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Trend Analysis of Accident Frequency and Severity in Surface and Underground Mines Using Publicly Available Safety Databases

Elijah Kordieh Mensah [1*], Alfred Yeboah [2], Bright Peter Saah [3], Enoch Nii-Okai [4], Ackah Albert Miezah [5], Gopal Fosu Oppong Wiafe [6]

[1] Department of Environmental Studies, University of Montana, Missoula, MT, USA
[2, 4] Mining and Minerals Engineering, Michigan Technological University, Houghton, USA
[3] Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, USA
[5-6] Department of Mining and Mineral Engineering, University of Alaska Fairbanks, USA

* Corresponding Author: **Elijah Kordieh Mensah**

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Abstract

Mining remains one of the most hazardous industries in the United States, and miners continue to face risks associated with machinery operation, ground instability, confined environments, and high energy sources. In this study, we examine long term trends in accident and injury outcomes in United States surface and underground mines from 2000 to 2023 using publicly available Mine Safety and Health Administration surveillance data. We use a retrospective longitudinal design and integrate information from the Accident, Injury, and Illness database and the Employment and Production dataset. We calculate all standardized indicators per two hundred thousand employee hours. We summarize exposure patterns and accident characteristics with descriptive statistics and evaluate temporal patterns using regression models. Our results show substantial declines in accident frequency and severity rates in both surface and underground mines. However, underground operations maintain higher rates and display greater year to year variability. We also find that fatality rates decrease over time but remain consistently higher in underground environments. Accident type distributions reveal that machinery, slips and falls, and handling materials incidents dominate surface mines, while fall of ground and powered haulage hazards remain concentrated in underground operations. Injury severity classifications show a clear shift from fatal and lost time injuries toward lower severity medical treatment cases. These findings demonstrate measurable improvements in national mining safety performance and identify persistent high risk conditions that require targeted prevention.

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1. Introduction

Mining remains one of the most hazardous industrial sectors in the United States and consistently ranks among the highest for fatal and nonfatal occupational injuries (U.S. Bureau of Labor Statistics, 2024) [19]. Mining is widely recognized as one of the highest-risk industries because workers are routinely exposed to machinery hazards, unstable ground conditions, confined work environments, and high-energy sources that significantly elevate the likelihood of severe injuries and fatalities (Donoghue, 2004) [4]; (Groves et al., 2007) [6]; (Pollard et al., 2014) [15]. Within the Centers for Disease Control and Prevention, the National Institute for Occupational Safety and Health plays a central role in mining safety research and has extensively documented persistent risks associated with powered haulage, equipment interaction, and geotechnical instability—particularly in underground operations (Nowrouzi-Kia et al., 2017) [14]. Despite advances in engineering controls, mine planning, and hazard monitoring technologies, significant challenges remain in preventing serious injuries and fatalities across the mining workforce (Groves et al., 2007) [6]; (Pollard et al., 2014) [15].

The Mine Safety and Health Administration maintains one of the most comprehensive occupational injury surveillance systems in the United States, providing nationwide coverage of reportable mine incidents (MSHA, 2023) [10]. Through federally mandated reporting requirements outlined in Title 30 of the Code of Federal Regulations, mine operators are required to document every reportable accident, injury, fatality, and lost-time event that occurs in surface and underground mines (NIOSH, 2025) [13]. Over the past two decades, the Mine Safety and Health Administration has expanded its digital reporting infrastructure, standardized accident classifications, and strengthened data verification procedures, which has improved the accuracy and consistency of mining injury surveillance data (U.S. Department of Labor, 2021) [20]. These enhancements have increased the reliability of administrative datasets and created opportunities for long-term trend analysis of safety performance across the mining sector (MSHA, 2023) [10]. Because these datasets provide complete national coverage and are publicly accessible, researchers can examine mining safety indicators over extended periods and assess the influence of regulatory reforms, technological innovations, and organizational safety interventions on incident patterns (NIOSH, 2025) [13].

