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POSITIVE RISK BALANCE FOR AUTONOMOUS VEHICLES

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Abstract: *This paper presents a collaborative research project with an automotive company aimed at implementing positive risk balance in mining environments. The study focuses on utilizing established standards such as ISO 26262, SOTIF ISO 21448 and ISO TS 5083 to develop an optimal risk assessment framework for our specific use case. The research emphasizes the importance of achieving a positive risk balance and its potential to bring significant safety improvements to the mining industry. The paper outlines the methodology employed to implement the risk assessment framework, including the utilization of ISO 26262, SOTIF ISO 21448, and ISO TS 5083 as guiding principles. The collaborative nature of the research ensures that insights and expertise from both industry and standards bodies are incorporated into the development process. Additionally, the paper proposes a verification strategy to assess the effectiveness of the implemented risk acceptance framework. The results of the research demonstrate the significant positive impact of achieving a positive risk balance in mining environments. The findings surpass traditional outcomes, showcasing the potential for a substantial safety boost in the mining industry. Overall, this paper highlights the importance of collaboration with industry experts and the application of established standards in the pursuit of positive risk balance. The research findings contribute to advancing safety practices in mining environments and provide insights for future implementations of positive risk balance in various industries.*

Key words: *Positive Risk Balance; Mining environments; ISO 26262; SOTIF ISO 21448; Risk Acceptance Framework; Safety Improvements*

1. INTRODUCTION

Autonomous vehicles (AVs) have emerged as promising technology with the potential to transform the transportation sector. The deployment of AVs has the potential to bring numerous benefits, such as improved road safety, reduced congestion, and increased mobility for those who cannot drive. However, these benefits only apply to public road users and vehicles. What we are going to analyze and develop up on, are heavy-machinery that will work on a closed-road system, where the main reason for introducing autonomous features is the safety of the driver and road users. Safety in our use-case is referred to as a state of being "safe", to be protected from harmful situations or other danger.

One of the key challenges in the deployment of these AVs is to ensure a positive risk balance between the benefits and risks associated with the technology. Positive risk balance in the context of AVs refers to the point where the benefits of the technology outweigh the risks, and the deployment of AVs results in overall improved safety and well-being for the public. To achieve positive risk balance, it is essential to consider both the technological and non-technological aspects of AV deployment.

This paper aims to provide a comprehensive overview of positive risk balance in the deployment of commercial AVs. We will examine the benefits and risks associated with commercial AVs, as well as the technological and non-technological considerations that must be considered to ensure a positive risk balance. By exploring the various factors that contribute to positive risk balance, this paper will provide insights and recommendations for ensuring that AVs are deployed in a manner that maximizes the benefits and minimizes the risks to the users of the AV. Worth to mention, is the fact that we chose this area of expertise because we can have impact on this use-case, sooner than if we would research positive risk balance for public road transport. This method is applicable for public road transport as well with some minor changes in the application of the Positive Risk Balance (PRB) formulae.

2. THEORETICAL FRAMEWORK

Self-driving cars can operate without human drivers. Individuals can be restrained in these solutions, but technologies can offer a high level of control. There are 5 stages of automation of these advanced driver assistance systems (ADAS), as defined by SAE (Society of Automotive Engineers), and this part will highlight the advantages of self-driving cars.

2.1 Levels of driving automation

The J3016 [1] standard defines six levels of driving automation, from SAE Level Zero (no automation) to SAE Level 5 (full vehicle autonomy). It serves as the industry's most-cited reference for AV capabilities.

LEVEL 0 of automated driving systems - At this level 0 the features provided are warnings and partial support. You can also find automatic emergency braking, lane departure warning, blind spot warning or others that fall in this direction.

LEVEL 1 of automated driving systems - At this we have assistance functions for lane centering, steering or braking, acceleration, adaptive cruise control and others.

LEVEL 2 of automated driving systems - With this we have functions with simultaneous control and include assistance for steering and braking and acceleration or simultaneously adaptive control of lane and adaptive cruise control simultaneously.

LEVEL 3 of automated driving systems – At this level, the human driver only intervenes if requested to do so, otherwise it does not drive when the functions are activated. The system will drive if certain conditions are met.

LEVEL 4 of automated driving systems - The system will drive if certain conditions are met, as it happens at level 3. This level does not require human intervention. The steering wheel or pedals may not be installed in the vehicle.

LEVEL 5 of automated driving systems - This is identified with the highest level. Vehicles can operate in all conditions compared to level 4. It does not require a driver.

Among the benefits brought by self-driving vehicles can be listed: reducing the number of accidents through the ability of cars to avoid collisions, reducing the amount of greenhouse gases, the comfort offered to individuals in the car and others. We can see the benefits of self-driving vehicles in Fig. 1. It's important to note that while these potential benefits are significant, the widespread adoption of self-driving vehicles also comes with challenges and considerations related to cybersecurity, job displacement, ethical dilemmas, and regulatory frameworks.

