneously, automation generates new roles in areas such as system monitoring, data analysis, and maintenance, prompting companies to create new job categories that integrate real-time operations with planning functions [5].

Successful automation requires balancing technological progress with social responsibility. Open communication about the objectives and process of automation is vital to alleviating employee concerns . Modern Key Performance Indicators (KPIs) — including safety, productivity, and employee satisfaction — are crucial for evaluating the success of automation initiatives [9]. Training programs play a critical role in equipping workers with the skills necessary for emerging technology-driven roles. To ensure long-term success, companies must develop strategies that manage evolving responsibilities while maintaining fairness and stability. Workforce reductions should primarily occur through natural attrition rather than abrupt layoffs. While newly developed mines can incorporate automation from the outset, existing operations face greater challenges related to workplace culture and the need for extensive retraining . Past experiences, such as the unsuccessful Sudbury automation project in 1998, highlight the importance of careful coordination and employee support . In mining communities, fears of job loss can negatively impact corporate reputation, making community outreach and education essential. Although automation disrupts traditional roles, it also offers opportunities for workforce development, skill enhancement, and the creation of higher-quality jobs when managed thoughtfully [5].

2.8 Robot Ethics

The growing adoption of automation across industries raises important ethical and legal questions regarding accountability. Traditional legal frameworks have primarily addressed human actions, but there is an increasing need to define the rights and responsibilities associated with autonomous systems [13]. A key motivation for automation is improving health and safety, making it essential to train workers on safely interacting with autonomous machinery. Automated trucks, equipped with advanced software, differ significantly from conventional vehicles and require specialized training and ongoing education to shift perceptions and ensure safe use. Developers must integrate user training programs and actively gather feedback to enhance system safety [13].

Despite technological progress, machines remain susceptible to failures and unpredictable behavior, introducing new ethical and legal challenges when incidents occur [6]. Legal systems must evolve to determine liability involving autonomous machines, and the insurance industry must adapt to cover risks associated with automation [6]. Although mining automation is still developing, proactive public engagement is critical to foster understanding and address potential benefits and concerns. Beyond operational improvements, robotics also offer insights into human behavior and societal values [6]. As global regulations for automation will differ, collaboration among governments, companies, and communities is essential for sharing experiences and best practices as adoption expands.

3 INFRASTRUCTURE

3.1 Autonomous Operating Zone (AOZ)

Maintaining the safety of autonomous truck operations requires clearly defining and restricting the operational zone. An authorization management system is crucial for controlling access to this area. It serves two primary functions:

- Preventing unauthorized personnel from entering the Autonomous Operating Zone (AOZ)
- Ensuring autonomous trucks remain within the designated area, avoiding unintended or erroneous departures

By integrating with the central or fleet management system, access controls help safeguard both personnel and equipment, securing the environment in which autonomous trucks operate.

3.1.1 People's access to the autonomous operating zone

To manage human access within the autonomous zone, all personnel must carry a Radio-Frequency Identification (RFID) tag. When an autonomous truck detects a nearby individual, it should automatically shift to a safe mode, issue an audible warning, and notify the control room.

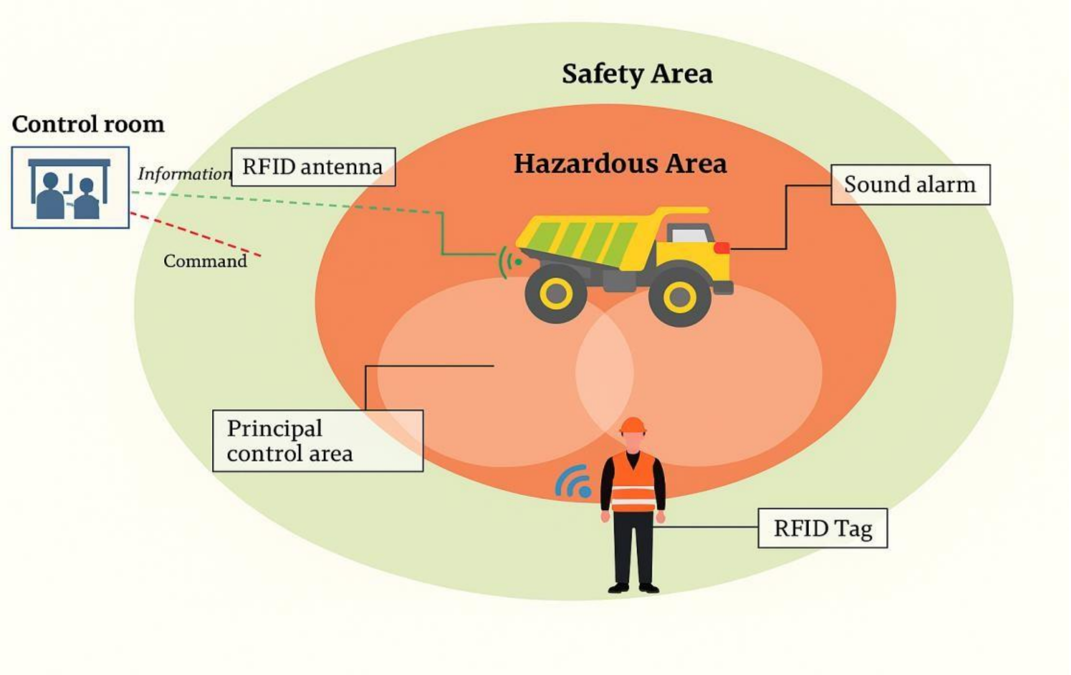

Figure 1: Configuration scheme of the People's access control to the AOZ [11].

3.1.2 Vehicle’s access to the autonomous zone

Implementing autonomous trucks in haulage operations requires a comprehensive risk assessment, which mandates that each vehicle operating within the Autonomous Operating Zone (AOZ) be monitored or accompanied by a supervised vehicle [14]. The assessment should evaluate the following factors:

- Vehicle position
- Vehicle speed
- Minimum and maximum separation distances between the supervised vehicle and the autonomous truck
- Destination
- Estimated time spent within the AOZ [11].

Both light vehicles and autonomous trucks are equipped with GPS, network connectivity, and emergency stop systems, allowing autonomous trucks to be immediately halted with the press of a button. The reliability of these systems is critical to ensuring a safe and efficient operation. The Autonomous Truck Control System automatically halts truck movement whenever other equipment enters the AOZ. Accurate location data is essential, as errors in positioning can cause unnecessary disruptions. If a heavy or light vehicle completely loses GPS signal, the autonomous truck will stop until accurate positioning is restored. Additionally, when a light vehicle approaches an autonomous truck, the system assesses the risk of path crossing and slows the truck if necessary to avoid collisions.

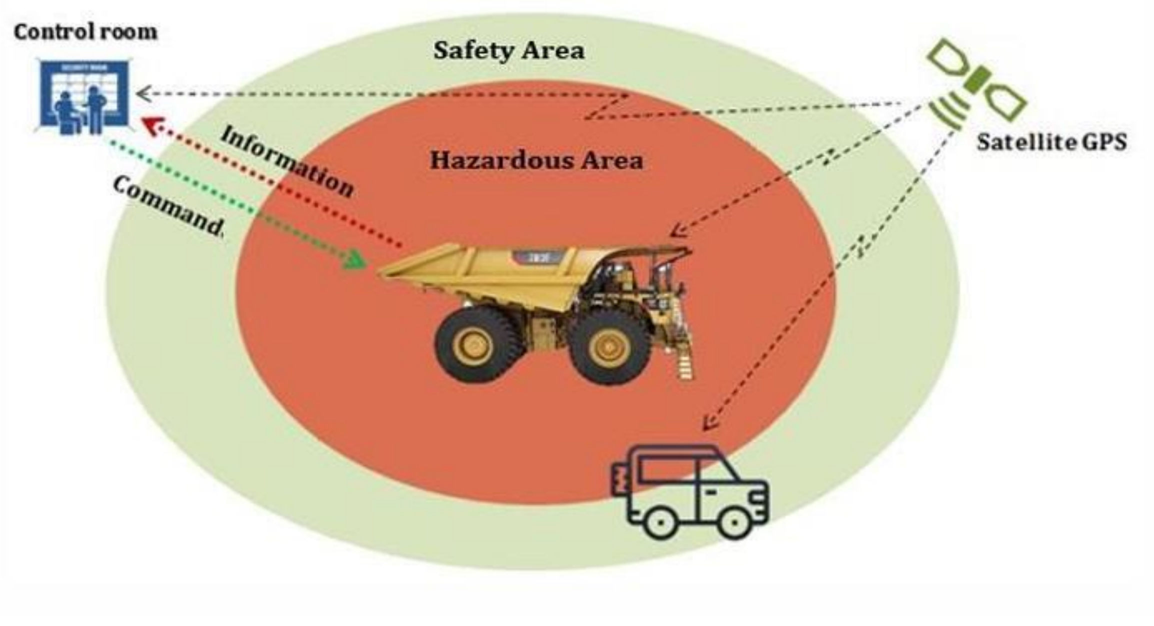

Figure 2. Configuration scheme of the vehicle’s access control to the AOZ [11].

3.2 Design of Haul Roads for Autonomous Trucks in Open-Pit Mines

The design of haul roads in open-pit mines is crucial for the safe and efficient operation of autonomous trucks. These systems depend on well-planned infrastructure to achieve optimal performance. All geometric elements of the haul roads must support safe travel at standard operating speeds. A critical consideration is ensuring that the truck's sensors can detect obstacles at distances equal to or greater than the required stopping distance. This section examines how factors such as truck speed, road gradient, and vehicle weight influence stopping distances, as well as key design principles for vertical and horizontal road alignment [15].

3.2.1 Vertical Alignment

Vertical alignment focuses on designing slopes and vertical curves that provide adequate stopping and sight distances throughout the haulage road. Safe autonomous truck operations cannot be guaranteed if road gradients exceed the braking capabilities of the specific autonomous vehicles [15,16]. Truck manufacturers must validate required stopping distances in compliance with ISO 3450:1996 [17], which defines braking system performance standards and testing procedures for earth-moving and rubber-tired machinery. This standard serves as a benchmark for evaluating braking performance in both mining and public road equipment. For autonomous vehicles, braking tests must measure performance from the moment the onboard system initiates braking until the truck comes to a complete stop [18].

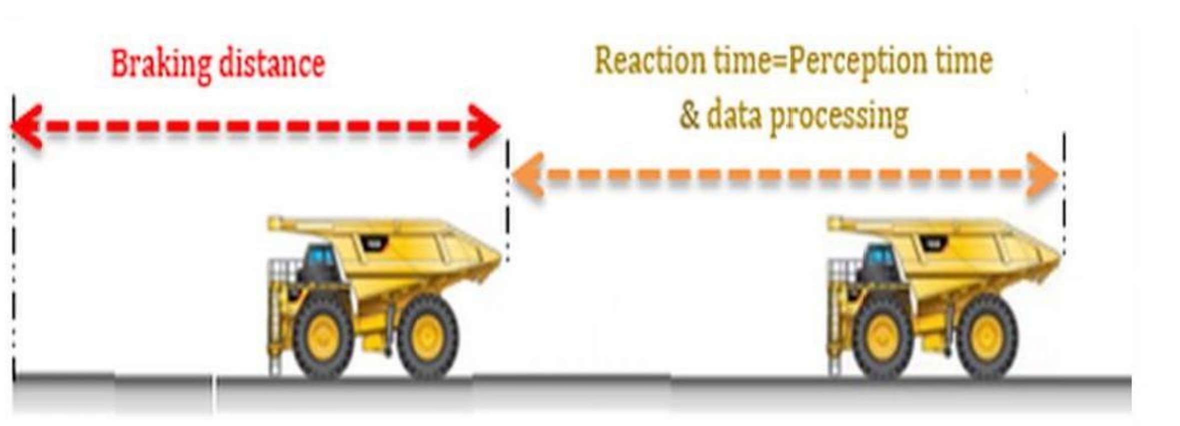

Figure 3 Braking distance of autonomous truck [11].