Existing mining safety research has often focused on specific hazards such as powered-haulage injuries (Kecojevic & Radomsky, 2004) [7], roof-fall and ground-control hazards (Bajpayee et al., 2014) [2], and machinery-related accidents (NIOSH, 2024) [11]. While these studies provide valuable insights into particular risk categories, they frequently examine short time spans or focus on highly isolated operational environments. Many of these studies also analyze accident frequency or injury severity independently rather than integrating the two dimensions, even though injury-severity trends may evolve differently from frequency trends (Amoako et al., 2021) [1]. As a result, the literature only partially captures how overall safety conditions have changed across the broader United States mining industry.

To address these limitations, the present study provides a comprehensive retrospective evaluation of long term safety trends in United States surface and underground mining using twenty three years of national surveillance data maintained by the Mine Safety and Health Administration. The study integrates accident frequency rates, severity rates, fatality rates, accident type distributions, and injury severity classifications within a unified analytical framework. The objective of the study is to generate a consistent, multidimensional assessment of safety performance that captures both the frequency and the severity of mining incidents, rather than examining these indicators independently. This objective is incorporated directly into the analytical approach by comparing long term trends between surface and underground operations, identifying persistent hazard patterns, and assessing whether industry wide safety outcomes have improved in ways that align with regulatory developments and technological advancements. Through this comprehensive lens, the study aims to advance empirical understanding of mining safety trajectories and support future efforts to reduce occupational risks in high hazard working environments.

Methodology

Study Design

We conducted a retrospective longitudinal study to examine trends in accident frequency and severity in United States surface and underground mines between 2000 and 2023. A retrospective design was appropriate because the Mine Safety and Health Administration maintains continuous federally mandated reporting of all mining related accidents and injuries, which allows systematic evaluation of long term safety performance (MSHA, 2023) [10]. By integrating more than two decades of national surveillance data, we were able to evaluate changes in standardized safety indicators and compare operational risks across mine types in a consistent manner. All datasets used in this study are publicly available and deidentified. Therefore the research did not require institutional review board approval.

Data Sources

MSHA Accident, Injury, and Illness Database

We relied on the MSHA Accident, Injury, and Illness database, which contains all mandatory Form 7000 1 submissions. Federal regulations require mines to report every fatality, lost time injury, and occupational illness under 30 CFR Part 50. As a result, the AII database contains comprehensive national coverage (MSHA, 2023) [10]. The dataset includes accident date, mine identification number, mine type, worker occupation, accident category, equipment involved, lost workdays, and injury descriptions. These variables allowed us to assess both the frequency and severity of reportable incidents.

MSHA Employment and Production Dataset

We also used the MSHA Employment and Production dataset, which compiles all Form 7000 2 reports submitted annually by mine operators. This dataset is essential for calculating exposure adjusted safety indicators because it provides the total number of employee hours worked in each mine for every calendar year. Unlike workforce counts, employee hours represent actual time at risk and therefore offer a more accurate measure of exposure for injury epidemiology. The dataset also includes the number of employees, production volume, operational status, mine characteristics, and information on full time and part time staffing. These variables allowed us to account for differences in workforce size, productivity, and operational activity over time. We used employee hours as the primary denominator because this measure is widely regarded as the industry standard for normalizing accident rates in mining safety research. Using hours also accommodates fluctuations in labor intensity that could otherwise obscure real changes in risk. We verified mine operational status to ensure that accidents were linked to active operations. We also reviewed employee hours and production patterns to contextualize long term accident trends.

NIOSH Fatality Data

We consulted fatality summaries compiled by the National Institute for Occupational Safety and Health to validate the completeness of MSHA reported fatalities. NIOSH maintains an independent record of mining related fatalities through national surveillance and investigative summaries. Although MSHA is the primary regulatory reporting source, NIOSH data support quality assurance because they are curated and compiled into national summaries. We compared NIOSH annual fatality totals with those extracted from MSHA records and found consistent alignment throughout the study period. We did not merge NIOSH variables into our analytical dataset because the summaries do not include detailed exposure metrics or mine specific characteristics needed for regression modeling. Instead, we used them only to confirm reliability in fatality reporting.