Table 1

J3016 levels of driving

Level	**Name**	**Vehicle Motion Control**	**Object and Event Detection and Response (OEDR)**	**Dynamic Driving Task (DDT) Fallback**	**Operational Design Domain (ODD)**
0	No driving automation	Driver	Driver	Driver	Not applicable
1	Driver assistance	Driver and system	Driver	Driver	Limited
2	Partial driving automation	System	Driver	Driver	Limited
3	Conditional driving automation	System	System	Fallback-ready user	Limited
4	High driving automation	System	System	System	Limited
5	Full driving automation	System	System	System	Unlimited

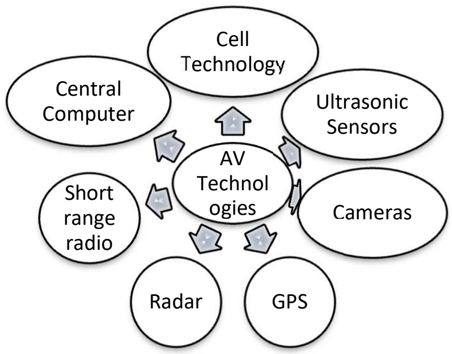

Fig. 1 AV Technologies

2.2 Potential Insufficiencies and trigger conditions

Self-driving vehicles, being in a still development phase, can still have some conditions that will require the system to fallback to either the driver or a prepared fallback user. There are two main categories that are considered potential insufficiencies and trigger conditions, that we will represent with the below table.

2.3 Sustainable through Autonomous Vehicles

Autonomous vehicles beside adding safety to humans inside the vehicle and outside the vehicle, have also less talked about ideas, but with the same importance, such as sustainable transportation [2] categorizes parameters of sustainability in three categories. Economic, Social and Environmental.

Table 2

Categories and examples of potential Insufficiencies

Planning algorithms	**Sensors and actuators**
Environment	The ODD
Location	Weather Conditions
Road infrastructure	Mechanical Disturbance
Urban or rural infrastructure	Dirt on sensors
Highway infrastructure	Electromagnetic interference
Driver or user behaviour	Interference from other vehicles
Potential behaviour of other drivers	Acoustic disturbance
Driving scenarios	Glare
Known planning alg. Limitation	Accuracy
Insufficiencies of ML	Range
	Response time

Table 3

Categories of sustainable parameters

Economic	**Social**	**Environmental**
Congestion	Community interaction and livability	Pollution -air, water, land
Mobility barriers	Health impacts	Land use changes
Accidents	Accessibility	Degradation of renewable sources
Facility and consumer costs	Equity	Climate change

Referring to the afore mentioned sustainability metrics, one significant benefit of AVs lies in their potential to alleviate congestion, a major issue in today's urban centers. According to a study by [3], it is predicted that AVs will likely lead to a decrease in congestion and a reduction in fuel consumption ranging from 0% to 4%. However, the reduction in fuel consumption extends beyond congestion alleviation. Accidents, which also contribute to global fuel consumption, can be mitigated through the implementation of improved crash avoidance systems in AVs. This provides car manufacturers with the opportunity to reduce vehicle weight and size, resulting in an additional approximate fuel consumption reduction of 5% to 23%.

Social metrics are highly applicable in the context of autonomous public transport, as elucidated in [2] and [4]. The concept of equity encompasses not only providing equal access to public transport but also treating individuals based on their specific circumstances. Furthermore, the health impacts associated with AVs can be categorized into indirect and direct effects. Indirect health impacts are primarily caused by pollution and can be mitigated by reducing CO_2 emissions through the energy-saving nature of AVs. Direct health impacts are often related to accidents, which will be discussed further in this research. Environmental metrics, including air, water, and land pollution, as well as the depletion of renewable resources, are significantly influenced by conventional human-driven vehicles. Therefore, if AVs are planned and implemented with a focus on contributing to these sustainable metrics, a tangible improvement in overall quality of life can be observed.

2.4 Safety

Safety holds paramount importance in systems where human lives are at risk. ISO 26262 [5], an internationally recognized standard for functional safety in the automotive industry, provides comprehensive guidelines and requirements to ensure safety throughout the lifecycle of automotive electrical and electronic systems. The objective of this chapter is to delve into the concept of safety as defined by ISO 26262 and provide a brief introduction to risk assessment frameworks.

According to ISO 26262, safety is defined as the absence of unacceptable risk, which is determined by considering both the probability of a hazardous event occurring and the severity of its potential consequences. The standard places significant emphasis on reducing risks through measures that mitigate both the probability and severity of hazards. Safety goals, which serve as measurable criteria for achieving acceptable risk levels, play a critical role within ISO 26262.

To ensure the systematic consideration of safety aspects, ISO 26262 introduces a comprehensive safety lifecycle framework that spans various stages, from concept development to decommissioning. This framework guides the development and operation of automotive systems, incorporating activities such as hazard analysis, risk assessment, safety requirements specification, development of functional safety concepts, and validation and verification processes.

Risk assessment is a fundamental process within ISO 26262 aimed at identifying and evaluating potential hazards and associated risks. This process involves analyzing the system's functions, interactions, failure modes, and effects to determine their impact on safety. Risk assessment plays a crucial role in establishing safety goals and defining the necessary safety requirements to achieve those goals.