Given the increased complexity of autonomous operations, additional safety requirements must also be satisfied [d]:

- Autonomous trucks must be equipped with onboard systems capable of fully stopping the vehicle.
  Control systems must apply braking safely while operating within the Autonomous Operating Zone (AOZ).
- Trucks must verify that braking and steering systems have achieved safe operating temperatures and pressures before switching to autonomous mode.

3.2.1.1 Sight distance and vertical curvature of the truck

Sight distance for an autonomous truck refers to the range within which its perception sensors can detect obstacles. It is essential that this distance allows the truck, traveling at its current speed, to safely stop before reaching any hazard. The distance between the sensors and any detected obstacle must always be equal to or greater than the truck's required stopping distance. Therefore, the sight distance must never fall below the calculated stopping distance for the vehicle.

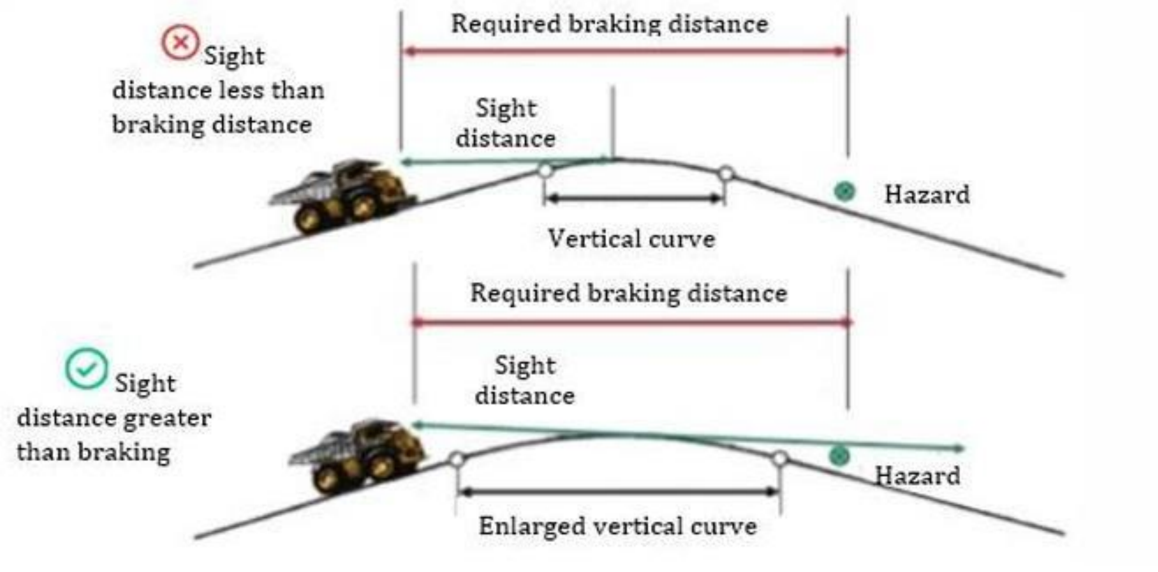

Figure 4 Normal sight distance on a slope for autonomous driving [11].

3.2.2 Maximum safe slope limit

For safety, haul road gradients for autonomous trucks must be designed according to the braking capabilities of the least capable vehicle, considering the trucks' significant weight and operating speeds. The *Mining Haul Road Design Manual* [6] highlights that reducing road slopes can substantially enhance truck climbing speeds, leading to shorter cycle times, lower fuel consumption, reduced mechanical stress, and decreased maintenance requirements. Slopes also have a major impact on the vertical detection range of onboard sensors. As an autonomous truck approaches a ramp, its ability to detect obstacles decreases. Without proper slope design, ramps may be incorrectly perceived as obstacles, while real hazards could fall outside the sensor’s range. Therefore, braking performance and sensor detection capabilities must be carefully analyzed to determine the maximum allowable slope and corresponding ramp distance. Additionally, truck speed should be reduced before descent and consistently regulated during the descent to maintain safe operations. [15]

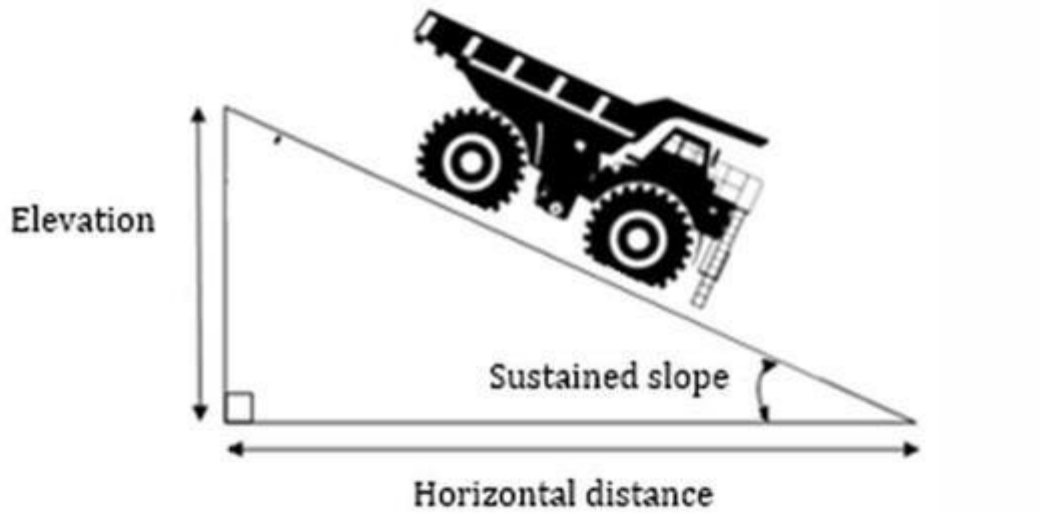

Figure 5 Scheme of the slope angle [11].

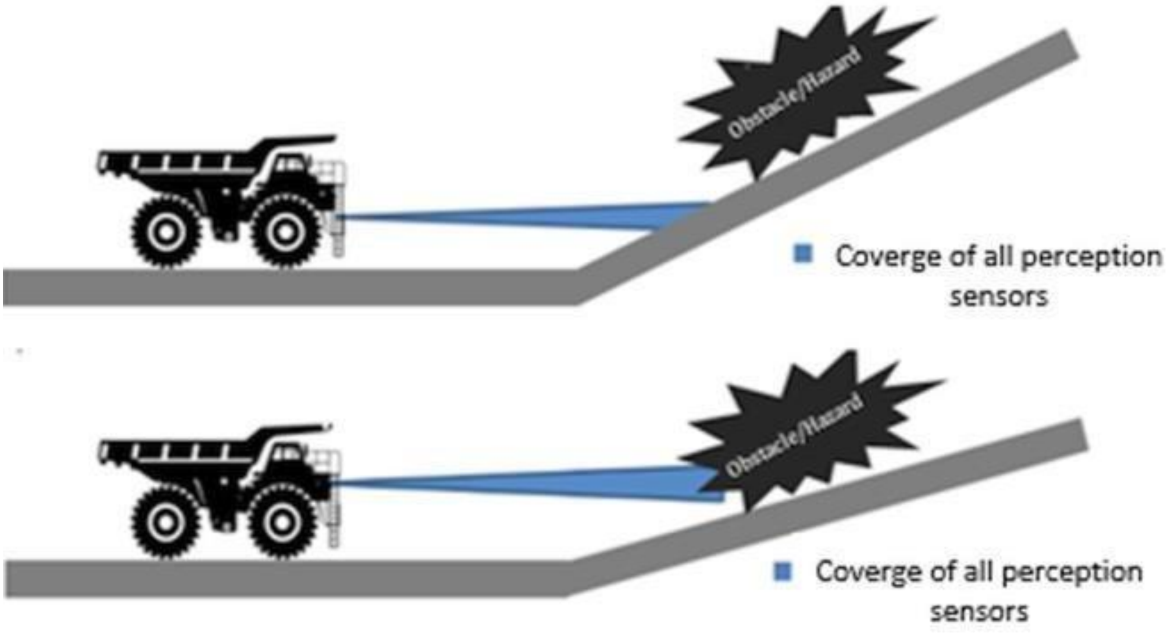

Figure 6 Scheme of the impact of a slope on obstacle/hazard perception [11].

3.2.3 Horizontal alignment (Longitudinal)

3.2.3.1 Radius of curvature: Turning angle

Horizontal curves must be designed to allow autonomous trucks to navigate safely at designated speeds, taking into account both sight distance and the minimum turning radius [16]. The curve radius must balance the centrifugal force acting on the truck with the available friction between the tires and the road surface. Besides setting an appropriate minimum radius, applying superelevation—raising the outer edge of the road—further reduces the effects of centrifugal force as the truck enters and moves through the curve.

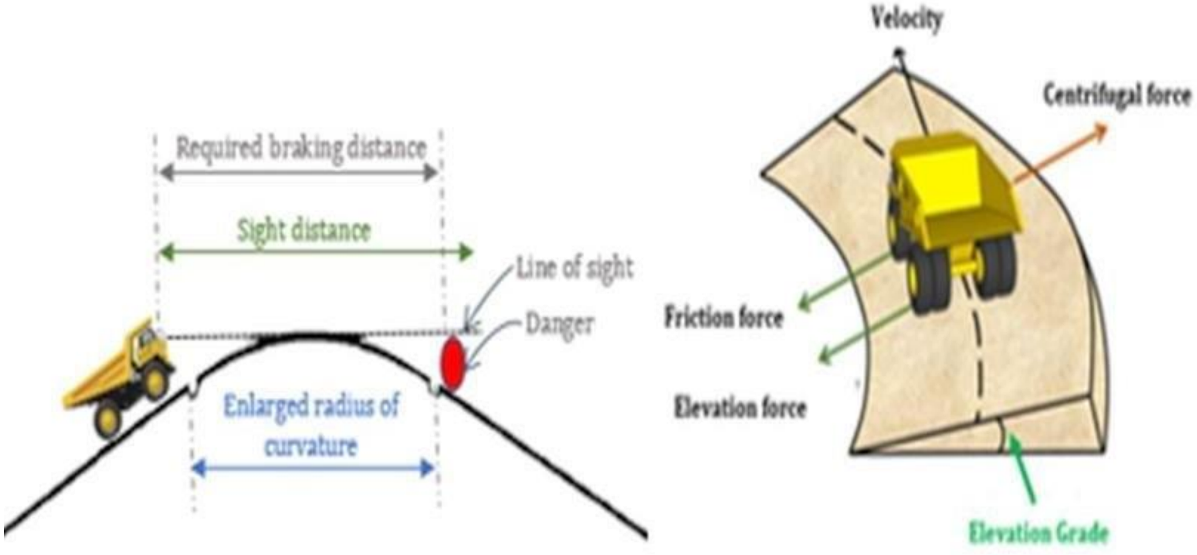

Figure 7 Scheme of the radius of curvature Vs the elevation grade [11].

3.2.4 Road elevation and transverse slope of road

When transitioning from a straight section to a super-elevated curve, the change in cross slope must be gradual to ensure autonomous trucks can navigate safely. For trucks traveling at 56 km/h, a 5% change in transverse slope is recommended, corresponding to a total curve transition length of 60 meters. Of this distance, one-third (20 meters) should be placed at each end of the curve, while the remaining 40 meters should be distributed along the adjoining straight sections [11].