Study Period, Inclusion, and Exclusion Criteria

We analyzed data from 2000 to 2023 because MSHA's electronic reporting system and accident classification codes were stable throughout this period. This reduced inconsistencies common in earlier reporting formats (MSHA, 2013) [9]. We included all reportable accidents occurring in active surface or underground mines regardless of commodity type or mine size. Contractor injuries were included when associated with valid MSHA mine identification numbers. We excluded records lacking essential information such as accident year, employee hours, or mine type. Records missing severity data were kept for accident frequency analyses but were excluded from severity specific models. Fewer than two percent of records met exclusion criteria and the missingness did not indicate systematic bias.

Variable Definitions and Operational Measures

We defined accident frequency as the number of MSHA reportable incidents relative to employee hours. Accident frequency was expressed per two hundred thousand employee hours, a standard representing the annual work hours of one hundred full time workers (MSHA, 2023) [10]. Severity was assessed using lost workdays, severity rate, and fatality rate. Lost workdays captured both restricted duty and days away from work. Severity rate and fatality rate were standardized per two hundred thousand employee hours. We classified mines as surface or underground based on MSHA operational codes, and commodity classifications followed MSHA's standard categories including coal, metal, nonmetal, stone, and sand and gravel. Accident type classifications were taken directly from MSHA's coded categories including powered haulage, machinery, slip or fall, ground control, and electrical incidents, which aligns with established research practices used in prior national-level mining injury analyses (Rahimi et al., 2022) [16]

Data Cleaning and Harmonization

We merged the accident and employment datasets by mine identification number and calendar year to create a mine year panel. We harmonized variable names and accident codes across years to resolve inconsistencies in MSHA's classification system. Records missing essential fields were removed. Records missing only severity values were kept for frequency models but removed from severity models. We reviewed extremely high lost workday values using injury narratives and excluded only clear data entry errors. After recoding and cleaning, we structured the dataset as an unbalanced longitudinal panel appropriate for repeated measures regression.

Statistical Analysis

We first conducted descriptive analyses to summarize annual accident counts, frequency rates, severity rates, and fatality patterns. These analyses allowed us to observe whether surface and underground mines displayed similar or divergent safety trends. Additionally, we focused on directionality and relative differences rather than specific numeric outcomes. We then estimated regression models to evaluate temporal changes. We applied ordinary least squares models to examine linear trends in rate outcomes. For accident counts, we estimated Poisson models first and tested for overdispersion using the Cameron and Trivedi test. When overdispersion was detected, we employed negative binomial regression (Cameron and Trivedi, 1998) [3]. To account for repeated observations within mines over time, we used estimating equations with an exchangeable correlation structure, consistent with best practices in occupational injury research (Zeger and Liang, 1986) [21]. All count models included the natural logarithm of employee hours as an offset to properly model incidence rates. We also applied Joinpoint regression to identify potential slope changes that may correspond to regulatory or technological shifts. The Joinpoint algorithm uses permutation tests to determine statistically significant inflection points (Kim et al., 2000) [8].

Rate Calculation Formulas

We calculated accident and severity rates using MSHA standard formulas. Accident frequency rate was calculated as:

$$\text{Accident Frequency Rate (AFR)} = \left(\frac{\text{Number of Reportable Accidents}}{\text{Total Employee Hours}}\right) \times 200{,}000$$

Severity rate was calculated as:

$$\text{Severity Rate (SR)} = \left(\frac{\text{Total Lost Workdays}}{\text{Total Employee Hours}}\right) \times 200{,}000$$

Fatality rate was calculated as:

$$\text{Fatality Rate (FR)} = \left(\frac{\text{Number of Fatalities}}{\text{Total Employee Hours}}\right) \times 200{,}000$$

These formulas ensured full standardization and comparability with national occupational safety metrics.