While ISO 26262 provides specific guidance for the automotive industry, various risk assessment frameworks are employed across different domains and industries. These frameworks offer systematic approaches to identify, analyze, and manage risks. Although numerous frameworks exist, they typically share common elements such as hazard identification, risk analysis, risk evaluation, and risk treatment strategies. These frameworks facilitate the assessment and prioritization of risks, ultimately leading to effective risk mitigation and informed decision-making processes.

2.5 Safety in Autonomous Vehicles

Ensuring safety in the context of AVs is a critical consideration as technology becomes increasingly prevalent on roads and highways around the world. Safety is of high importance for AVs, as the vehicles are designed to operate without human intervention, and any failure or malfunction could result in serious accidents and fatalities. This section will discuss the key safety considerations in the context of AVs, including the technological and non-technological aspects of safety.

2.5.1 Technological Aspects of Safety in AVs

The technological aspects of safety in AVs refer to the measures taken to ensure that the vehicles operate safely and effectively. These measures include:

Redundancy and fail-safe systems: AVs rely on complex software and hardware systems that are prone to failure. Redundancy and fail-safe systems can help minimize the risks of failures in critical components by ensuring that there are backup systems and processes in place to detect and address any malfunctions.

Sensor fusion and perception systems: AVs rely on a range of sensors, including cameras, radars, and lidars, to perceive and interpret the environment around them. Sensor fusion and perception systems ensure that the vehicles can accurately and reliably detect and respond to obstacles and other road users.

Machine learning and artificial intelligence: Machine learning and artificial intelligence is and can be used to perfect safety in AV’s, being able to perform perception tasks, similarly to how a human would do in the act of driving.

2.5.2 Non-Technological Aspects of Safety in AVs

The non-technological aspects of safety in AVs refer to the measures taken to ensure that the deployment of the vehicles is safe and responsible. These measures include:

Regulation and legal frameworks: Governments and regulatory bodies play a crucial role in ensuring the safety of AVs. Appropriate regulation and legal frameworks can help to set safety standards, ensure compliance, and address liability and insurance issues.

Public perception and acceptance: The success of AV deployment depends on public perception and acceptance. AV manufacturers and developers must address public concerns and communicate the benefits of the technology to ensure public trust and confidence in the safety of vehicles.

Ethics and moral considerations: AVs raise a range of ethical and moral considerations, such as the question of how to program the vehicles to respond in life-or-death situations. These considerations must be addressed to ensure that the deployment of AVs is safe and responsible.

In conclusion, ensuring safety in the context of AVs requires a holistic approach that addresses both the technological and non-technological aspects of safety.

By taking appropriate measures to address the key safety considerations, it is possible to ensure that AVs are deployed in a manner that maximizes the benefits of the technology while minimizing the risks and ensuring public safety.

2.6 Safety improvements in mining

Underground mining presents various health and safety risks for workers due to hazardous operating conditions including thermal stress, ventilation hazards, and rock bursts, as well as heavy equipment accidents. Such risks can lead to both fatal and chronic illnesses. Given the severity of these dangers, ensuring worker safety is of the utmost importance in the mining industry. Over the years, the industry has made notable progress in creating a safer work environment through technological advancements and the implementation of rigorous safety regulations by the Mine Safety and Health Administration (MSHA). Although these measures have led to a decrease in workplace incidents, the possibility of safety hazards cannot be eliminated.

We will present four of the most used and useful innovations that have the potential to reduce the safety in mining drastically [6,7]:

1. Wearable Technology;
2. Robotics and Automation;
3. Radio-frequency Identification;
4. Drones.

There are also research papers and data available on the use of these technologies in real-world mining scenarios. Many mining companies and equipment manufacturers have conducted studies and published reports on the effectiveness of these technologies in improving safety and productivity in the mining industry.

For example, a study published by the National Institute for Occupational Safety and Health (NIOSH) found that the use of proximity detection systems in underground mines reduced the number of injuries and fatalities related to mobile equipment by 40%.

Another study conducted by Caterpillar, a leading manufacturer of mining equipment, found that autonomous haulage systems [8] (AHS) can increase productivity by up to 30%, reduce fuel consumption by up to 10%, and improve safety by reducing the risk of accidents caused by human error.

Similarly, the use of drones for aerial surveys and inspections has been shown to improve safety and efficiency in the mining industry. According to a report by PwC, drones can reduce the time and cost of conducting surveys and inspections by up to 90%, while also reducing the risk of injuries and fatalities associated with working at heights or in hazardous areas.

2.7 Risk Acceptance Frameworks

The development of AVs has brought about a new set of risks that must be assessed and managed. To address these risks, several risk assessment frameworks have been proposed in recent years. In this section, we will introduce these frameworks and discuss their strengths and weaknesses.

One of the most widely used risk assessment frameworks for AVs is the ISO 26262 [5] standard. This framework provides a systematic approach to safety management and is designed specifically for automotive systems. It requires a hazard analysis and risk assessment to be conducted at the system, hardware, and software levels. The ISO 26262 standard also provides guidance on the development of safety requirements and the verification and validation of safety measures.

In addition to these frameworks, several other approaches to AV risk assessment have been proposed. As Low As Reasonably Practicable (ALARP), where the risk has to be reduced without having a gross disproportion of cost compared to the risk reduction. Other approaches that we will discuss include Nicht Mehr Als Unvermeidbar (Not more than unavoidable - NMAU), Minimum Endogenous Mortality (MEM), At least the same safety (MGS), Globalement Au Moins Aussi Bon (GAMAB) and PRB.