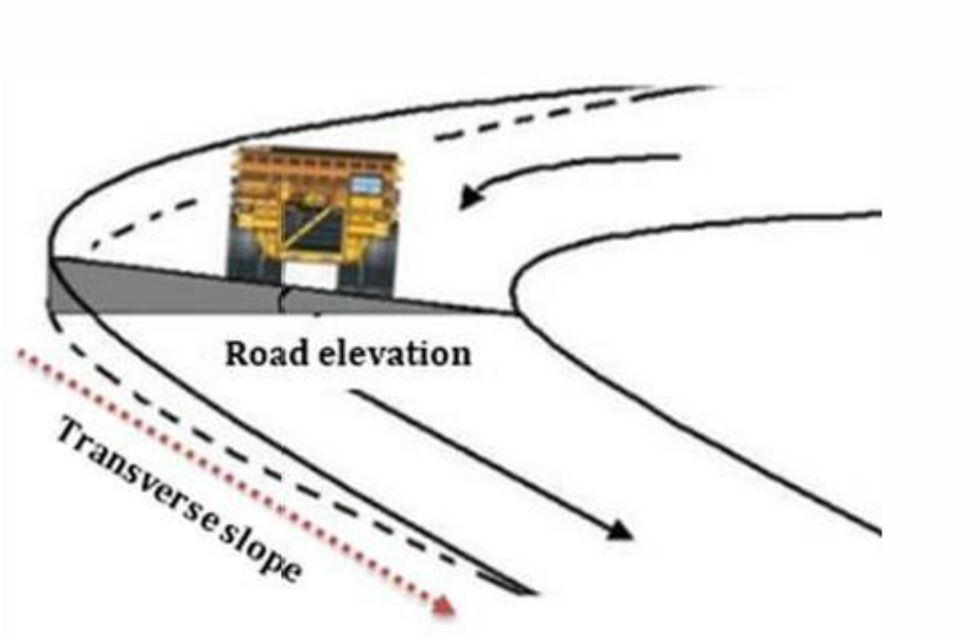

Figure 8 Scheme of the road elevation and transverse slope of road [11].

Road Width: Narrow haul roads can significantly shorten tire life by forcing trucks to drive over berms when passing, increasing the risk of sidewall damage. To ensure safe operations and maintain consistent haul cycles for autonomous trucks, adequate road width must be provided at all times. Road design should account for the required number of lanes, based on the dimensions of the largest trucks operating at the site [11]

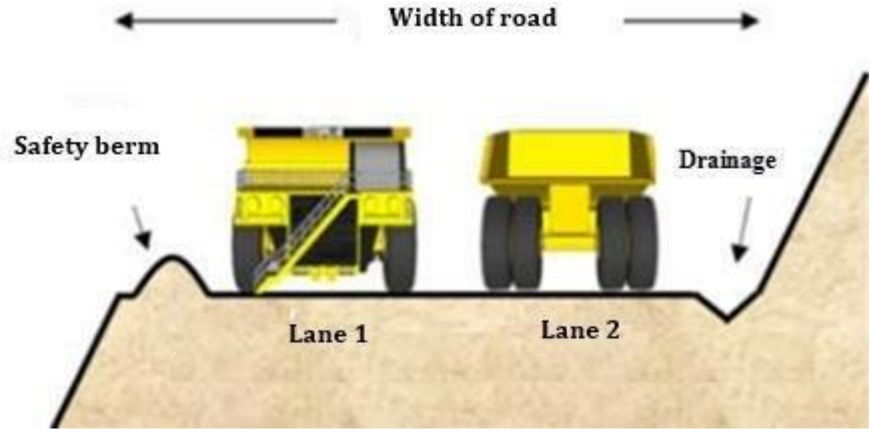

Figure 9 Scheme of the width of road, drainage facility and safety berm [11].

3.2.5 Safety berms

Safety berms, typically constructed from mine waste, are designed to keep haul trucks within their designated travel paths [7]. For autonomous trucks, berms offer additional visual and physical guidance to help maintain correct alignment. Berms are generally built with widths ranging from 1 to 2 meters and spaced about 25 meters apart, aiding both vehicle guidance and road surface drainage. In addition, drainage ditches are excavated along both sides of the haul road.

Figure 10 Scheme of safety berms and drainage [11].

3.3 Combined Alignment

Poorly coordinated horizontal and vertical alignments can create weaknesses and unexpected hazards for autonomous truck operations. To reduce these risks, horizontal curves should begin before vertical curves wherever possible [16].

Key issues to avoid include:

- Positioning sharp horizontal curves at or near the crest of a slope, as sensors on autonomous trucks may have difficulty accurately detecting slope angles.
- Failing to maintain sight distances equal to or greater than the truck’s required braking distance.
- Designing intersections with significant elevation changes; intersections should be as level as possible.
- Neglecting to apply appropriate superelevation (typically between 4% and 6%) on horizontal curves, depending on the curve radius and vehicle speed.
- Designing curve radii smaller than the minimum turning radius required for the autonomous trucks [11].

4. SAFETY OF AHS

In conventional mining operations, the introduction of Autonomous Haulage Systems (AHS) transforms dump trucks into unmanned vehicles, transferring safety responsibilities from human operators to AHS subsystems. Although operators are no longer physically present in Autonomous Haulage Trucks (AHTs) during operation, both AHTs and manually operated vehicles often share the same working areas. Human intervention remains essential for tasks such as initiating or halting AHT operations, performing maintenance and inspections, and maneuvering vehicles within parking areas and workshops. Given the conditions at mining sites, achieving complete physical separation between AHTs and manned vehicles—critical for inherent safety—is often not feasible. As a result, system functions must actively ensure operational safety. This chapter outlines the AHS safety concepts and system architecture necessary for secure and efficient mine operations.

4.1 AHS Architecture

Autonomous Haulage Systems (AHS) can be designed using different system architectures. In a fully centralized model, even the actuator controls of dump trucks are managed via a cloud server. In contrast, a decentralized model allows each vehicle to independently determine its destination and route. Centralized architectures offer advantages such as fewer onboard devices and simplified software updates but heavily rely on stable wireless communication, which can restrict scalability in areas with poor network coverage. Decentralized systems, on the other hand, reduce dependence on continuous communication but can lead to less coordinated operations, potentially impacting overall efficiency [19] .To overcome these challenges, the AHS described here adopts a hybrid architecture that blends centralized and decentralized features. This approach grants each vehicle a certain degree of autonomy, enhancing operational efficiency while reducing reliance on wireless networks.

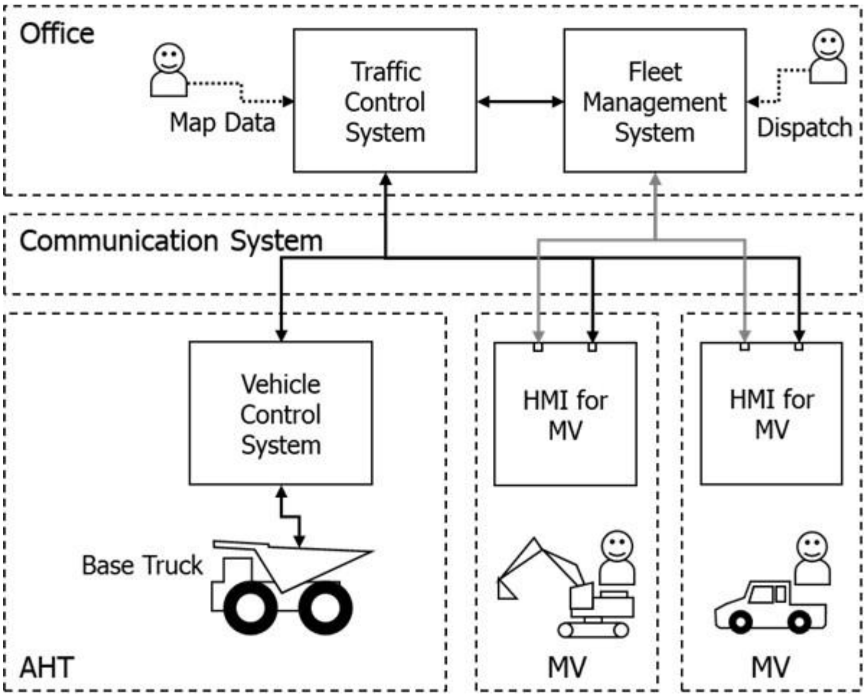

Figure 11 . Architecture of AHS [19].

The Autonomous Haulage System (AHS) consists of several key subsystems: a Fleet Management System (FMS) and a Traffic Control System (TCS) based at the central office, a Vehicle Control System (VCS) installed on each Autonomous Haulage Truck (AHT), and a Communication System that links all components. Additionally, manned vehicles (MVs) operating within the AHS zone are equipped with a Human-Machine Interface (HMI), enabling real-time monitoring of AHS operations and AHT statuses. The roles and functions of each subsystem are detailed in the following sections.

4.2 Fleet Management System (FMS)

The Fleet Management System (FMS) is responsible for assigning dispatch instructions to each Autonomous Haulage Truck (AHT), designating destinations such as loading or dumping sites based on the truck’s current location or loading status. Instructions can either be manually set by an office operator or automatically generated for routine trips to predefined destinations. Once created, the dispatch instructions are forwarded to the Traffic Control System (TCS), which converts them into detailed driving commands and transmits them to the AHTs. In addition to dispatching, the FMS monitors the operational status of the AHTs and estimates production volumes using collected operational data [19].

4.3 Traffic Control System (TCS)

In addition to multiple Autonomous Haulage Trucks (AHTs), human-operated manned vehicles (MVs) such as excavators, dozers, and light vehicles are also active within the AHS operation area. The Traffic Control System (TCS) wirelessly communicates with both AHTs and MVs to manage site traffic and prevent conflicts between AHTs or between AHTs and MVs. The AHT's travel path is divided into multiple sections, with each section exclusively assigned to a single AHT to avoid overlap. If an AHT's assigned section intersects with the buffer area of an MV's travel path, the MV operator receives avoidance instructions through the Human-Machine Interface (HMI) installed on the MV. Simultaneously, the TCS issues a deceleration or stop command to the AHT to prevent interference [20].

4.4 Vehicle Control System (VCS)

The Vehicle Control System (VCS) guides the dump truck along the route to its destination as specified by the Fleet Management System (FMS) and within the travel-permitted section managed by the Traffic Control System (TCS). The Autonomous Haulage Truck (AHT) navigates by comparing the preloaded route map from the TCS with its self-position estimates obtained through GNSS and the Inertial Measurement Unit (IMU). In addition, the AHT uses environment recognition sensors to detect obstacles, automatically decelerating or stopping when necessary.

4.5 Communication System (CMS)

The Communication System (CMS) enables information exchange between the Fleet Management System (FMS), Traffic Control System (TCS), Vehicle Control System (VCS), and the Human-Machine Interface (HMI) for manned vehicles (MVs).It also continuously monitors communication status, including wireless network performance.

4.6 Safety Concept

4.6.1 Principle

In traditional hauling operations, workplace safety depends heavily on the proper actions and communication among individuals such as operations managers, dispatchers, dump truck operators, and other vehicle drivers. In contrast, within an Autonomous Haulage System (AHS), many of the safety responsibilities previously managed by human operators must now be fulfilled by the system itself. However, the concept of safety in AHS operations is still evolving. Because AHS has only been deployed at a limited number of mines and has yet to achieve widespread global adoption, a standardized structure and set of functions—similar to those established for earthmoving machinery—have not yet been fully developed. System configurations and functionality differ across manufacturers, resulting in no common methodology for safety design or clear performance targets for safety functions.

To address these challenges, AHS safety is secured following the basic policies below:

- Ensure compliance with relevant international safety standards.
- Conduct risk assessments tailored to the operating environment and system architecture.
- Define clear safety design requirements for protective measures derived from risk assessments [19].