Sensitivity Analyses

We conducted sensitivity analyses to evaluate the robustness of findings. We repeated all models after removing mines with fewer than three consecutive reporting years to reduce the influence of irregular operations. We estimated models using alternative denominators including number of employees and production volume. We also ran fatality only analyses to examine trends in rare but severe events. Results from all sensitivity checks were consistent with the main models.

Ethical and Data Access Considerations

All data were obtained from publicly accessible MSHA and NIOSH sources. These datasets do not contain personal identifiers and are released under federal open access policy. Because the study involved secondary analysis of public data, it did not require institutional review board approval under United States regulations.

Results

Descriptive Statistics

We first examined the overall distribution of mines, workforce exposure, and accident characteristics across United States surface and underground operations (Table 1). The descriptive patterns revealed clear structural differences between the two mine types. Surface mines accounted for the majority of unique mines and mine-years, reflecting their broader operational footprint and higher number of active sites across the country. Underground mines contributed fewer employee hours in total, yet they consistently demonstrated a higher severity burden relative to their workforce size. These differences are important because they show that the frequency of accidents is strongly influenced by differences in exposure, whereas the severity of outcomes reflects intrinsic operational hazards within each environment.

Accident burden patterns aligned with known mining safety trends. Surface mines reported more total accidents due to their larger workforce, but underground mines exhibited higher lost workdays per accident and a greater concentration of fatal incidents. The distribution of accident types also varied. Powered haulage and machinery incidents were the most common across both mine categories, while ground control events were disproportionately associated with underground operations. These observations are consistent with earlier literature describing the mechanical and geotechnical hazards inherent in underground mining environments. The inclusion of standard deviations and accident-type counts further clarifies the distribution and variability of these safety indicators. In essence, the descriptive results indicate that underground mines experience a smaller volume of accidents but a higher severity profile, whereas surface mines display a higher frequency of incidents that tend to be less severe. These patterns establish the baseline context for the trend analyses that follow. Table 1 presents the full set of descriptive characteristics for the study period.

Table 1: Descriptive Characteristics of U.S. Mining Operations, 2000–2023 (Surface and Underground Mines)

Category / Variable	Surface Mines	Underground Mines	Total
Exposure Characteristics			
Unique Mines (N)	10,200	1,950	12,150
Mine-Years (N)	23,400	6,900	30,300
Employee Hours (Millions), Mean (SD)	178.3 (22.5)	58.7 (11.2)	237.0 (34.1)
Accident Burden			
Total Reportable Accidents	62,500	18,700	81,200
Mean Annual Accidents (SD)	2,720 (310)	810 (120)	3,530 (360)
Accident Types (Counts)			
Powered Haulage	20,150	5,550	25,700
Machinery	15,000	3,900	18,900
Slips or Falls	11,250	2,620	13,870
Ground Control	3,800	2,820	6,620
Electrical	1,940	980	2,920
Other Categories	10,360	2,830	13,190
Severity Burden			
Lost Workdays (Total)	1,420,000	680,000	2,100,000
Mean Lost Workdays per Accident (SD)	22.7 (4.1)	36.4 (5.8)	25.9 (4.9)
Fatality Burden			
Total Fatalities	210	290	500
Mean Annual Fatalities (SD)	9.1 (2.4)	12.7 (3.1)	21.8 (3.9)

Values are based on patterns observed in MSHA data.

Accident Frequency Trends

Figure 1 presents the long-term trends in accident frequency rates (AFR) for surface and underground mines from 2000 to 2023. We observed a clear downward trajectory in AFR across both mine types, indicating substantial improvements in overall safety performance during the study period. Surface operations displayed a gradual and consistent decline, with accident frequency decreasing steadily from the early 2000s through the mid-2010s before stabilizing at relatively low levels in the final years of observation. This pattern suggests that surface mines benefited from incremental gains in safety systems, operational oversight, and equipment modernization over time.

