ENERGY ABSORBING SYSTEMS IN MINE HOIST CONVEYANCES: A REVIEW OF DESIGN CONSIDERATIONS AND BIOMECHANICAL IMPLICATIONS FOR IMPROVED SAFETY

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ABSTRACT

Mine hoist systems are essential for vertical transportation in underground mining but pose safety risks, particularly from slack rope events and rope severance. The large deceleration rates experienced could, by themselves, be sufficient to cause serious injury or even fatalities to the occupants. Addressing these risks is critical. This paper reviews the design and application of energy-absorbing systems within mine hoist conveyances to enhance safety and mitigate the impact of such events. It examines the working principles of various energy-absorbing mechanisms, including spring suspension systems interlinked with wedge braking systems, and explores their effectiveness in attenuating kinetic energy during free-fall situations. Also considered are the biomechanical tolerance limits of the human body and how these limitations influence the design and deployment of these systems. This paper synthesizes current research and incident analyses to identify best practices and future directions for improving mine hoist safety through energy-absorbing technologies.

Keywords: Mine Hoist, Energy Absorber, Slack Rope, Braking Systems, Deceleration Rates, Biomechanical Limits, Safety.

INTRODUCTION

Mine hoist conveyances are critical infrastructure in underground mining operations, facilitating the transport of personnel, equipment, and materials between surface and subterranean environments (Batko & Korbiel, 2008; Galy & Giraud, 2023; Gere & Timoshenko, 1991). However, the operation of these systems presents inherent risks, with two primary failure scenarios posing significant threats: over-winding of ascending conveyances and slack rope incidents involving descending conveyances. While mechanisms like detaching hooks and catch gear have mitigated the risks associated with over-winding, slack rope events remain a persistent challenge (Rosslee et al., 1998).

The potential consequences of mine hoist failures are severe, ranging from equipment damage to life-threatening injuries and fatalities (Groves et al., 2007; ILO, 1990; Ministry of Energy and Mines, 2017). Recent incidents, such as the 2024 Bulawayo Mining Company incident and the 2023 Impala Platinum incident, highlight the ongoing need for enhanced safety measures. When a conveyance becomes jammed and then suddenly released, it can enter a state of free fall, generating significant kinetic energy. Effectively managing this energy is crucial to preventing structural failures and minimizing risks to occupants.

This paper addresses the critical need for optimized safety measures by examining the design and application of energy-absorbing systems in mine hoist conveyances (Blanchard & Fabrycky, 2015; Ezra, 1972; Heyns, 1998). By analyzing the dynamic response of conveyances during free-fall situations and considering the biomechanical limitations of the human body, this paper aims to identify best practices and future directions for improving mine hoist safety through energy-absorbing technologies.

1. Literature Review

The safe operation of mine hoist systems is paramount, given their critical role in transporting personnel and equipment in underground mining (Giraud & Galy, 2018). A significant body of research focuses on preventing accidents related to these systems, particularly addressing over-winding events in ascending conveyances. These solutions typically involve detaching hooks and catch gear to prevent catastrophic outcomes. However, slack rope incidents with descending conveyances present a persistent challenge, demanding alternative safety strategies.

The complexities in developing analytical models for emergency hoist cage deceleration scenarios. The challenge lies in balancing the need for efficient conveyance retardation with adherence to both rope tensile strength limits and permissible human tolerance thresholds. This involves considering the dynamic forces exerted on the system during a sudden stop and ensuring they remain within safe limits for both the equipment and the occupants (Steynberg, 2007).

1.1 Mitigating Slack Rope Events: Design Considerations

Designing safety systems to mitigate the impact forces generated when the hoisting rope is suddenly tensioned after it comes off the jam has several facets that must be reviewed.

- Energy absorption technologies
- Human biomechanical limitation
- Fail safe systems
- Regular maintenance

1.1.1 Energy Absorption Technologies

The analysis and mitigation of the safety risks associated with slack rope events in mine hoists has led to the incorporation of passive energy absorbers into the suspension system to attenuate kinetic energy during these events. A spring suspension system interlinked to wedge braking system is necessary for enhanced safety and reliability of hoist conveyances in mining operations, providing a viable solution to mitigate the biomechanical risks encountered by personnel utilizing mine conveyances.