4.6.2 International standards

In 2017, ISO published ISO 17757, *Earth-moving Machinery and Mining – Autonomous and Semi-autonomous Machine System Safety*, with a revised edition released in 2019. This standard broadly addresses autonomous functionalities in earth-moving equipment, particularly mining applications such as dump trucks. It specifies design requirements for autonomous systems, the information to be provided by the system integrator (who may also be the machine manufacturer), and the operational conditions to be managed by users [14]. Regarding system safety, ISO 17757 requires a risk assessment based on the principles outlined in ISO 12100. However, it does not define uniform safety functions or performance targets, as these must be tailored to site-specific operating conditions. Instead, system integrators are responsible for determining appropriate safety performance levels through risk assessment. To support the design of safety-related control systems, the standard references ISO 13849, IEC 62061, and IEC 61508 [21] [22] [23]. ISO 17757 has been used as the foundation for developing our Autonomous Haulage System (AHS) safety concept. However, it does not provide detailed procedures for conducting risk analyses of autonomous systems or for defining the required performance levels of safety functions. Therefore, methodologies commonly applied in the process industry—where standards such as IEC 61508 and IEC 61511 are used in plant design—were incorporated [24] [25].

4.6.3 Layers of Protection

ISO 17757 establishes risk management criteria for both Autonomous Haulage System (AHS) system integrators and users. As a result, a hierarchical protection layer approach was adopted to ensure safety, combining system functions with operational management practices. This concept is illustrated in **Table 1**.

PL#	Protection Layer Category	Provided by
PL4	AHS Safety Functions	System Integrator (OEM)
PL3	AHS Control Functions	
PL2	Physical Barricades/ Signage	User
PL1	Sites Rules / Education	

Table 1 Protection Layers of AHS [14].

At the foundational level, Protection Layer 1 (PL1) consists of user-driven actions, including AHS operational guidelines, training programs, and established procedures. Protection Layer 2 (PL2) involves the use of physical barriers and signage to clearly separate autonomous and manned operation areas. Protection Layer 3 (PL3), managed by system integrators, includes control functions such as map management and route tracking that support system operation while enhancing safety. Protection Layer 4 (PL4) comprises dedicated safety functions designed to mitigate risk independently of PL3 operations or potential failures. While PL3 enhances operational control, failures in PL3 do not immediately elevate risk. In contrast, PL4 aligns with the definitions of safety functions under ISO 12100 and ISO 13849, where a failure would directly lead to an immediate increase in risk. For AHS safety to be effective, proper implementation and maintenance of user-side protections in PL1 and PL2 are also essential [14] [26].

4.6.4 Risk Assessment

A risk assessment was conducted following the procedures outlined in ISO 12100 to identify the system and user requirements necessary to ensure the safe operation of the Autonomous Haulage System (AHS).

The risk assessment process involved the following steps:

- Identifying potential hazardous events resulting from system malfunctions or human errors.
- Developing protective measures aimed at reducing either the likelihood of occurrence or the severity of harm.

- Assigning each protective measure to the appropriate layer within the hierarchical protection structure [26].

Origin	Hazardous Scenario	Target of Harm
AHT fault	Unexpected movement of AHT cause a collision with personnel	Bys
AHT /TCS /CMS fault	AHT deviates from its travel route due to any abnormality in VCS/TCS/CMS, which cause a collision with personnel /MV.	Bys /MV OP
MV Op human error	The MV operator inadvertently enters MV into the AHT travel route, which causes a collision with the AHT	MV Op
Bys human error	Personnel accidentally approaches the AHT, which causes collides with the AHT	Bys
MV Op: Manned Vehicle Operator Bys: Bystander (Field Operator, Maintenance Personnel)		

Table 2 Examples of hazardous events [14].

Table 3 presents examples of key protective measures (PRMs) developed for hazardous events identified during the risk assessment. Each PRM is assigned to one of the protection layers (PL1–PL4). By combining multiple PRMs for a single hazardous event, the likelihood or severity of harm can be effectively reduced. Protective measures in PL1 and PL2 are implemented by the user, while those in PL3 and PL4 are provided by the system integrator.

RPM type	Description	PL#
Rules / Education	Restrict personnel and MVs from entering the AHS area and AHT traveling routes.	PL1
Rules /Education	AHT start/stop procedure.	PL1
Barricades	Install a protective barrier between the AHS area and the	PL2

	manned area.	
Barricades / Signage	Install AHS area entrance/exit gates.	PL2
AHT mode switching device	Proper placement of AHT start and mode switching devices.	PL3
AHT anomaly detection	AHT stops when it detects a system malfunction.	PL3
AHT deviation detection	AHT stops when it detects a deviation from the given route.	PL3
AHT obstacle detection	AHT stops when it detects an obstacle with the onboard sensor.	PL3
AHT permission control	AHT will stop within the given permit section if the next permit is not obtained.	PL3
AHT indicator	Notify the surroundings of the operating status of the AHT using indicators etc.	PL3
AHT audible warning	External notification of AHT start/start via horn, etc.	PL3
Site info provision	Provision of AHS area map information to MV operator.	PL3
Approach notification	Notify MV operator when MV and AHT approach each other.	PL3
AHT status info provision	Notify MV operator of moving/stopping status of AHT.	PL3
AHT Remote	MV operator or personnel on site	PL4

Stop	remotely stops AHT.	
AHT approach speed limit	Limit the speed of the AHT when the MV and the AHT are close to each other.	PL4
speed limit AHT control system shutdown	Shut off the AHT vehicle control system during non-AHS operation.	PL4

Table 3 Examples of Protective Measures [14].

The following section outlines the procedure for selecting PL4 safety functions from the protective measures (PRMs) provided by the system integrator.

4.6.5 Selection of Safety Functions and PLr Determination

Figure 12 shows the safety function selection procedure.

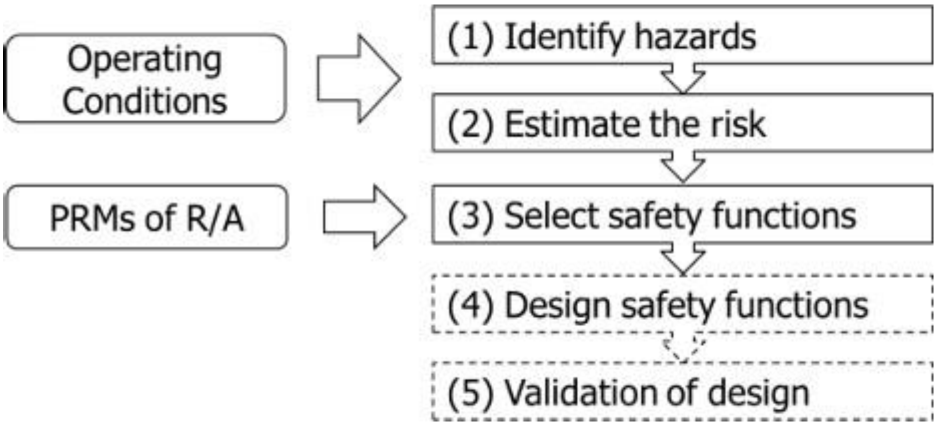

Figure 12 Safety functions selection process [19].

4.7 Identify hazards

Accident scenarios arising from Autonomous Haulage Truck (AHT) operational failures are considered hazards. An AHT operation failure refers to instances where the truck does not perform as expected or behaves unpredictably. Such failures are not limited to hardware or software issues within the AHT itself; rather, they can result from any malfunction or human error within the broader Autonomous Haulage System (AHS), which includes the Fleet Management System (FMS), Traffic Control System (TCS), Communication System (CMS), and Vehicle Control System (VCS). Failures can occur due to incorrect human inputs, such as setting an improper destination in the FMS, errors in map data entry, or software bugs in the TCS that transmit incorrect instructions to the AHT. Communication failures can also disrupt the transmission of essential commands to the vehicle. Given that AHS is a complex system involving numerous hardware and software components with intricate interactions, conducting a complete Failure Mode and Effects Analysis (FMEA) on every subsystem to identify all potential hazards is impractical. Instead, a Hazard and Operability Study (HAZOP) was adopted to analyze hazardous AHT behaviors. Dump truck movements were classified into categories: acceleration, deceleration, steering, stopping, and body lifting. Using HAZOP guide words such as "NO OR NOT," "MORE," "LESS," and "REVERSE," potential hazards associated with these movements were systematically identified [24].

4.7.1 Estimate the risk

Risk estimation was conducted for all identified hazards, and the required performance level (PLr) for the corresponding safety functions was determined to mitigate those risks. The risk estimation process applied the risk graph analysis method outlined in Annex A of ISO 13849-1 (refer to Figure 13) [23].

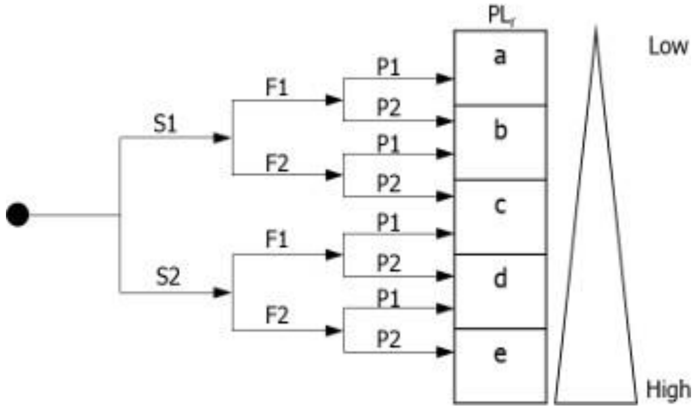

Figure 13 Graph for determining PLr for safety function [23].

- **S** (Severity of injury)
- **S** (1Slight)
- **S2** (Serious)
- **F** (Frequency and/or exposure to hazard)
- **F1** (Seldom-to-less-often and/or exposure time is short)
- **F2** (Frequent-to-continuous and/or exposure time is long)
- **P** (Possibility of avoiding hazard or limiting harm)

- **P1** (Possible under specific conditions)
- **P2** (Scarcely possible)

The procedure for determining the required performance level (PLr) using the risk graph is outlined below.

Before defining the intended safety function, the following situation is assumed:

- The risks associated with the failure or absence of the safety function are estimated.

Risk estimation is based on evaluating the following parameters:

- **Severity of injury** resulting from the hazard
- **Frequency and/or duration of exposure** to the hazardous condition
- **Possibility of avoiding the hazard** and the **likelihood of occurrence** of the hazardous event

By selecting appropriate values for these parameters, the PLr corresponding to the intended safety function is determined.

4.7.2 Select Safety Functions

A specific protective measure capable of reducing the risk associated with an identified hazard was selected based on the results of the risk assessment. This selected protective measure was designated as a PL4 safety function, with the corresponding PLr, determined in the previous section, applied.

The selection of safety functions for actual system design was guided by the following principles:

- Achieving risk reduction for multiple hazards using as few safety functions as possible.
- Ensuring safety functions are independent from standard control functions.
- Minimizing the size and complexity of the safety-related parts of the control system (SRP/CS) by reducing the number of components.

Table 4 provides examples of the safety functions assigned to each AHT operational scenario, selected through this process.

AHT Operation Scene	Safety Function
Unmanned /Autonomous Mode	ASL: Approach Speed Limit
	R-Stop: Remote Stop
Manned /Manual Mode	AHT Control System Shutdown

Table 4 Examples of Safety Functions [19].

During AHS operation, scenarios where an Autonomous Haulage Truck (AHT) approaches a manned vehicle (MV) represent significant hazards. To mitigate this risk, the AHT automatically reduces its speed when an MV is nearby, thereby lowering its kinetic energy and potential impact severity. Reduced speed also improves the MV operator's ability to avoid a collision. Risk reduction is further enhanced if the MV is equipped with a device capable of remotely stopping the AHT. In non-AHS (manual) mode, where the AHT is operated by a driver, there is a risk that unintended activation of AHS functions could interfere with human control. To address this, the mode-switching circuit disables the AHT's autonomous control system during manual operation, minimizing the risk of unexpected behavior. For each safety function, a required performance level (PLr) is determined based on the estimated risk associated with the absence of that function, supporting a deterministic evaluation process. However, this chapter focuses on the development of the AHS safety concept rather than specifying particular safety functions or universal PLr values, as these depend on the system architecture and site-specific operating conditions.