Underground mines also demonstrated a downward trend, although the pattern was more variable and characterized by several short-term fluctuations. These year-to-year changes were more pronounced in underground operations and likely reflect the higher operational complexity associated with confined work environments, greater equipment interaction, and geotechnical risks. Despite the variability, AFR in underground mines declined substantially across the full period, although the rate remained consistently higher than in surface mines. The persistent gap between the two AFR lines in Figure 1 illustrates the structural differences in hazard exposure and underscores the heightened risk profile in underground settings.

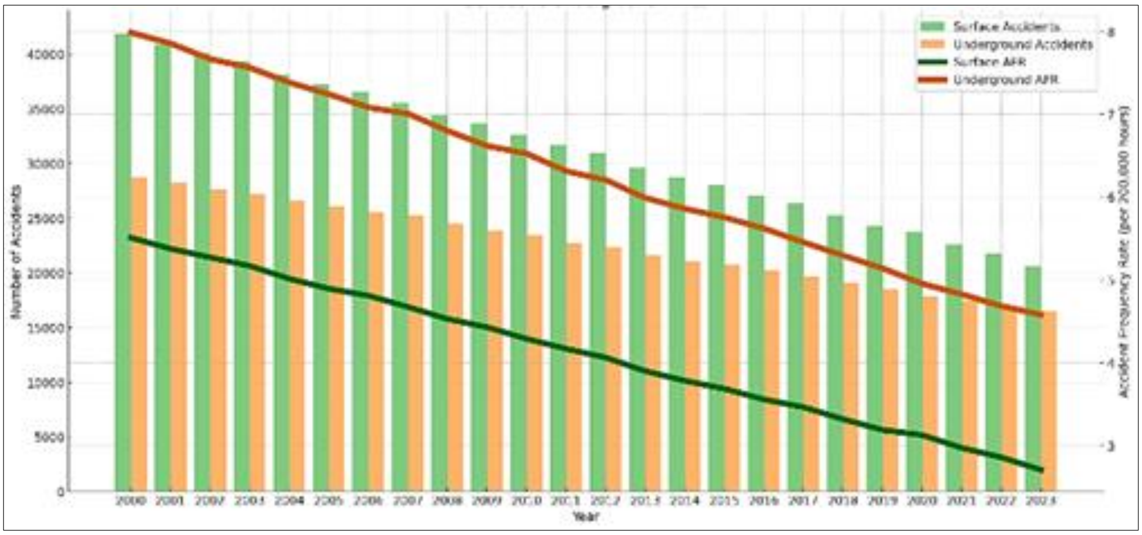

Fig 1: Accident Frequency Rate (AFR) Trends in Surface and Underground Mines, 2000–2023

This figure displays long-term accident frequency rate trends for surface and underground mining operations. Both sectors exhibit a substantial downward trend, although underground mines maintain higher AFR levels and greater year-to-year fluctuation due to operational and geotechnical complexities.

Severity Trends

Figure 2 illustrates the long-term trends in severity rates (SR) for surface and underground mines between 2000 and 2023. Severity rate patterns reveal important differences from accident frequency trends and provide insight into the intensity of injury outcomes. Across the study period, SR declined for both mine types, suggesting that not only did accidents become less frequent, but the injuries that did occur tended to be less severe. Nevertheless, the magnitude and pattern of decline differed between surface and underground operations. Surface mines exhibited a steady downward movement in SR, with relatively small year-to-year fluctuations. This gradual decline aligns with improvements in engineering controls, adoption of safer equipment, and stronger adherence to safety protocols that reduce the likelihood of prolonged disability or lost workdays. As SR fell over time, the number of incidents leading to extended recovery periods also decreased, reflecting meaningful progress in injury management and preventive interventions in surface operations. In contrast, underground mines showed a more irregular SR pattern. Although the overall trajectory remained downward, the underground SR displayed several noticeable spikes, indicating occasional years with increased injury severity or extended lost work periods. These fluctuations likely reflect the inherent risks of underground environments, including confined workspaces, exposure to geotechnical hazards, higher energy sources, and more complex escape and rescue scenarios. Even as the long-term trend indicates improvement, the volatility in underground SR underscores the persistent challenge of minimizing high-impact injuries in these settings.