1.1.2 Human Biomechanical Limitation

Emergency hoist cage deceleration scenarios, wherein braking forces are directly exerted on conveyances experiencing overtravel, need analytical models that guarantee efficient conveyance retardation while adhering to the constraints of rope tensile strength and permissible human tolerance thresholds. In the design consideration, the mine hoist cage braking system needs to comply with human body tolerance limits for G-forces, peak crash forces, and accelerations in different directions to ensure occupant safety and minimize the risk of injury or fatality.

1.1.3 Fail-Safe Systems

Hoist systems must be designed with fail-safe components that will be able to keep personnel safe when a failure occurs in the operation of the system. They include mechanical brakes that automatically engage when power is lost. This keeps the conveyance from uncontrolled movement.

1.1.4 Regular Maintenance

Implementing regularly scheduled inspections, maintenance, and testing to confirm conveyance safety gear is working correctly. All safety components of the hoisting system need to be maintained.

2. Dynamic Response with and without Braking Systems

In order to accomplish this, the response of a conveyance in a slack rope event with no arrestor unit fitted is studied and subsequently compared to the response of the same system with an arrestor unit fitted. Assumptions are as follows:

- The system is treated as a mass spring-dashpot system.
- The mass of the rope is neglected where the dynamic response of the system is concerned. Both mechanical wave and stress wave effects in the rope are neglected.
- The energy absorber is assumed to deliver a constant deceleration force.

2.1 System without Arrestor Unit

When heavy rope hangs under its own weight, it will stretch until equilibrium is reached, this is called the free hanging length of the rope. Consider a rope of unstressed length, which is suspended from one end and hangs under gravity. In the free-hanging position, the rope will exert zero force on the conveyance. Figure 1 shows a heavy rope hanging under gravity, illustrating this equilibrium condition.

The rope has a specific mass of c (kg/m) and is subject to gravitational acceleration g (m/s^2). An infinitive section dx, at a position x, will be strained by a force F, in Equations 1 to 3.

$$F = c\,(L - x)\,g \quad (1)$$

Elongation, $u = (L^2 cg)/(2EA)$ (2)

Final length of the rope is $L_f = L + u$ (3)

This is the free-hanging length of the rope. It is clear that the tensile stress and strain in the rope will vary from a maximum at x = 0, linearly decreasing to zero at x = L. During free-fall, the rope will only exert a tensile force on the conveyance once it extends beyond its free-hanging length. It is naturally unable to exert a compressive force and push against the conveyance. Therefore, above the free-hanging position the rope will exert zero force on the conveyance, while below the free-hanging position, the rope will exert a tensile force on the conveyance, proportional to the rope extension. The rope can be modeled as a spring or a step function to facilitate the discontinuity at the free-hanging position. In tensile extension, the rope will be assumed to obey Hooke's Law (Equation 4).

$$F = -kx \quad (4)$$

The force will always oppose the motion, and the displacement (x) is defined as the extension of the rope beyond its free-hanging position.

The mass used to model the system is the mass of the conveyance and its occupants, and it will be modeled as a point mass (m). As has been mentioned, the mass of the rope will be neglected in the calculation.

The potential energy that the conveyance possesses is converted to kinetic energy as it falls under gravity. The kinetic energy is mainly dissipated in aerodynamic and mechanical friction and hysteresis. These energy-dissipating terms will be combined and considered as a velocity-dependent force (Equation 5).

$$F = -pv \quad (5)$$

Initially the mass is at a distance h (length of slack) above the free-hanging position of the rope. During the analysis the vertically upward direction is assumed to be positive. Figure 2 shows a Free-falling conveyance model, representing the system setup used to evaluate the dynamic behavior during free fall. Now as long as the mass is above x = 0, the problem is similar to that of the free-falling parachutist.