4.7.3 AHS architecture with safety functions

Figure 14 illustrates the system architecture in which the safety function components selected in the previous section are integrated into the AHS main function system described in the previous chapter. To implement the Autonomous Speed Limiting (ASL) function, the manned vehicle (MV) is equipped with a system for measuring its own position and wirelessly transmitting this information. The Autonomous Haulage Truck (AHT) is equipped with its own position measurement system and a receiver for MV position data. The AHT compares its position with the received MV position, and if proximity is detected, speed-limiting control is triggered to reduce the truck's speed. Similarly, for the Remote Stop (R-Stop) function, the MV is equipped with a wireless transmission system linked to a stop switch. When the AHT receives a stop signal from the MV, the brake activation control is triggered, bringing the truck to a complete stop. The same MV transmitter and AHT receiver are utilized for both the ASL and R-Stop functions. Importantly, the communication system used to transmit ASL and R-Stop signals is provided separately from the AHS main function Communication System (CMS) and is dedicated solely to safety functions.

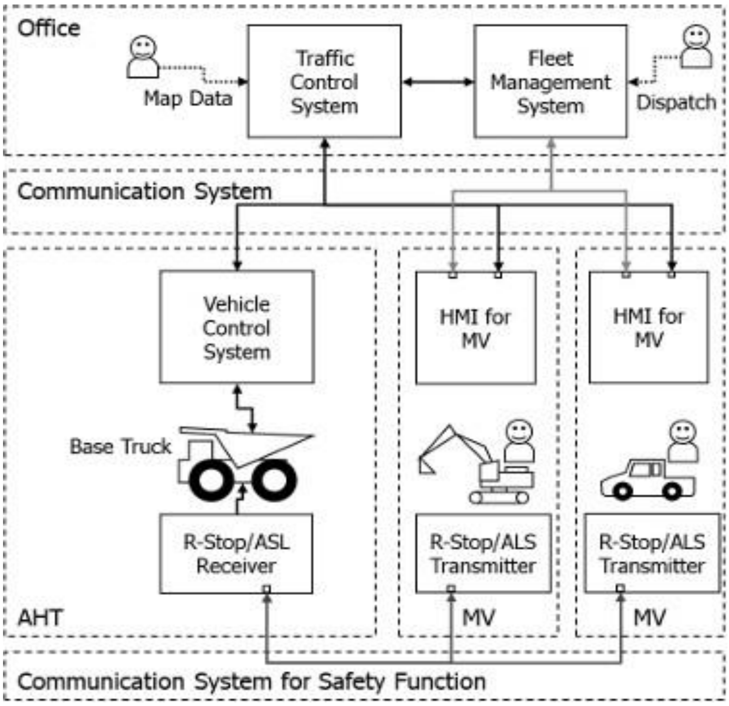

Figure 14 AHS architecture with safety functions [19].

Implementing the system that provides the PL4 safety function independently from the PL3 control function, as described above, offers several advantages:

- The safety function can be reliably activated as needed, regardless of the operational status or malfunctions within the main control system.
- The design of the separated Safety-Related Part of the Control System (SRP/CS) becomes simpler, and its performance can be evaluated deterministically.
- Because the safety function remains largely unaffected by changes to the main control system specifications, it is possible to expand or modify the overall system functionality without requiring adjustments to the safety function.

5 VEHICLE MOTION MODEL

The model presented in this chapter was developed by the author using deterministic time-step logic and Caterpillar 793D data. All approximations, calculations, and coding were performed independently to evaluate vehicle dynamics and fuel consumption.

5.1 Small Increment Approach

The primary objective of this method is to calculate the speed of haul trucks using small time increments. To determine rimpull forces and subsequently calculate acceleration and speed, it is essential to know several parameters: truck weight, rolling resistance, grade resistance, traction coefficient, and drive axle weight distribution. The truck's weight is a dynamic variable, changing as material is loaded or dumped. Additionally, haul road characteristics—such as section length, maximum allowable speed, maximum acceleration, and grade resistance—are influenced by the specific layout of the mine [27].

5.2 Forces Considered in the Model

In this section, the forces acting on the truck at the road surface are categorized as follows:

F_r represents the sum of all forces opposing the truck's motion, including:

- Rolling resistance forces
- Aerodynamic drag forces (wind opposing movement)
- Gravitational force (on slopes)

Thus:

$$F_r = F_{rr} + F_D + F_G \text{ Eq. 1}$$

F_{assist} represents the sum of all forces aiding the truck's movement, including:

- Rimpull force (available or required)
- Aerodynamic forces (wind assisting movement)
- Gravitational force (when favorable)

Thus:

$$F_{assist} = F_{Rimpull} + F_D + F_G \text{ Eq. 2}$$

The **resultant force** acting on the truck is the difference between the assisting forces and the resisting forces:

$$F_{resultant} = F_{assist} - F_R \text{ Eq. 3}$$

5.2.1 Available Rimpull

Available rimpull refers to the mechanical force transmitted from the engine through the transmission and drivetrain to the points where the driven tires contact the ground. The maximum attainable speed, gear range, and available rimpull can be determined using the rimpull-speed curves provided by the manufacturer [28], based on the machine's weight and the total effective grade (resistance). In the model, the manufacturer's rimpull-speed curve was approximated using 12 straight-line segments (Appendix 1). By knowing the instantaneous speed at each time step, the model selects the corresponding linear equation to determine the available rimpull (see Figure 15). For each road segment, the model checks the truck's combined weight (machine + payload) and the total effective grade to identify the maximum mechanical speed achievable (Appendix 1). Until reaching this speed, gear shifts are applied instantaneously according to the piecewise linear equations. It is important to note that, although some Mongolian mines are located at altitudes around 1,400 meters above sea level, derating effects were not considered in the model. In scenarios where the truck interacts with another vehicle, it will not reach its maximum mechanical speed but instead match the speed of the leading vehicle to maintain a safe following distance. Additionally, if the road segment has a posted speed limit lower than the mechanical speed, the system will apply the road speed limit as the maximum permissible speed.

Example:

If an empty truck traveling on a flat (zero-grade) road segment could theoretically reach 52 km/h, but the road's permitted speed limit is 40 km/h, the truck will operate close to 40 km/h, with slight variations reflecting driver behavior.

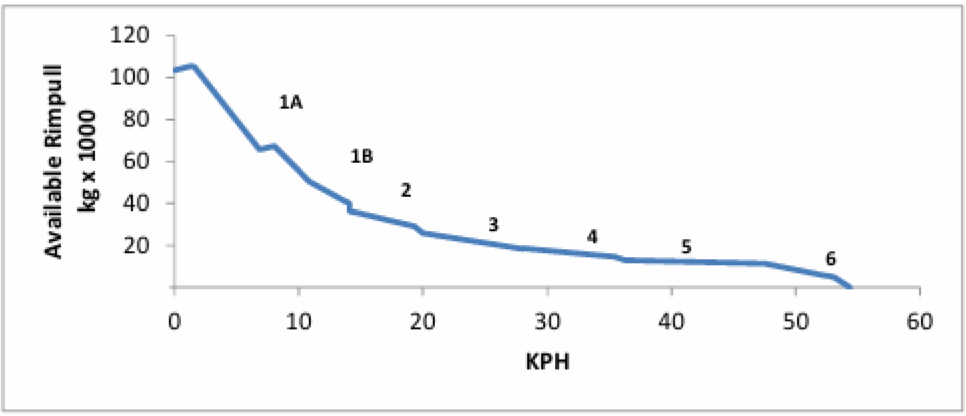

Figure 15 CAT 793D rimpull-speed curve used in the model – gears are used to engage each specific speed-rimpull range [29].

5.2.2 Braking Performance

When a truck is descending a grade, its maximum mechanical speed is determined based on the retarder performance curve [29] (see Appendix 1), provided the machine weight and total effective grade are known. By adhering to the allowable mechanical speed, braking can be performed safely without exceeding the cooling capacity of the system. During downhill travel, the model references the retarder database to select the appropriate maximum mechanical speed according to the truck's actual weight and the effective grade of the road segment.

5.2.3 Traction Force

The total energy produced by the truck engine can be converted into movement only if sufficient traction exists between the driving wheels and the road surface. If traction is inadequate, the wheels will slip, and the engine's power will not be effectively used to perform work. The coefficient of traction between rubber tires and the road surface varies depending on tire tread type and road conditions [30]. The traction coefficients for different surfaces are provided in Appendix 2. For baseline calculations, the model uses a traction coefficient of 0.55, based on the dry clay loam typical of the South Gobi region, where many Mongolian mines are located. This coefficient can fluctuate depending on road conditions and weather, potentially dropping as low as 0.45. When wheel slip occurs, an additional force, known as the usable rimpull (Ru), must be considered. Usable rimpull is defined as the amount of pull exerted by the truck at the point where the drive tire contacts the ground.

$$R_u = C_t W D \qquad \text{Eq. 5}$$

R_u = useable rimpull
C_t = traction coefficient
W = truck weight
D = drive axle weight fraction (see Eq.6)

A dump truck typically has 67% of its weight on the Rear axle when fully loaded, while an empty truck has 50%. The nominal payload capacity of the CAT 793D is 232,000 kg, with a gross machine weight of 383,789 kg. Based on this data [29], the following formula was developed to dynamically adjust the weight distribution on the drive axle based on the truck’s load:

$$D = (0.13/21800)GVW + 0.442 \qquad \text{Eq. 6}$$

D = drive axle weight fraction
GVW = Gross Vehicle Weight

After calculating the available rimpull and usable rimpull, the effective rimpull—the assisting force that actually propels the truck—is determined by selecting the smaller value between the two.

5.2.4 Resistive Forces

To determine the force responsible for truck movement, the total resistance must be subtracted from the effective rimpull. The total resistive force is defined as the required rimpull, which accounts for resistance forces caused by rolling resistance, grade resistance, and wind (air) resistance.

$$F_r = F_{RR} + F_G + F_D \qquad \text{Eq. 7}$$

F_r = resistive force
F_{RR} = rolling resistance force
F_G = gravity force
F_D = drag force

5.2.5 Rolling Resistance

Rolling Resistance (FRR) is the force that must be overcome to roll a wheel across the ground. It is influenced by road conditions and the truck's payload; the deeper the wheel sinks into the surface, the higher the FRR value. The rolling resistance for different haulage surfaces is provided in Appendix 2 and can be calculated using the following equation:

$$F_{RR} = 10WCr \qquad \text{Eq. 8}$$

F_{RR} = rolling resistance force
W = truck weight
Cr = rolling resistance coefficient

Truck speed is affected by the rolling resistance at the ground-wheel interface. If the rolling resistance in a specific road segment is higher than the mine’s average, truck efficiency decreases, and the frequency of equipment failures and tire wear increases. FRR is challenging to estimate, and each mine establishes its own rolling resistance value based on a combination of road conditions and equipment. The rolling resistance coefficient is determined according to factors representing a well-maintained, hard, smooth, stabilized-surface roadway with no significant penetration under load. To maintain this coefficient, the schedules for water trucks and graders must be adjusted according to changes in road quality and the water content of the road surface. The water truck and grader are scheduled to pass through all routes every 12 hours, resetting the route's rolling resistance coefficient to 2% and the traction coefficient to 0.55 (see Appendix 2). This process is governed by a map of precipitation factors, which includes rain or snow intensity (mm) and duration (hours). Each time a truck enters a road segment, these factors are applied, adjusting the rolling resistance and traction coefficient. The variables for watering and grading depend on the time elapsed since the last pass by the water truck and grader. A counter is used in the model to track this: when the water truck and grader pass a point, the counter resets to zero. The intensity (mm) and duration (hours) of precipitation are reset every time a truck starts a new route.