While these frameworks provide valuable guidance in AV risk assessment, they also have some limitations. For example, the ISO 26262 standard was developed specifically for automotive systems and may not fully capture the unique risks associated with AVs. PRB requires a comprehensive understanding of the hazards and probabilities involved, which can be challenging in complex systems such as AVs.

Positive Risk Balance (PRB) is a risk management concept that refers to a situation where the benefits of an action or decision outweigh the potential risks. It is used to evaluate whether the potential benefits of a particular course of action justify the risks involved.

In the context of autonomous vehicles, PRB is used to assess whether the benefits of deploying self-driving cars on the roads outweigh the risks associated with their use. Some of the potential benefits: reducing the number of accidents through the ability of cars to avoid collisions, reducing the amount of greenhouse gases, the comfort offered to individuals in the car and others. However, there are also risks associated with the use of autonomous vehicles, such as the potential for accidents, cybersecurity threats, and ethical considerations related to decision-making algorithms.

To achieve a PRB in the deployment of autonomous vehicles, the benefits of the technology must outweigh the risks associated with its use, as per (1). For example, if a self-driving car is able to significantly reduce the number of accidents on the road, then the benefits of its deployment would likely outweigh the risks associated with its use. On the other hand, if the risks associated with self-driving cars are deemed too high, then the technology may not be deployed until those risks can be mitigated.

$$SP_{AV} < SP_{HD} \tag{1}$$

3. POSITIVE RISK BALANCE APPROPRIATNESS FOR AUTONOMOUS VEHICLES

In the rapidly evolving world of autonomous vehicles, ensuring safety remains a paramount concern. As self-driving technology continues to advance, it becomes crucial to establish a framework that appropriately evaluates the risks associated with these vehicles. One such framework gaining attention is the concept of Positive Risk Balance (PRB) Appropriateness. PRB is a metric that allows for a clear deductible measure of risk in relation to a baseline threshold, providing a comprehensive approach to assessing the safety of autonomous vehicles.

The first key aspect of PRB Appropriateness is its focus on expected societal acceptance. Unlike traditional risk assessment models, PRB recognizes that what is already deemed acceptable in society should serve as the starting point for evaluating autonomous vehicle risks. By doing so, PRB acknowledges that the introduction of self-driving technology should aim to improve upon existing safety standards rather than merely meeting them. This consideration of societal acceptance ensures that PRB Appropriateness is aligned with the evolving expectations of the public, fostering a smoother transition to autonomous vehicles.

Furthermore, PRB Appropriateness is rooted in the scientific method and driven by analytics. This evidence-based approach enables a comprehensive evaluation of risk factors associated with autonomous vehicles. By collecting and analyzing vast amounts of data, PRB facilitates a systematic assessment of potential hazards, allowing policymakers and researchers to make informed decisions. The reliance on scientific methodology ensures that PRB Appropriateness is not based on subjective opinions but rather on objective and measurable criteria.

One notable aspect of PRB Appropriateness is its particular emphasis on human harm, specifically safety, rather than property damage. While property damage is certainly a concern, PRB prioritizes the protection of human lives. By focusing on safety, PRB Appropriateness aligns with the fundamental principle of minimizing harm to individuals, which is crucial when evaluating the appropriateness of autonomous vehicles. This narrow focus allows for a more targeted assessment of risks associated with self-driving technology, providing a clear and straightforward framework for analyzing potential dangers.

3.1 Steps for PRB

In this section we will discuss the methods used to define the area, the data sources used to gather crash statistics, and the techniques employed to analyze the data. By taking the next steps, we can develop a comprehensive understanding of the risks and benefits associated with our project and develop effective strategies to ensure its safe and effective deployment.

Our research will be based on commercial vehicles, more than likely mining equipment of great sizes.

Mining trucks that carry ore are a critical component of the mining industry. These trucks are designed to transport large quantities of ore from the mining site to processing facilities or stockpiles. They are typically massive vehicles that can carry up to several hundred tons of material in a single load.

The design and specifications of mining trucks vary depending on the specific mining operation and the type of ore being extracted. However, most mining trucks are equipped with large, rugged tires that can traverse rough terrain, and powerful engines that can propel the truck up steep inclines.

In addition to their size and power, mining trucks also have advanced safety features that are designed to protect the driver and other workers in the mine. These features may include backup cameras, proximity sensors, and collision avoidance systems.

Despite their advanced features and capabilities, mining trucks also present significant risks and challenges. The heavy loads they carry can cause significant wear and tear on the vehicle and can also increase the likelihood of accidents if not properly managed. Furthermore, the challenging working conditions in a mining operation can put drivers and other workers at risk of injury. Types of injuries that occur in this environment are displayed in the below figure. It represents the last 5 years of incidents from a dataset acquired from MSHA, with the corresponding injury for each incident. As we can observe, almost half of the incidents represent sprains, which if we analyze more in-depth, the severity of this type of injury, is classified as “Slightly” or “Incident only”, Figure 2.