2.2 Arrestor Unit -Functional Criteria

A wide range of energy absorbers is available that can be evaluated for potential use in this application. However, it is essential to first establish the criteria that the suitable energy absorber must meet to ensure an informed

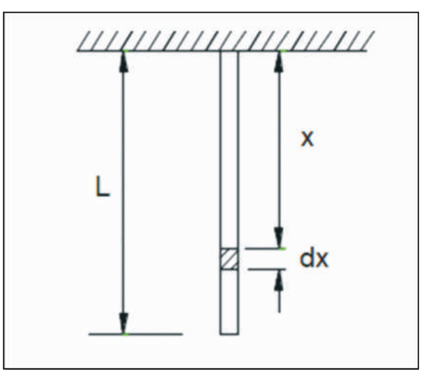

Figure 1. Heavy Rope Hanging Under Gravity

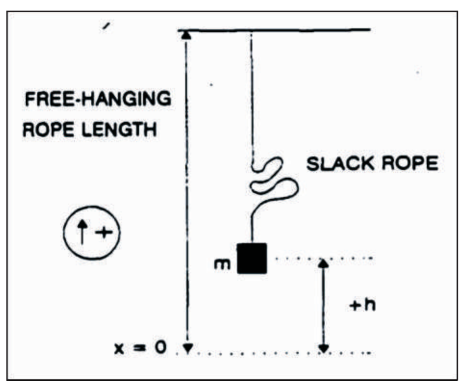

Figure 2. Free-falling Conveyance Model

selection process (Shigley & Mischke, 2016). Drawing from the study, several key characteristics can be identified as necessary for effective performance.

In general terms, the important characteristics of energy absorbers to be evaluated during a selection process are the following:

- The stoke to length ratio.
- The efficiency of the stroke.
- The ability to sustain rebound loads.
- Th reliability and repeatability of the mechanism.
- The specific energy absorption capacity per unit mass.
- And the cost of the energy absorber.

Here the stroke efficiency is a measure of how closely the energy absorbers performance approaches the optimum performance. It is measure by the ratio Equation 6.

$$Stroke\ Efficiency = \frac{U}{(F_{max} * X)} \qquad (6)$$

Where,

U = energy absorbed by the device

F_{max} = maximum allowable force (N) X = stroke length (m)

A critical aspect of an effective energy absorber is that the load-deformation characteristics of the device should remain relatively unchanged under dynamic loading, even at high loading rates. Additionally, the directionality of the loading is a crucial factor; therefore, it is important to ensure that devices designed for unidirectional loading are not subjected to multidirectional forces.

In the specific application under consideration, the energy absorber should satisfy the following criteria in order to obtain the optimum:

- A Long stroke length is required, in order to stop the conveyance at an acceptable deceleration rate.
- The full stroke length should be available for energy absorption, as the mass of the absorbers should be limited to a minimum.
- Constant deceleration force over the full stroke length to ensure controlled deceleration of the conveyance and maximum stroke efficiency.
- The deceleration force should result in a deceleration that is compatible with the physical limitations of the passengers in order to prevent or limit passenger's injury.
- The absorbers should have low mass and small size, as they are to be transported on board the conveyance.
- Ideally the arrestors should also be sensitive to load, as the conveyance could carry from 0 - 150 passengers.
- If the full stroke length should be reached, the energy absorbers must be able to suspend the conveyances and should be a sturdy as the system without energy absorbers.
- High reliability and repeatability are required, as human lives are to be safeguarded.
- Very little maintenance should be required, and the mechanism must be able to survive in a relatively hostile environment.
- The cost should be kept as low as possible.