5.2.6 Grade Resistance

Grade resistance refers to the contribution of the force of gravity. In an uphill segment, this force opposes the truck's movement, while in a downhill segment, gravity assists the truck's movement [31]. Grade resistance is typically expressed as a function of the road's grade percentage or as a grade resistance factor. The grade resistance is calculated using the following equation [21]:

$$F_G = 10\,WG \qquad \text{Eq. 9}$$

F_G = grade force or gravity force
W = truck weight
G = grade of the road (%)

5.2.7 Drag Force (Wind Resistance)

Air resistance generally opposes truck movement, although a tailwind can assist with forward motion. The force exerted by wind on an object is proportional to the vehicle's contact surface area, the air density, and the relative wind speed [32]. The following equation is used in the model to calculate the opposing (or assisting) force due to wind resistance:

$$F_D = 0.5\rho C_x A V^2{}_r \qquad \text{Eq. 10}$$

ρ = air density (kg/m3)

C_x = Drag Coefficient

A = frontal area of truck (m2)

$V\ \ _r$ = speed of the wind relative to the direction of the truck (m/s)

A significant challenge with this equation is determining an accurate value for C_x. The drag coefficient can also vary with wind direction, as turbulent air flow around the truck body may alter the drag forces. However, since mining trucks generally do not operate at speeds above 50 km/h, the effects of turbulence on drag forces are minimal. Similarly, strong winds (above 60 km/h) typically lead to the suspension of mining operations, so any change in C_x due to wind speed fluctuations is expected to have a negligible effect. For the CAT 793D, the exact drag coefficient (C_x) is unknown [29]. Based on reference values, drag coefficients for off-road trucks typically range between 0.8 and 1.0. Given that mining trucks have a larger cross-sectional area than regular haulage trucks, C_x was assumed to be 1.0.

5.3 Acceleration

As previously mentioned, in order to calculate the forces acting on a truck, the road grade must be known. The model computes acceleration in a deterministic manner at each time step. When the truck is operating on a flat road, the acceleration responsible for its movement is given by the following equation:

$$Acc_{movement} = (Rimpull_{eff} - F_R \pm F_D)/M \quad \text{Eq. 11}$$

$Acc_{movement}$ = acceleration responsible for truck movement

$Rimpull_{eff}$ = effective rimpull (smaller value of Available rimpull and Useable rimpull)

M = truck mass

F_R= resistive force

F_D= drag force (depending on wind direction)

Figure 16 Truck parallel forces when moving on a grade = 0%. [7].

If the road grade is greater than zero, the resistive force (F_R) is the sum of gravitational force (F_G), rolling resistance force (F_{RR}), and drag force (F_D). If the grade is zero, the equation simplifies to: $F_R = F_{RR} \pm F_D$
The drag force depends on wind direction, either opposing or assisting the truck's movement. If the computed acceleration ($Acc_{movement}$) exceeds the set threshold, the acceleration responsible for the truck's movement is limited to the maximum driver acceleration. This maximum acceleration is determined by the design specifications for all drivers, adjusted by the driver behavior factor.

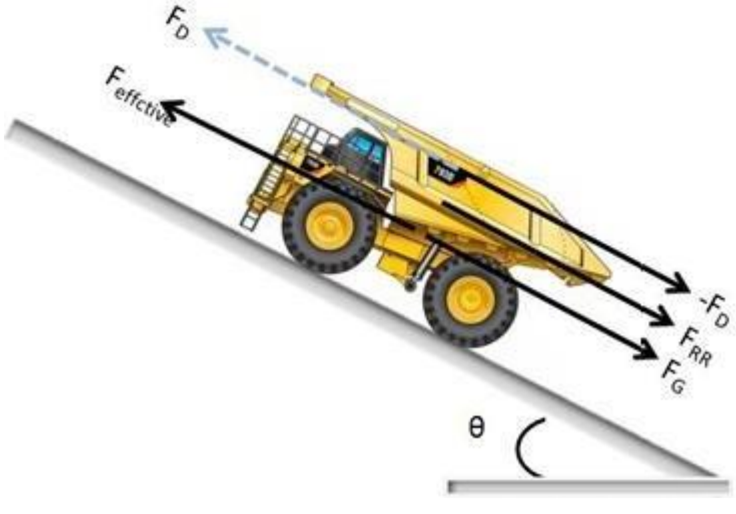

Figure 17 Truck parallel forces when moving on a grade > 0%.[7].

Once the truck reaches a steady-state speed, the acceleration ($Acc_{movement}$) is calculated based on the resistive forces that work to slow the truck down, whether on a flat or uphill grade, as shown in the equation below. For downhill driving, the driver applies the brakes to maintain the maximum speed according to the resistive force.

$$Acc_{movement} = -(F_R)/M \quad \text{Eq12}$$

When drivers are in steady-state mode on an uphill or flat section, the brake pedal is only used in emergency situations. Any small variation in speed is caused by the resistive forces that naturally slow the truck down. In this scenario, when the truck slows due to resistance, the driver will apply the accelerator again to maintain the desired speed range. The total acceleration is then used to calculate the fuel consumption required for movement, as described in Chapter 6.

Figure 18 illustrates the forces acting on a truck when it is moving on a grade of less than 0. When the truck is traveling downhill, acceleration can be calculated using the following equation:

$$Acc_{movement} = [F_{assist} - (F_{RR} \pm F_D)]/M \quad \text{Eq13}$$

$Acc_{movement}$ = acceleration responsible for truck movement

F_{assist} = assisting force to propel the truck

F_{RR} = rolling resistance force
F_D= drag force (depending on wind direction)
M= truck mass

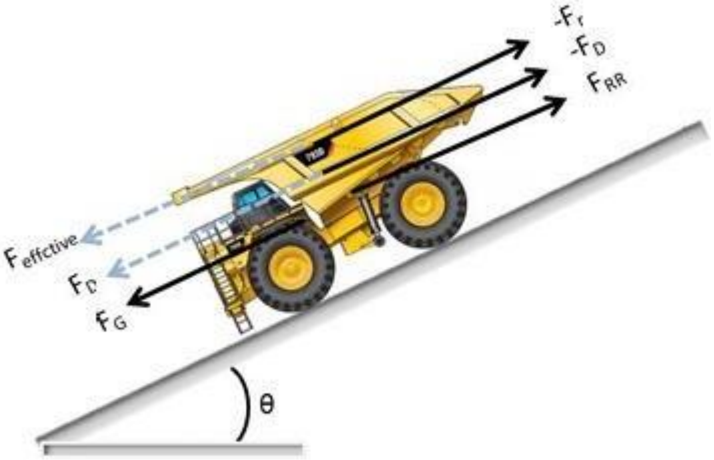

Figure 18 Truck forces when moving on a grade < 0%. [7].

When gravitational force (truck weight) initiates truck movement, it serves as the assisting force. However, if the gravitational force is insufficient, additional force (rimpull) must be generated by the engine. It is important to note that, in downhill mode, the engine produces less power compared to the previous example.

For an empty truck after a full stop on a grade less than 0%, if the driver does not apply the brake, the resistive forces are not strong enough to slow the truck down, as the gravitational force in this scenario exceeds the resistive force. In this case, the engine generates extra force to propel the truck. When the driver applies the brake pedal, the engine only produces idling power.

5.4 Kinematics

For each time step Δt, acceleration is known, allowing the instantaneous speed and distance traveled to be calculated as follows:
Speed variations over time step: $V_f = V_i \pm a \cdot \Delta t$ Eq. 14
Position changes over time step: $S_f = V_i \cdot \Delta t \pm 0.5 \cdot a \cdot \Delta t^2$ Eq. 15
With the instantaneous speed known, the acting forces can be determined, and the appropriate gear, engine speed, and power are calculated for each time step. These calculations continue in a loop until the truck reaches the destination [7].

5.5 Vehicle Interactions.

At each time step, the model checks the safe following distance for all trucks operating on the road. Key data—including direction, truck ID, segment location, current speed, and distance traveled—are recorded in an internal database. When performing deterministic calculations (e.g., for Truck 1), the model retrieves data from the database to evaluate the following conditions:

- How many trucks occupy the same segment?
- How many trucks are traveling in the same or opposite direction?
- Among trucks traveling in the same direction, which one is closest?

The maximum and current speeds of the nearest forward truck are then used to set operational parameters for Truck 1. If Truck 1 is traveling faster and the distance to the forward truck is 50 meters or less, its speed is adjusted to match the forward truck's speed. Truck 1 continues operating at this reduced speed until the leading truck pulls aside or changes routes, at which point Truck 1's speed parameters are updated accordingly. When Truck 1 reaches a critical following distance, its deceleration is recalculated as previously described. This procedure also manages vehicle movements at shift beginnings or after breaks. When a truck in the parking area is ready to depart, the model verifies whether the road is clear or if a minimum 50-meter distance exists behind the last departing truck. If conditions are not met and the truck must wait, this delay is included in its cycle time calculation. Similar checks occur at dumping locations, crushers, and loading areas. Additionally, the model counts and records the total number of interactions each truck experiences.

Figure 19 Safety distance between trucks [7].

For each time step, trucks data are stored to ensure that safe following distances are maintained. Figure 19 illustrates an example of this logic. The truck on the right detects two trucks ahead; since the middle truck is within the 50-meter safety threshold, the right-hand truck adjusts its speed to match that of the middle truck. The middle truck detects the truck on the left, but since the distance exceeds 50 meters, it continues at its original speed.

6 FUEL CONSUMPTION MODEL

All results in this chapter are based on calculations performed using the author's model. Fuel consumption, RPM, and engine power were determined at each time step using formulas and data series derived from original equipment specifications.

6.1 Fuel Consumption

Fuel consumption is influenced by various factors, including load, speed, engine power, vehicle weight, acceleration, aerodynamics, tire condition, road and fuel quality, idling time, wheel alignment, tire pressure, road gradient, driver behavior, ambient temperature, weather, and maintenance [33].

Fuel consumption can be estimated using various methods. For example, Runge and Filas applied Equation 21 with different load factors (L_F). According to Runge, L_F typically ranges from 0.18 to 0.50, whereas Filas suggests a broader range of 0.25 to 0.75, influenced by driver skill and equipment efficiency [34] [35].

$$F_C = P\ 0.3\ L_F \qquad \text{Eq. 20}$$

F_C = Rate of Fuel Consumption (L/h)

P (kW) = engine power (kW)

0.3 = unit conversion factor

L_F = engine factor

A similar equation was proposed by Hays who incorporated Specific Fuel Consumption (SFC) and fuel density into the calculation [36].

$$F_C = (S_{FC} P\ L_F)/F_D \qquad \text{Eq. 21}$$

F_C = rate of fuel consumption (L/h)

S_{FC} = specific fuel consumption

P= engine power (kW)

L_F = engine factor

F_D= fuel density

Specific Fuel Consumption (S_{FC}) is defined as the ratio of the fuel flow rate to the useful power output of an engine during testing. When the useful power is measured directly from the crankshaft, S_{FC} is specifically referred to as Brake Specific Fuel Consumption (BSFC). BSFC indicates how effectively the engine converts fuel into useful mechanical work. As explained in Chapter 5, the model applies a deterministic method to first calculate instantaneous speed and then uses this information to determine engine speed, power, and BSFC for calculating fuel consumption. Fuel usage is influenced significantly by driver behavior as well as terrain and road grade. Upon completing a simulation, the model provides total fuel consumption data for each driver and driver behavior category.

6.2 Gear Efficiency and Reduction

To estimate engine speed, the model uses linear equations that approximate the Caterpillar speed–rimpull curve (Appendix 1), which in turn are used to determine gear efficiency [28]. Efficiency is defined as the ratio of power delivered at the axle to the power output at the engine flywheel. For reference, the maximum rated power of a standard CAT 793D engine is 1801 kW [27]. Using the available rimpull and truck velocity, the model applies the following equations to calculate engine power (P) and gear efficiency (E):

$$P = 9.806 \; x \; 10^{-3} \; VR \quad \text{Eq. 22}$$

$$E = 100P/P_{max} \quad \text{Eq. 23}$$

P = power (kW) V = truck speed (m/s)

R = rimpull (kg)

P_{max} = maximum power (kW)

E = engine efficiency (%)

Table 5 was created to apply the power and efficiency equations for Gear 1B, based on the Caterpillar speed–rimpull curve. For each combination of speed and rimpull, the corresponding efficiency value is provided. As shown in the table, when the truck speed is 8.05 km/h, the calculated efficiency is 84.54%. However, this does not necessarily represent the actual gear efficiency, as engine conditions such as torque may vary. Instead, the highest efficiency within the gear range is selected to represent gear performance. In this case, the peak efficiency is 86.78%, which occurs when the available rimpull is 57,510 kg at a speed of 9.66 km/h.