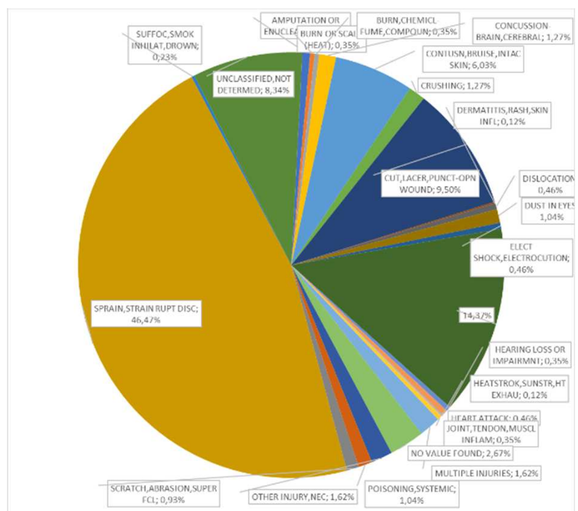

Fig. 2 Nature of Injury based on last 5 years of accidents.

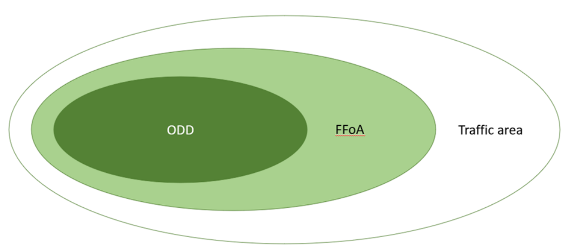

Fig. 3 Contents of traffic area

3.2 Dataset

The next step for achieving a positive risk balance for this application would be to have a dataset with incidents caused during usage of these ore haulage trucks. On of the most comprehensive and public datasets would be the one published by the MSHA [9]. This Dataset provides information about every reported incident in mining facilities, starting from the 2000's until the writing of this paper. The data found in this database, covers accident types, nature of injury, place of accident and much more incident-centered data, majority of the information is very useful for us to establish the cause of the incident, which later on will help us determine PRB for this case, Figure 3.

Based on Fig. 3, we can accurately say what assets we took from the MSHA Dataset. First, we have the entire "Traffic Area", which in our case refers to everything traffic related to the Mining Community. FFoA, represents collisions on which our system can have a direct or indirect impact, and ODD represents our Operational Design Domain which refers to our specific use-case Ore Trucks of great sizes inside of mining facilities.

Currently we restrict the data to the last 5 years of incidents, which totals to about 864 incidents that vary in days restricted from work, from 0 days up to 572 days. This metric has been one of the first choices, as it explains the gravity of the situation more easily. Other metrics will be considered too, such as injury nature, hours from shift begin time, and a MSHA graded degree of injury etc. The reasoning behind the choice of analyzing the last 5 years of incidents, comes from the fact that in these 5 years, no influencing on our research type of technology has been introduced in these mining facilities, detail that is observed in our shown data as the number of incidents remains fairly constant throughout the years.

So far, we found three main causes for these incidents:

- Too many working hours in one single day, which adds to fatigue of the driver's average accident time, from clocking into work to accident is 5 hours with maximum being 12 hours of continuous work.

[Minimum value should not be considered, as it's equal to the clocking in time].

- Damaged roads that provoke sprains, representing almost half of our incidents.
- Falling from or onto objects, which is related to accessing, respectively leaving the machine during work hours.

3.3 Analyzing data

We now know that for achieving PRB on our use case, we will have to compare the safety performance of our AV system with the safety performance of human drivers, with the formula stated at (1). Given the above charts, we can set targets for each metric, using the PRB, safety performance formula:

$$SP = \frac{n_{collision}}{4} \tag{2}$$

(2) was adapted for our use case and originates from [10]. The initial formula uses a ratio of annual mileage per annual number of crashes. (3) represents the initial formula used in [10].

$$SP_{IL_i} = d_{IL_i} \frac{m}{n_{collisionJL_i}} \tag{3}$$

In our case, this formula equals to a ratio of "Ore haulage trucks - off highway trucks" crashes per quarter of a year.

The baseline will be set with human drivers. Normally in an Autonomous Driving System (ADS) scenario, this safety performance metric will be calculated only with experienced drivers, but as for Ore haulage truck drivers there is a requirement of having a truck license, and appropriate training at the hiring company.

We describe a method to quantify the safety performance of human drivers 〖SP〗_HD based on our accident data. We evaluate the above-described dataset from MHSA [9]. Given that for the moment there is no availability of measured experience of the drivers, we concluded to use all the data available in the dataset.

With the given data, we created table 4, this shows the number of accidents involving mining trucks per year, categorized by severity, for the years 2018 to 2023.

The severity of accidents is classified into four categories, using the MSHA defined degree of injury:

- Fatal: accidents resulting in the death of one or more people.

- Severe: accidents resulting in serious injuries.
- Slightly: accidents resulting in minor injuries.
- Incident only: accidents that did not result in any injuries.

Looking at the table, we can see that the number of accidents with mining trucks per year varies across the different severity categories and over time. In 2018, there was one fatal accident, while in 2019 there were no fatal accidents. However, in 2021 there were five fatal accidents, which is the highest number of fatalities in the given time period.