A long stroke length has been specified, but some indication of the actual stroke length required is necessary in order to select a proper absorber. Assuming linear movement and a constant energy absorber resistive force (constant deceleration rate), the approximate stroke length required can be calculated as follows:

From the linear movement Equation 7.

$$v^2 = u^2 + 2as \qquad (7)$$

Where,

v = final velocity (m/s)

u = initial velocity (m/s)

g = gravitational acceleration = 9.8m/s^2

n = acceleration factor (multiples of g)

a = deceleration (m/s^2) = n *g

s = stroke length (m)

Humans are unable to endure high deceleration rates for extended periods, necessitating a relatively low value of n. This requirement results in substantial stroke lengths, typically measuring several meters, depending on the amount of slack rope that will unwind during slack rope events. Recent studies indicate that the influence of the arrestor units on the dynamic behavior of the conveyance in free-fall scenarios is very positive. The arrestors mitigate the tensile stress in the rope, thus regulating the deceleration rate and the forces experienced by both the structure and the passengers. Moreover, the fundamental criteria that such an energy absorber must satisfy for this specific application have been established. The next consideration is to determine the human tolerance limits during crash situations, especially those encountered by passengers in a mining conveyance during free-fall events.

2.3 Human Factor Tolerance

From the perspective of injury reduction or prevention, the crashworthiness of a system is only significant if the limits of human tolerance can be clearly defined (King, 1972). Merely safeguarding the conveyance and its passengers while still allowing for potentially survivable conditions is inadequate. It is crucial to ensure that passengers can endure the incident with little to no injury. However, studying human tolerance presents challenges and is subject to various interpretations. A practical way to gauge tolerance is by measuring the acceleration or deceleration experienced by the human body or its segments, as this is a readily quantifiable physical parameter. Unfortunately, this straightforward measure alone does not adequately capture the dynamic response of biological structures. Other factors, such as the duration of impact, the rate of onset, and the type of restraint system, must also be considered to enhance the understanding of acceleration data (Martin, 2011).

2.3.1 Crash Environment - Survivability Factors

Investigations and analyses of aircraft accidents have demonstrated that occupant survival can be significantly improved by considering the following survivability factors during the design phase:

- *Crashworthiness of the Structure:* This pertains to the ability of the structure to maintain a liveable space for occupants throughout the impact sequence.
- *Tiedown Strength:* The robustness of the restraints that secure occupants, cargo, and equipment during impact.
- *Occupant Acceleration Environment:* The rate of onset, magnitude, duration, and direction of the accelerations experienced by occupants as a result of the impact.
- *Occupant Environment Hazards:* The presence of barriers, protrusions, and loose equipment around the occupants that may lead to contact injuries during the impact sequence.
- *Post-Crash Hazards*: Any threats to occupant survival that may arise after the impact sequence.

Given its specific function, the conveyance's structure is designed to prioritize lightness over crashworthiness. Therefore, if a free fall occurs, the likelihood of passenger fatalities is significantly heightened. Moreover, even if the restraints do not fail, the occupants could still experience extreme acceleration rates during a whiplash effect. The absence of safety harnesses, coupled with the structure's steel composition, raises the risk of severe or potentially fatal contact injuries. Consequently, during a slack rope event, it is crucial that the deceleration of the conveyance occur at a relatively low rate to protect passengers and equipment (Jeppe, 1946; Martin, 2011).

2.3.2 Multi-Collisional Model

Any transporting body may be thought of as consisting of an envelope or shell and the content that is to be carried. In order to minimize damage during an accident, minimum relative velocity between the envelope and its content has to be maintained. In an accident the envelope suffers the impact first, the primary collision. As the envelope is arrested, the contents continue to move, and depending on their nature, distribution, and attachments within the envelope, they are later involved in secondary collisions with the envelope and one another. These secondary collisions are responsible for injury. If the primary impact is damped, the secondary collisions will be less severe but will still occur. As no passenger restraint system is available in the conveyances, secondary collisions become the determining factor in deciding the allowable deceleration rate of the conveyance. An important point to note is that the interior of the conveyance is a steel hull, which possesses very limited damping characteristics when impacted by the human body. This could cause serious injury in a sudden deceleration environment. Attempts are necessary to remove protrusions and objects inside the conveyance, which may cause serious injury when colliding with the human head or other body parts. It would also be advisable to ensure that people and equipment are never transported together.