Table 5 Estimating gear efficiency.

Equation For Gear 1 B*	km/h	Rimpull (x 1000)	Efficiency	Reduction Ratio	RPM	Power (kW)	BSFC
R(v) = 255	8.05	67.23	84.54%	121.4	1458	1698	201
	8.45	64.8	85.56%		1531	1718	202
	8.86	62.37	86.27%		1604	1733	203
	9.26	59.94	86.68%		1677	1741	206
	9.66	57.51	86.78%		1750	1743	212
	10.06	55.08	86.57%		1823	1698	219
	10.47	52.65	86.06%		1896	1718	227

*The linear equations used here were derived by the author to approximate the manufacturer's rimpull-speed curve for Gear 1B. Appendix 1.

Once gear efficiency is estimated, the gear reduction ratio (Rr) can be determined. This ratio represents the relationship between flywheel speed and axle speed and is calculated using the following equation [37]:

$$R_r = (RPM_{rated} 2\pi\ r)/60\ V \qquad \text{Eq. 24}$$

In this equation, 2π is used to convert angular speed to linear (horizontal) speed, and r represents the radius of the 40.00R57 tire, which is 1.778 meters [29]. The constant 60 converts engine speed from revolutions per minute (RPM) to revolutions per second (RPS), while the factor 3.6 is used to convert velocity from kilometers per hour (km/h) to meters per second (m/s). The rated engine speed (RPM_{rated}) for a standard CAT 793D engine is 1750 RPM [29].

In the example above, the reduction ratio is calculated as follows: R_r = (1750 x 2π x 1.778)/ (60 x 9.66/3.6) = 121.40. This value reflects the gear reduction based on the point of highest gear efficiency. Once both the reduction ratio and gear efficiency are estimated, the engine speed in revolutions per minute (RPM) can be calculated using the following equation [37]:

$$RPM = (R_r V)/2\pi r \qquad \text{Eq. 25}$$

For the example above, the engine speed is calculated as: RPM = 121.40 x 8.05/(2π x 1.778) = 1458. To validate this method, the resulting instantaneous power was computed using the following formula and then compared with actual Caterpillar reference data [29].

$$P = RV/\,E \qquad \text{Eq. 26}$$

P = power (kW)
V = truck speed (m/s)
R = rimpull (kg)
E = engine efficiency

Power and engine speed data provided by the manufacturer were used to derive linear equations representing the power–RPM relationship. These equations are implemented in the model to estimate instantaneous engine power at each time step (see Appendix 3). Similarly, the variation of Brake Specific Fuel Consumption (BSFC) with engine speed for the CAT 793D is also available from Caterpillar data [29]. This relationship was incorporated into the model using a series of linear equations. Once RPM is determined within the simulation, the corresponding BSFC value is retrieved. The model calculates both BSFC and power at each time step throughout the simulation. Refer to Appendix 3 for the detailed Power–RPM and BSFC–RPM equations. After determining BSFC and engine power, the model calculates the fuel consumption rate (in liters per hour) at each time step using the following formula. In this model, fuel consumption is directly proportional to the net power delivered by the engine.

$$F_c = (BSFC_{instant}\, P_{instant})/F_D \qquad \text{Eq. 27}$$

In this equation, F_D represents fuel density. According to Hays, diesel fuel density typically ranges from 0.84 to 0.96 kg/L [36]. For this model, a constant value of 0.85 kg/L was assumed, reflecting the standard diesel type used in Mongolian mining operations.

6.3 Fuel Consumption Manual vs AHS Truck

Uphill driving is responsible for the highest fuel consumption in a mine, as the engine must produce enough power to overcome both rolling resistance and gravitational forces and the trucks are fully-loaded. Downhill runs have a significantly lower consumption rate especially if the grade is steep enough such that gravity does all the work and no engine power is necessary to move the truck [28]. Note that idling is about

10% of the instantaneous power [37]. The model also assumes idling fuel consumption when the truck is queuing, dumping, loading and refuelling.

The **table 6** clearly shows that although autonomous trucks consume slightly more fuel per hour, they are more fuel-efficient per tonne and per cycle. They also have faster average speeds, shorter cycle times, and significantly reduced idle time due to the absence of shift changes and breaks. Payload remains nearly the same between both systems, but autonomous trucks achieve noticeably higher utilization rates (73–78% vs. 65%), resulting in better overall performance and productivity.

Table 6 Performance Comparison of Manual vs. Autonomous Haul Trucks

Metric	Manual Truck	Autonomous Truck	Notes	Source
Fuel Consumption (L/hour)	218 L/h	239 L/h	AHS slightly higher because of no breaks	[7]
Fuel Efficiency (L/tonne)	0.83 L/t	0.78 L/t	AHS more efficient per tonne	[7]
Fuel Consumption (L/cycle)	185.3 L/cycle	172.9 L/cycle	AHS uses less per cycle	[7]
Average Speed Loaded (km/h)	17.4 km/h	18.5 km/h	AHS slightly faster	[7]
Average Speed Empty (km/h)	27.1 km/h	28.6 km/h	AHS slightly faster	[7]
Average Cycle Time (minutes)	51 min	45.7 min	AHS faster cycles	[7]
Idle Time (Shift change, breaks)	2.3 hr/day	0.4167 hr/day	No breaks in AHS	[7]
Payload (tonnes per cycle)	223.9 t	222.1 t	Almost identical	[7]
Utilization (%)	65%	73–78%	AHS higher utilization	[7] [38]

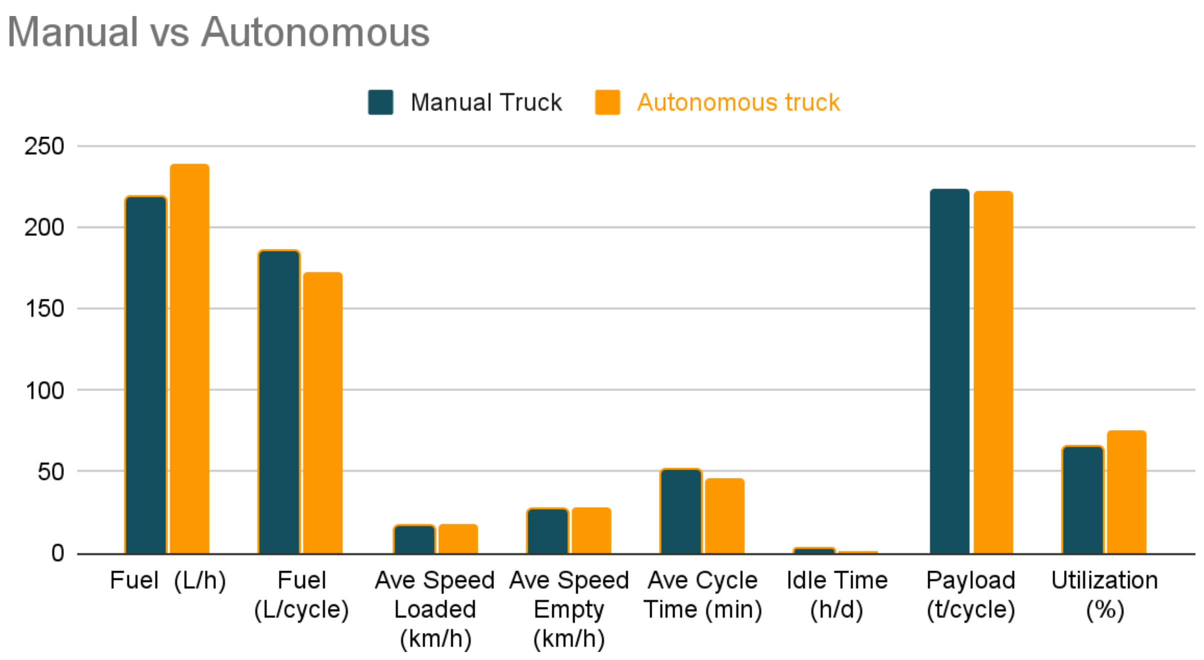

Figure 20 . Performance of Autonomous vs Manual truck.

6.3.1 Why Autonomous Trucks Are More Efficient Overall

Factor	Manual Truck	Autonomous Truck	Impact
Idle time	2.3 hours/day (breaks, shift change)	0.4167 hours/day (Refueling tank)	Truck burning fuel while idling
Cycle Time	51 minutes	45.7 minutes	Faster trips = More efficient hauling
Driver Behavior	Human variation (inconsistent acceleration, braking)	Perfect, optimized machine operation	Smoother driving = Better fuel efficiency
Utilization %	65 %	73-78%	Higher work output per hour of operation

Table 7 Operational Factors Fuel Efficiency Manual vs. Autonomous Trucks

The table indicates that autonomous (driverless) trucks are more economical than manually operated trucks. This is primarily because autonomous trucks experience minimal downtime; they eliminate idling caused by morning and evening shift changes, lunch breaks, and trips to the parking spot during shift transitions. Additionally, autonomous trucks can regulate their speed more efficiently with the help of advanced control systems, avoiding unnecessary braking, which not only saves time but also reduces fuel consumption. Furthermore, since autonomous trucks do not require lunch periods during shift changes, their utilization rate is significantly higher compared to manually operated trucks. From the operational data, it is evident that autonomous haul trucks (AHS) offer significant economic advantages over manually operated trucks. Although the hourly fuel consumption of autonomous trucks (239 L/h) is slightly higher than that of manual trucks (218 L/h), autonomous trucks demonstrate superior fuel efficiency per tonne hauled—0.78 L/t compared to 0.83 L/t for manual trucks. This improvement is attributed to the elimination of idle times, as well as smoother driving patterns enabled by automated control systems. Autonomous trucks maintain optimal speeds with minimal unnecessary braking, further enhancing fuel efficiency. Economically, if the average diesel price in Mongolia is approximately 3,800 MNT per liter, the fuel cost per tonne is calculated as 0.83*3800=3154 MNT for manual trucks and 0.78*3800=2964 MNT for autonomous trucks. This results in a savings of 3154-2964=190 MNT per tonne. In a daily operation where 5,000 tonnes are transported, the total daily fuel savings would be approximately 950,000 MNT. Additionally, autonomous trucks achieve higher utilization rates (73–78%) compared to manual trucks (65%), meaning more productive hours are generated per day without requiring additional fleet size. With shorter cycle times (45.7 minutes for autonomous vs. 51 minutes for manual) and improved average speeds (both loaded and empty), autonomous haulage systems substantially lower the cost per tonne hauled while simultaneously increasing production output. Overall, transitioning to autonomous operations leads to major daily fuel cost savings, better fleet utilization, and a more sustainable and economically efficient mining operation. Also, based on the utilization coefficient, the company previously used its equipment for approximately 15.6 hours per day. However, with the autonomous trucks, the effective operating time can increase by an additional 1.92 to 3.12 hours per day. This improvement would significantly boost daily production capacity, reduce equipment downtime, and lead to substantial time and cost savings over the long term.

8 Discussion

This thesis developed and applied a deterministic simulation model to evaluate the fuel consumption, operational efficiency, and economic impact of Autonomous Haulage Systems (AHS) against manually operated haul trucks in open-pit mining. The results demonstrate that, although autonomous trucks consume slightly more fuel per hour due to continuous operation, they exhibit greater efficiency per tonne and per cycle, owing to optimized speed control, reduced idle times, and minimized human variability. Key performance metrics such as utilization rate, cycle time, and payload per cycle were analyzed. AHS trucks showed improved utilization (73–78% compared to 65%) and reduced cycle times, contributing to better fleet productivity. Fuel efficiency per tonne was higher in AHS operations, primarily because idle times from breaks and shift changes were eliminated.