In terms of severe accidents, there were 87 incidents in 2018, which decreased to 74 in 2019 and then decreased to 28 in 2023. Similarly, the number of slightly severe accidents and incident-only accidents also fluctuated over the years.

Overall, this table provides valuable information on the safety performance of mining trucks, highlighting areas where improvements may be needed and where safety initiatives have been successful.

Table 4

Number of accidents per year

Severity	**Number of accidents with mining trucks per year**					
	2018	2019	2020	2021	2022	2023
Fatal	3	0	2	5	1	3
Severe	87	74	69	56	74	28
Slightly	78	139	95	91	96	20
Incident only	4	13	9	18	10	3

Table 5

Number of accidents per quarter

Quarter	**Number of accidents with mining trucks per quarter**					
	2018	2019	2020	2021	2022	2023
1	51	52	42	44	54	
2	50	49	35	40	38	
3	63	60	51	50	45	
4	57	66	37	38	54	

Table 6

Number of accidents per year

Year	2019	2020	2021
Accidents	226	175	170
DbA	1.61	2.08	2.14

Table 5 provides information on the quarterly trends in mining truck accidents, which can help identify areas where safety improvements may be needed and where safety initiatives have been successful.

Looking at the table, we can see that the number of accidents with mining trucks per quarter fluctuates over the years. For example, in 2018, there were 51 accidents in the first quarter, 50 accidents in the second quarter, 63 accidents in the third quarter, and 57 accidents in the fourth quarter. In 2019, the number of accidents in each quarter was relatively consistent, ranging from 49 to 66 accidents per quarter.

In 2020, the number of accidents was generally lower than in the previous years, with the first quarter having the highest number of accidents at 42 and the fourth quarter having the lowest number of accidents at 37. However, in 2021, the number of accidents increased again, with the first quarter having 44 accidents and the third quarter having 50 accidents.

Having the number of accidents per quarter available, we can calculate the average time-distance between collisions for the individual severities (Eq. 1).

Table 6 shows the average distance between two collisions over the years. Fatal collisions are also included in this table, but are not separated, as there are a limited number of such accidents.

3.4 Using the targets

As highlighted in the previous chapter, our analysis revealed that the average time-distance between two accidents in mining traffic falls within the range of 1 to 2 days. However, it is important to acknowledge that the true value of today's mining traffic safety performance remains uncertain. Recognizing this, [11] proposed a methodology to address these uncertainties by assuming a Gaussian distribution to model the safety performance.

To design an Autonomous Driving System (ADS) that accounts for these uncertainties, [11] introduced two safety factors. The first safety factor involves setting a target threshold that is two times the standard deviation above the average value. This factor aims to establish a safety margin that accounts for potential variations and deviations from the average. The calculation for this first safety factor is as follows:

$$SP_{Target} = SP_{HD} + 2\sigma \tag{4}$$

By incorporating this safety factor into the design of the ADS system, [11] sought to enhance safety measures and ensure a robust performance that accounts for the inherent uncertainties in mining traffic safety. The consideration of both the average value and the standard deviation allows for a more comprehensive approach to safety, accommodating potential variations in accident occurrences.

Note: The reference [11] mentioned in the text is a placeholder and should be replaced with the appropriate and relevant reference specific to the study or research being cited.

The second safety factor within the ADS system design considers the need for a redundancy layer to address uncertainties related to sensor performance and the occurrence frequency of specific situations. The value of this safety factor increases as the level of uncertainty in a scenario or task grows. In the case of mining traffic safety, the availability of incident data is relatively limited compared to more traditional ADS tasks that have access to thousands of accidents for analysis.

In the context of our study, the value of the safety factor is inversely related to the amount of available data. As the dataset becomes more extensive and provides a higher volume of incident information, the value of the safety factor decreases. This reflects the idea that a larger dataset allows for more accurate assessments and predictions, reducing the need for a higher safety factor. By considering the appropriate safety factors based on the level of uncertainty and the availability of incident data, the ADS system can account for potential variations, enhance its capabilities, and ensure a robust performance in mining traffic safety.

3.5 Hazardous Scenario

Utilizing PRB involves selecting hazardous scenarios that can be effectively addressed using innovative technologies. These scenarios need to be modeled with well-defined events, incorporating specific details such as vehicle speed, weather conditions, the number of vehicles involved, and, in some cases, the deceleration rate of the vehicle. Additionally, considering the number of humans involved in the scenario can be proposed as a parameter.

One example of a relatively simple yet potentially fatal scenario could be a collision between two mining trucks at a junction due to low visibility presented in Table 7. This scenario could result from various factors, such as the junction appearing after a road curvature, reduced daylight, hardware issues on one of the mining trucks, and more.

Following the selection of the example scenario, the next step would involve comparing the incident with company's concept of universal safeguards, to which we would like to propose an additional safeguard called "Avoid hazardous behavior to achieve occupant safety" with a priority of 1.