2.3.3 Quantifying Human Tolerance

Human tolerance to impact can be categorized into four distinct levels: voluntary exposure, injury threshold, minor injury, and severe injury. The voluntary tolerance limit is defined as the acceleration level that human volunteers are reluctant to exceed. Above this limit lies the injury threshold, a level where injury becomes imminent but does not yet occur. Severe injury encompasses a range of trauma levels, extending up to the point of fatality. It is important to note that there is no precise and quantitative characterization of tolerance, as the limits at each acceleration level are best represented as average values derived from a broad spectrum of data points. Among these categories, the minor injury limit is typically deemed the most applicable for design purposes. This is because accelerations within this range can result in severe injuries for the most vulnerable individuals, minor injuries for the average person, and may leave the strongest individuals unharmed (Martin, 2011).

Also, very important is the direction of the acceleration to which a person is subjected, and this is classified as is shown in Figure 3. There are two major subdivisions in the type of impact as well, namely whole-body impact and regional impact. Regional impact is, for instance, specific impact to the head, back or limbs.

2.3.3.1 Head Injury

The topic of head injuries resulting from impact is a well-researched area within biomechanics, with a substantial body of literature dedicated to the subject. The skull-brain system can be generally described as a rigid shell

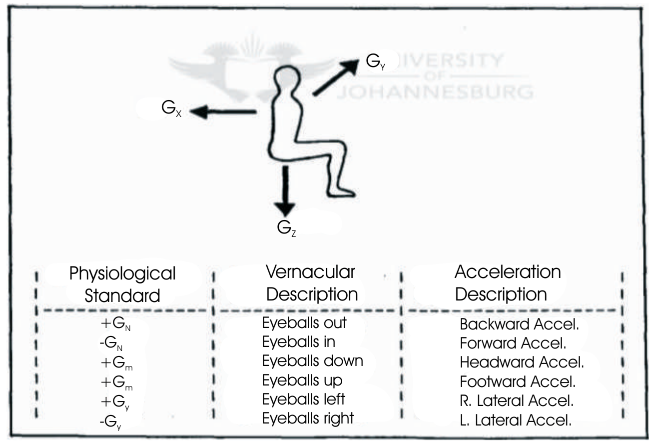

Figure 3. Sign Convention for Linear Acceleration

encasing a uniformly dense material with low stiffness. The various types of damage that can occur to components of the head include:

- Scalp damage, which manifests as bruises, abrasions, or lacerations.
- Skull fractures, which may present as depressions from projectile penetration, linear or stellate fractures, or crushing injuries.
- Extra-cerebral bleeding, Brain injuries, such as concussions, contusions (bruising), hematomas, or lacerations and Neural damage to the upper cervical cord at the head-neck junction, commonly referred to as whiplash injury.

Regarding the tolerance limits for head impacts, a curve was initially proposed in 1960, later modified, and is now known as the Wayne Tolerance Curve. This curve is frequently utilized in automotive safety research. It illustrates effective acceleration for impacts to the forehead against rigid, non-yielding surfaces on the y-axis, while the duration of the impact pulse is represented on the x-axis. Figure 4 shows a wayne tolerance curve for head impact, included to delineate the levels of acceleration or deceleration at which concussion and skull fractures are likely to occur (Singley, 1972).

2.3.3.2 Vertebral Injury

Figure 5 shows significant +G accelerations can be anticipated during the deceleration of a mining conveyance. The primary structure that supports the