Additionally, the automation of driving behaviors (e.g., smoother acceleration and braking) contributed to reduced mechanical wear and fuel waste. From an economic standpoint, the simulation estimated fuel cost savings of approximately 190 MNT per tonne, leading to daily operational savings of 950,000 MNT when hauling 5,000 tonnes. These savings compound over time and, combined with higher daily operating hours, create a strong business case for investing in AHS technology. Despite these benefits, several challenges remain. AHS deployment requires significant infrastructure upgrades, including road redesign, safety barriers, reliable GPS and wireless communication, and RFID-tagged personnel monitoring. Furthermore, workforce adaptation, ethical considerations, and regulatory readiness must be addressed for a smooth transition.

9 Conclusion

This research presented a comprehensive investigation into the performance, fuel consumption, and operational efficiency of Autonomous Haulage Systems (AHS) in open-pit mining, using a deterministic with Caterpillar 793D truck's manufacturing data. By simulating the motion, engine dynamics, and fuel usage of both autonomous and manually operated haul trucks under varying load and terrain conditions, the study quantified the performance gap between traditional and automated haulage systems. Key findings confirmed that while autonomous trucks consume slightly more fuel on an hourly basis due to continuous operation, they achieve better fuel efficiency per tonne hauled by reducing idle time, optimizing gear usage, and maintaining consistent operating behavior. This results in reduced fuel cost per tonne, less variability in production output, and longer equipment life due to smoother mechanical handling. For instance, AHS trucks demonstrated a 10–13% increase in utilization, 5.3-minute cycle time reduction, and fuel savings of approximately 190 MNT per tonne, translating to daily savings of up to 950,000 MNT per vehicle at full production capacity. Beyond economics, AHS systems also enhance safety by removing human operators from hazardous environments, improving situational awareness through real-time sensors, and reducing the risk of fatigue-related accidents. From an environmental perspective, increased efficiency contributes to lower emissions per tonne transported, aligning with global sustainability goals. The study also emphasized the importance of adherence to ISO standards in mine road design, safe zone access control through RFID systems, and multi-layer safety architectures to mitigate risks associated with autonomous operation. Despite these benefits, the research acknowledges that successful AHS implementation requires addressing several practical challenges. These include substantial initial capital investment, infrastructure adaptation, communication network reliability, workforce retraining, and organizational change management. Moreover, ethical considerations around automation's impact on employment and operational responsibility must be strategically managed. In conclusion, this thesis demonstrates that AHS technology, when properly integrated with infrastructure, safety protocols, and operational planning, can lead to significant gains in productivity, cost-efficiency, and sustainability. As the mining industry transitions toward digital transformation, the adoption of autonomous systems is not merely a technological upgrade—it represents a shift in how mining operations are designed, managed, and optimized. Continued research, industry collaboration, and field validation will be essential to unlock the full potential of AHS and ensure responsible, efficient, and future-proof mining practices.

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Appendix 1: Rimpull Curve and Retarder Curve – CAT 793D

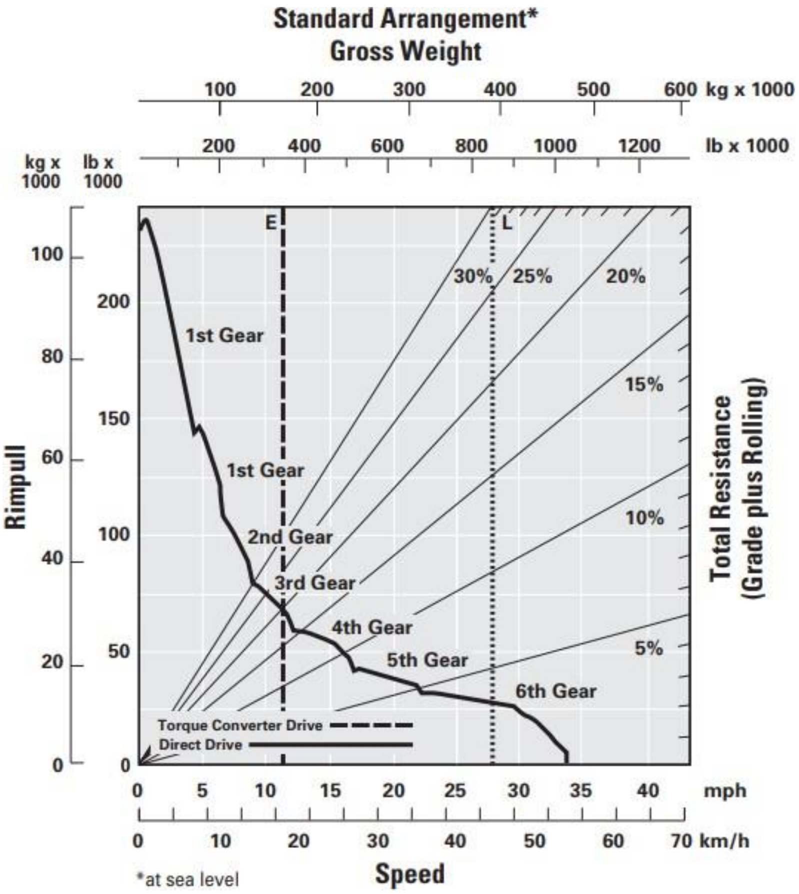

Figure 21 Rimpull curve – 793D [29].

#	Linear Equation	Gear	Speed (mph)
1	$R(V) = 228,04 + 5,36 * V$	**1A**	**0-1**
2	$R(V) = 258,15 - 26,70 * V$	**1A'**	**1 - 4.25**
3	$R(V) = 124,41 + 4,76 * V$	**1A'/1B**	**4.5 - 5**
4	$R(V) = 255,36 - 21,43 * V$	**1B**	**5 - 6.5**
5	$R(V) = 189,04 - 11,6 * V$	**2**	**6.5 - 8.75**
6	$R(V) = 123,62 - 4,95 * V$	**3**	**8.75 - 12**
7	$R(V) = 267,99 - 16,98 * V$	**3 / 4**	**12 - 12.4**

8	$R(V) = 98,57 - 3,34 * V$	**4**	**12.4 - 17.40**
9	$R(V) = 74,86 - 1,94 * V$	**5**	**17.40 - 22**
10	$R(V) = 189,23 - 7,14 * V$		**22 - 22.5**
11	$R(V) = 40,09 - 0,511 * V$	**6**	**22.5 - 29.5**
12	$R(V) = 148,9 - 4,2 * V$		**29.5 - 33.75**

Table 8 Linear equations of the above graph [29].

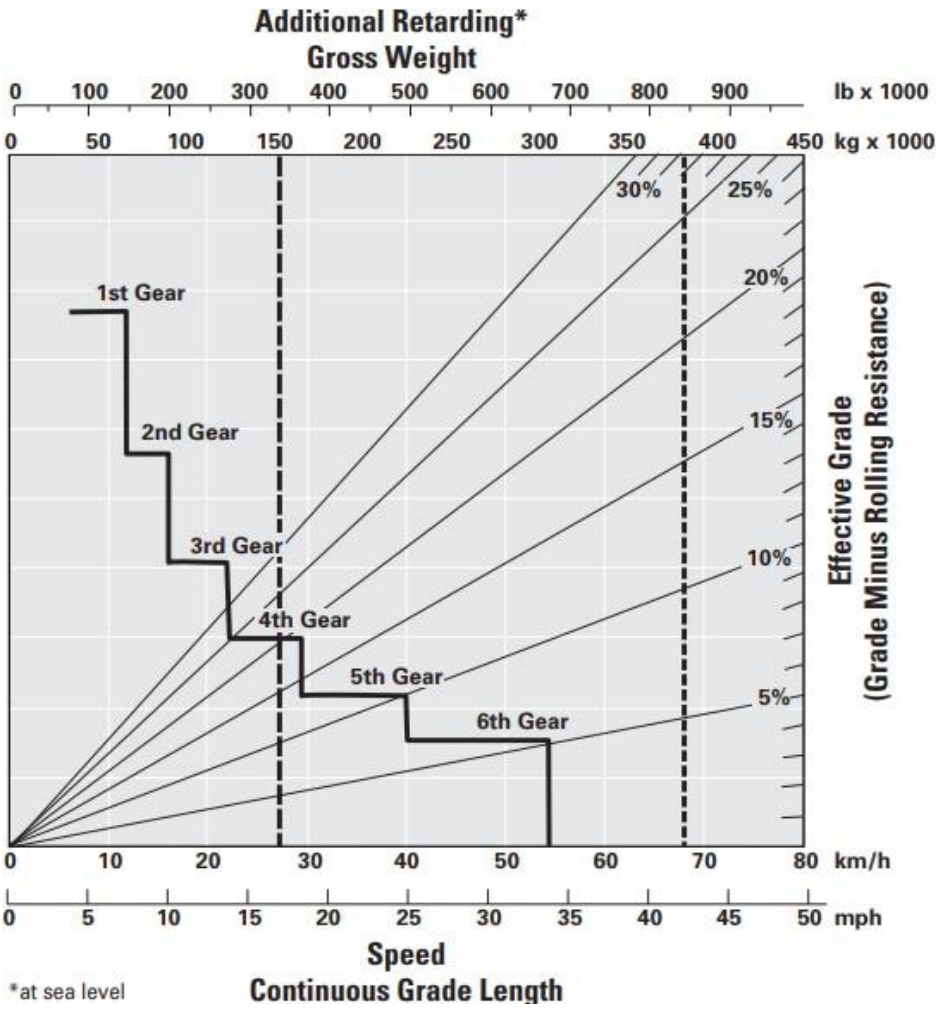

Figure 22 CAT 793D retarder curve [29].

Appendix 2: Traction and Rolling Resistance Coefficient

MATERIAL	**TRACTION FACTORS**	
	Rubber Tyres	**Tracks**
Concrete	0.9	0.45
Clay loam, dry	0.55	0.9
Clay loam, wet	0.45	0.7
Rutted dry loam	0.40	0.7
Dry sand	0.20	0.3
Wet sand	0.40	0.5
Quarry pit	0.65	0.55
Gravel road (loose not hard)	0.36	0.5
Packed snow	0.20	0.27
Ice Semi-skeleton shoes	0.12	0.12
Firm earth	0.55	0.9
Loose earth / stockpiled coal	0.45	0.6

Table 9 Traction coefficient for different road surfaces [39].

Under-footing	Rolling Resistance	
	F_{rr} (kg/t)	(%)
Hard, smooth surface with no tire penetration (well maintained).	20	2
Firm, smooth surface, flexing slightly under load (well maintained).	33	3.3

Flexible, dirt roadway (irregular surface with about 2.5 cm of tire penetration)	50	5
Flexible, dirt roadway (irregular surface with up to 10 cm of tire penetration)	75	7.5

Table 10 . Rolling resistance factor for different road surfaces [39].

Appendix 3: BSFC and Power Linear Equations for a CAT 793D

#	Linear equation	Speed	BSFC
1	y=228-0.02x	1300	202
		1400	200
2	y=186-0.01x	1400	200
		1500	201
3	y=171+0.02x	1500	201
		1600	203
4	y=139+0.04x	1600	203
		1700	207
5	y=37+0.1x	1700	207
		1900	227

Table 11 Linear equations for BSFC.

Linear equation	RPM	Power
Y=3.68*x-624	200	112
	300	480
	200	112
	400	848
	507	1242
Y=0.447*x+1015	507	1242

	700	1328
	800	1373
	900	1417
	1301	1597
	1500	1686
	1600	1730
	1750	1797
Y=-4.62*x+9884	1750	1799
	1800	1568
	1900	1106
	2000	644
X=2000	2000	584
	2000	400
	2000	300
	2000	200
	2000	0

Table 12 Linear equations for BSFC [28].