Table 7

Maneuver Risk Assessment

Location	**Mining Facility 5948**
Item Usage	Transport from Ore Mine to Ore processor
Road Conditions	Wet Mud Road
Environment	Dark/Low Visibility
Traffic and People	Regular same category trucks participating
Operation Mode of Item	Driven by HD
Vehicle Speed	30 mph
Operational Situation/Scenario	Traffic Participant yielding way to other traffic participant
Behavioral Competency	Reacting to traffic participant
Maneuver	Stop Before Obstacle / Slow down
Failure of the Maneuver	Not slowing down / Not stopping before obstacle
Hazardous Event	Collision with Traffic participant
Potential Effect	Severe to Fatal outcome for ego vehicle driver/Light to Severe Injuries for hit vehicle
Violated Universal Safeguard	Avoid collisions / Operate cautiously when visibility is limited
Top Level Safety Objective	Time distance/Measured distance to yielding vehicle should be greater to avoid collision
PRB Target for the Top-Level Safety Objective	Avoid collision

This Safeguard is essential for our use-case, as we could remove as many as 20% of all our cases, because these incidents could be easily avoided if the driver didn't have to start using the mining truck, for example when one driver injures himself while climbing the entrance ladder to the truck. The universal safeguard concept outlines different incident types that can occur in a mining facility and assigns a level of prioritization, like ASIL levels, based on the incident's severity.

In our case, the incident would fall under the category "Operate Cautiously when visibility is limited," which would have a prioritization level of 3. Additionally, a more critical level of 1 would be assigned to the category "Avoid Collision." By conducting this comparison, the specific safeguards applicable to the incident can be identified.

Subsequently, innovative technologies that can mitigate risks and prevent collisions should be identified and implemented. For instance, using sensors and cameras on trucks to enhance visibility and detect potential hazards could be a potential solution.

To evaluate the effectiveness of these innovative technologies, safety performance indicators need to be established and regularly monitored.

These indicators may include the number of near-miss incidents, the frequency and severity of accidents, and the overall safety culture within the mining facility. By consistently tracking these indicators, areas for improvement can be identified, allowing for the refinement and optimization of PRB practices to ensure a safer and more productive mining operation.

3.6 Verification and Validation Strategy

Setting a strategy to verify and validate the researched risk framework is crucial in a AV environment. As [11] states, a number of objectives and methods have to be defined, followed by rationalizing the selected methods and targets, to consider them suitable for the use-case. The strategy we are proposing:

- Environmental requirements for verification.
- Simulating and evaluating the example hazardous scenarios for the use-case.
- Implementing early-access systems with fallback-systems in real life scenarios
- Generation of evidence based on the last two bullet-points

The utilization of simulation examples involving hazardous scenarios plays a crucial role in establishing initial benchmarks for AV products. Even in the event of incidents, these simulations serve as valuable tools for evaluating the system's performance without incurring any human or material losses. A similar approach and strategy are highlighted in [12], where the authors emphasize the advantages of virtual simulations in creating clean baselines for system evaluations. Notably, virtual simulations eliminate the need to consider redundancy factors for sensors, cameras, and other hardware, which could otherwise impact the accuracy of evaluations.

Once the virtual simulation phase is successfully completed and meets the predefined targets, the logical next step is to implement the AV system onto real-life machinery operating within a closed-course environment. This phase necessitates rigorous testing and redundancy checks of the hardware to ensure the safety of individuals involved when the AVs are deployed in real-life scenarios.

It is worth noting that mining machinery primarily operates on private roads within private companies. This aspect facilitates the expedited implementation and evaluation of AV systems, as the controlled environment enables faster iterations and assessment of their performance.

The final step entails generating evidence based on the implementation of both the software and hardware components on the mining machines. This evidence serves as tangible proof of the AV system's functionality, reliability, and safety standards. Through rigorous testing, evaluation, and documentation, the AV technology can garner credibility and trust within the mining industry, paving the way for broader adoption and integration into operational practices.

4. RESULTS

By utilizing the afore-mentioned safety performance indicators, the results obtained from our analysis will enable us to assess and estimate the positive risk balance performance indicator for our specific use case. These indicators provide a means to evaluate the effectiveness and safety of our proposed implementation, ultimately allowing us to gauge the extent to which the risk is mitigated, and positive outcomes are achieved.

The provided chart illustrates the incidents that occurred over the course of the past five years, categorized by quarters. This data served as the basis for calculating a Safety Performance indicator for human-driven mining trucks, resulting in a value of 244.5. Subsequently, we conducted simulations to assess the impact of implementing company's Positive Risk Balance safety criteria for potential autonomous technology and our proposed universal safeguards. These simulations aimed to determine the number of incidents that would have potentially occurred if our proposal had been implemented during the same years of service, Fig. 4.

The results of our study demonstrate a significant advantage in utilizing Positive Risk Balance for autonomous vehicles within mining facilities, leading to a remarkable 50% increase in driver safety. This means that if before a potential RAF would have been implemented, having the number of incidents from Fig. 5, was socially acceptable, then using PRB during the same years of service would be socially acceptable, as the proposed results are over 50% smaller.