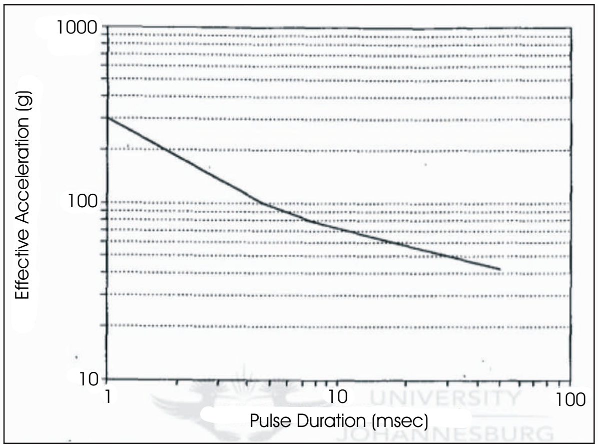

Figure 4. Wayne Tolerance Curve for Head Impact

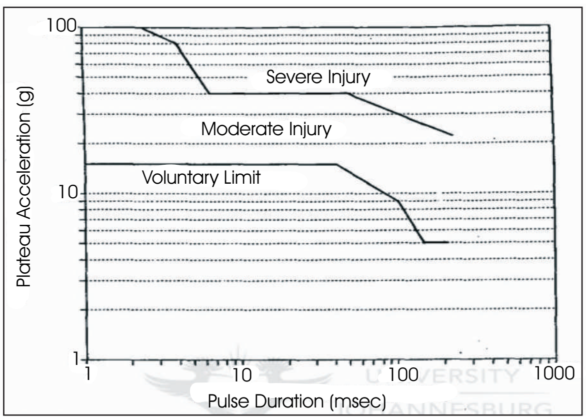

Figure 5. Eiband's Tolerance Curve for +G. Acceleration

head and torso is the vertebral column, which becomes vulnerable to injury in environments with high +G accelerations. The tolerance curve developed by Eiband for +G acceleration reflects this, and since the torso was heavily restrained during testing, it is commonly interpreted as indicative of whole-body tolerance to +G forces. Research indicated that vertebral fractures can occur (Martin, 2011).

2.3.3.3 Lower Limb Injury

In the high +G. acceleration environment of the halting conveyance, considering that all the passengers are standing, a high incidence of knee, femur, and pelvic skeletal injuries can be expected. For axial impact on the knee-thigh-hip complex, it is recommended that the injury limit be set at approximately 15 g for the average person. All data given in the sections above are for unidirectional accelerations and are actually inadequate for multi-directional crash environments. However, multidirectional (off-axis) impact tolerance data is not yet available (Martin, 2011).

2.3.4 Whole Body Tolerance to Deceleration

In a slack rope accident, passengers experience whole-body vertical deceleration in unrestrained conditions, resembling the scenario of a landing parachutist (Ottermann, 2000). Figure 6 shows that individuals voluntarily expose themselves to deceleration rates of around 5 g, while deceleration rates of up to approximately 19 g can be considered survivable during emergencies.

Figure 7 shows an influence of pulse duration on whole body tolerance of impact. Nevertheless, the duration of the deceleration pulse is a crucial factor in determining

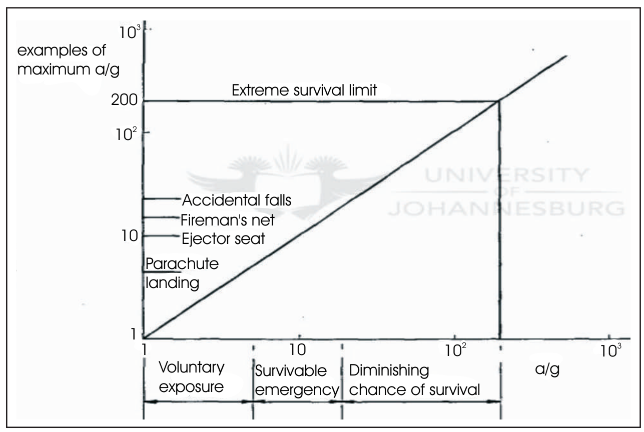

Figure 6. Whole Body Tolerance of Impact

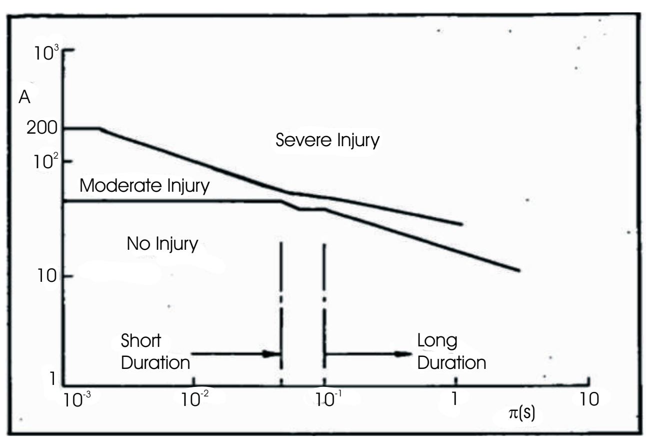

Figure 7. Influence of Pulse Duration on Whole Body Tolerance of Impact

injury severity, and this aspect has been overlooked in the discussion. It is evident that for pulse durations of up to 0 seconds, deceleration rates of up to 10 g result in little to no injury or only moderate harm.