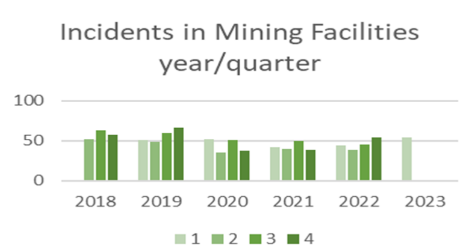

Fig. 4 Incidents in Mining Facilities year/quarter

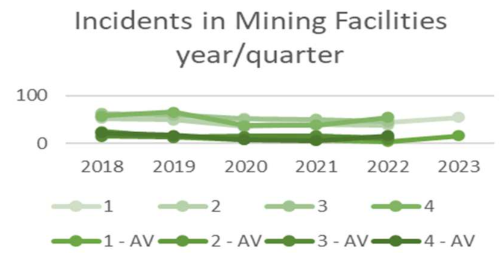

Fig. 5 Risk Assessment Framework (RAF) comparation to manual driven vehicle

Table 8

Distance between Accidents AV

Year	2019	2020	2021
Accidents	226	175	170
DbA	1.615044	2.085714	2.147059
$Accidents_{AV}$	57.2	39	41.6
DbA_{AV}	6.381119	9.358974	8.774038

These findings were obtained through simulations conducted with a safety factor of 30%. While 30% is already considered a conservative and safe choice, it is important to note that our extensive dataset and ultimate objective of enhancing safety in mining truck driving have driven these figures. By achieving over 50% reduction in incidents, we unequivocally establish a positive risk balance. Furthermore, with the availability of additional data, we anticipate the potential to further decrease incident rates by at least 20%. These results affirm the effectiveness of autonomous vehicles in improving safety within mining operations and reinforce the continuous pursuit of enhanced safety measures.

Referring to our previous analysis on accidents throughout the years, and the distance between two accidents, the results are significant as well. In table below we can observe that the increase in days between accidents, respectively the decrease of accidents has a difference of around 300%, Table 8.

5. CONCLUSIONS

Within the automotive and commercial domains, numerous risk assessment frameworks are employed, and a significant portion of these frameworks rely on quantitative methodologies. These approaches typically consider the financial costs associated with incidents, aiming to demonstrate that the cost of incidents in an autonomous implementation is lower than that of a human-driven vehicle. However, in the context of our specific use case, the consequences of incidents within mining facilities often involve casualties, severe injuries, or even fatalities. It is for this reason that our primary objective is to reduce the occurrence of such incidents, recognizing that human lives are a valuable resource that recovers slowly.

New technologies can contribute to reducing risks and the impact on the environment. At the same time, they can contribute to improving the lives of individuals and reducing other types of risks [13-17].

Furthermore, the utilization of quantitative approaches in other autonomous implementations is often driven by the fact that these implementations are employed in public settings, where potential lawsuits can be financially burdensome.

However, such cases are relatively rare within mining facilities due to the professional expertise of the drivers, who possess the necessary skills to navigate and manage situations within their designated work environments.

This paper presents a methodological approach to address the requirements of achieving a Positive Risk Balance, particularly in situations where an abundance of data is available. We put four solutions for calculating safety performance even when specific data on driven kilometers is not accessible. Additionally, we propose a universal safeguard that eliminates the need for human presence inside the vehicle when it is unnecessary, thereby reducing the occurrence of incidents.

Moving forward, it is crucial to gather new data for a more comprehensive analysis of incidents. This includes collecting information on factors such as weather conditions, the distance traveled between incidents, the speed at which the incidents occurred, and other pertinent general details. By incorporating this additional data into our analysis, alongside the existing information, we can gain a better understanding of how incidents can be avoided, and safety can be improved.

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Balanț pozitiv de risc pentru vehicule autonome

Această lucrare prezintă rezultatele unui proiect de cercetare în colaborare cu o companie din industria autovehiculelor care vizează implementarea unui echilibru pozitiv al riscurilor în mediile miniere. Studiul se concentrează pe utilizarea standardelor stabilite, cum ar fi ISO 26262, SOTIF ISO 21448 și ISO TS 5083 pentru a dezvolta un cadru optim de evaluare a riscurilor pentru cazul nostru specific de utilizare. Cercetarea subliniază importanța realizării unui echilibru pozitiv al riscurilor și potențialul acestuia de a aduce îmbunătățiri semnificative de siguranță în industria minieră. Lucrarea prezintă metodologia folosită pentru implementarea cadrului de evaluare a riscurilor, inclusiv utilizarea ISO 26262, SOTIF ISO 21448 și ISO TS 5083 ca principii directoare. Natura colaborativă a cercetării asigură includerea în procesul de dezvoltare a cunoștințelor și expertizei atât din industrie, cât și din partea organismelor de standardizare. În plus, lucrarea propune o strategie de verificare pentru a evalua eficacitatea cadrului implementat de acceptare a riscurilor. Rezultatele cercetării demonstrează impactul pozitiv semnificativ al atingerii unui echilibru pozitiv al riscurilor în mediile miniere. Descoperirile depășesc rezultatele tradiționale, arătând potențialul pentru o creștere substanțială a siguranței în industria minieră. În general, această lucrare evidențiază importanța colaborării cu experții din industrie și a aplicării standardelor stabilite în urmărirea echilibrului pozitiv al riscurilor. Rezultatele cercetării contribuie la promovarea practicilor de siguranță în mediile miniere și oferă perspective pentru implementările viitoare ale echilibrului pozitiv al riscurilor în diverse industrii.

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