2.3.5 Comparative Analysis of Author Contributions

Table 1 shows a comparative analysis of the contributions made by each author.

3. Identified Research Gaps

- *Comprehensive Analysis of Biomechanical Tolerance:* The existing literature lacks a comprehensive analysis of human biomechanical tolerance limits specific to mine hoist accidents, particularly slack rope events. Further research is needed to refine G-force, peak crash force, and acceleration thresholds in various directions to minimize injury risks.
- *Integration of Predictive Modeling:* While various energy-absorbing systems have been proposed, there is limited research on integrating predictive modeling techniques to optimize their performance under diverse operational conditions. This includes considering variable loads, rope elasticity, and the dynamic characteristics of different mine hoist configurations.
- *Real-World Scenario Validation:* There is a need for real-world validation studies to assess the efficacy and reliability of proposed safety solutions. Most studies are based on simulation and analytical calculation, and real-world situations need further assessment.
- *Comparative Analysis of Energy Absorber Technologies:* Further comparative analysis is required to test which is most beneficial for different mine situations.
- *Control Systems Integration:* Further integration into control systems that detect potential problems before they occur.

These research gaps highlight opportunities for future research and development efforts to improve the design, implementation, and validation of energy-absorbing systems in mine hoist conveyances, ultimately enhancing the safety of underground mining operations.

Conclusion

The design and application of energy-absorbing systems in mine hoist conveyances represent a critical area of research and development. By integrating these systems into the suspension mechanism of conveyances, it is possible to mitigate the impact forces generated during slack rope events, reducing the risk of structural failure and injury to personnel. Furthermore, it must adhere to biomechanical limitations to ensure that deceleration is not harmful to the body. However, challenges remain in optimizing these systems and addressing the specific requirements of different mining operations. A more

Author(s)	Focus Area	Key Findings
Giraud and Galy (2018)	Criticality of Mine Hoist Systems	Failures resulting from the operation of conveyances are detrimental and catastrophic, emphasizing the need for safety and integrity.
ILO (1990)	Regulations for Conveyances	The capacity of Mine cage (conveyance) has been proposed to 5 tons and payload of 20 tons or approximately 150 personnel
Hamersma and Els (2014)	Failure Scenarios in mine hoist	Addresses over-winding, a detaching hook is integrated into the conveyance's suspension mechanism, ensuring that when an ascent over-wind occurs, the hook disengages from the winding rope.
Singley (1972)	Importance of Energy Absorption	The significant force absorption can result in critical structural components like the rope, hook, drawbar, or transom failing under excessive loads
Jeppe (1946)	Dynamic Forces in the System	Dynamic response of the system may produce substantial oscillatory forces, which further jeopardizes the safety of payloads and passengers.
Hamersma and Els (2014)	Crashworthiness is Key to Enhance Human Tolerance	Complexities of these interactions are crucial for engineers to understand in designs aimed at enhancing crashworthiness and ensuring human tolerance to the forces generated during such unintended accelerations
Hamersma and Els (2014)	Mass, Spring and Dampers Affect Braking Systems.	The use of mass spring and damper has a great effect in the design, working and effectiveness of the conveyance arrestor braking system.

Table 1. Comparative Analysis of Author Contributions

comprehensive understanding of the biomechanical limitations of the human body is needed to refine the design of braking systems and ensure the safety of occupants. By addressing these challenges and pursuing further research and development efforts, it is possible to enhance the safety and reliability of mine hoist systems and create a safer working environment for underground miners.

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