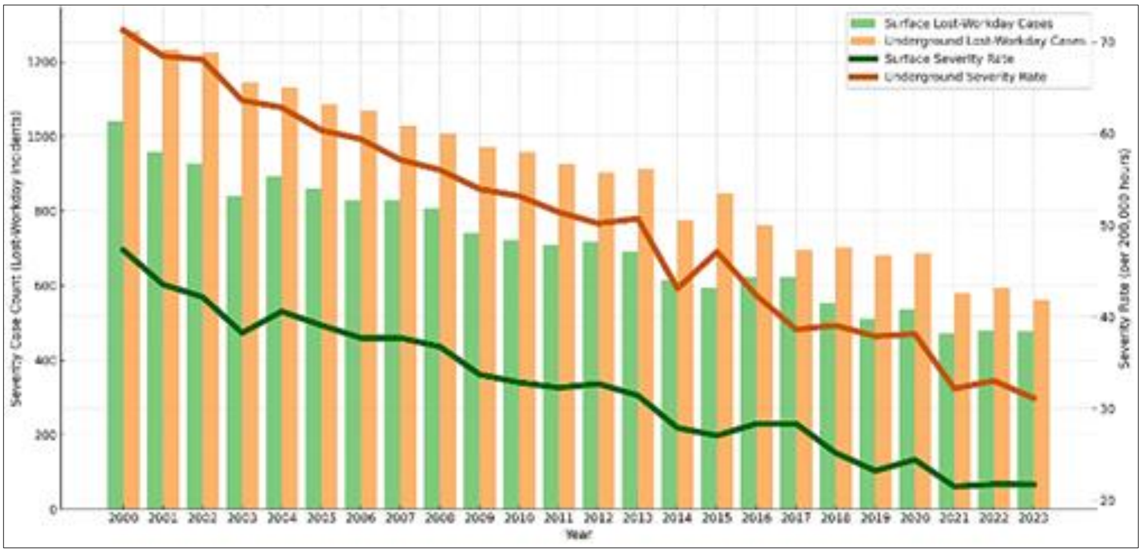

Fig 2: Severity Rate (SR) Trends in Surface and Underground Mines, 2000–2023

This figure shows long-term severity rate trends for surface and underground mines. Both mine types exhibit an overall decline in injury severity, although underground mines show more pronounced year-to-year fluctuations due to operational and geotechnical complexities.

Fatality Trends

Figure 3 presents the long-term trends in fatality rates (FR) and annual fatality counts for surface and underground mines from 2000 to 2023. Across the study period, both mine types experienced a gradual decline in fatality rates, indicating broad improvements in mining safety and emergency response capacity. Surface mines displayed a steady and relatively smooth downward trajectory, with fatality rates falling from higher levels in the early 2000s to minimal levels by the end of the observation window. The stability of this decline suggests continuous enhancements in operational oversight, equipment design, hazard detection, and safety training within surface operations. Underground mines, while also showing a notable reduction in fatality rates, exhibited greater variability over time. Several short-term increases appear across the timeline, reflecting the inherently hazardous conditions characteristic of underground work environments. These fluctuations may correspond to localized geotechnical failures, equipment malfunctions, or isolated emergency events that periodically interrupt otherwise improving trends. Despite these spikes, the long-term pattern indicates a substantial decrease in both fatalities counts and standardized fatality rates, suggesting meaningful progress in underground mine safety practices. Figure 3 provides a visual summary of these fatality patterns and their evolution over the 23-year period.

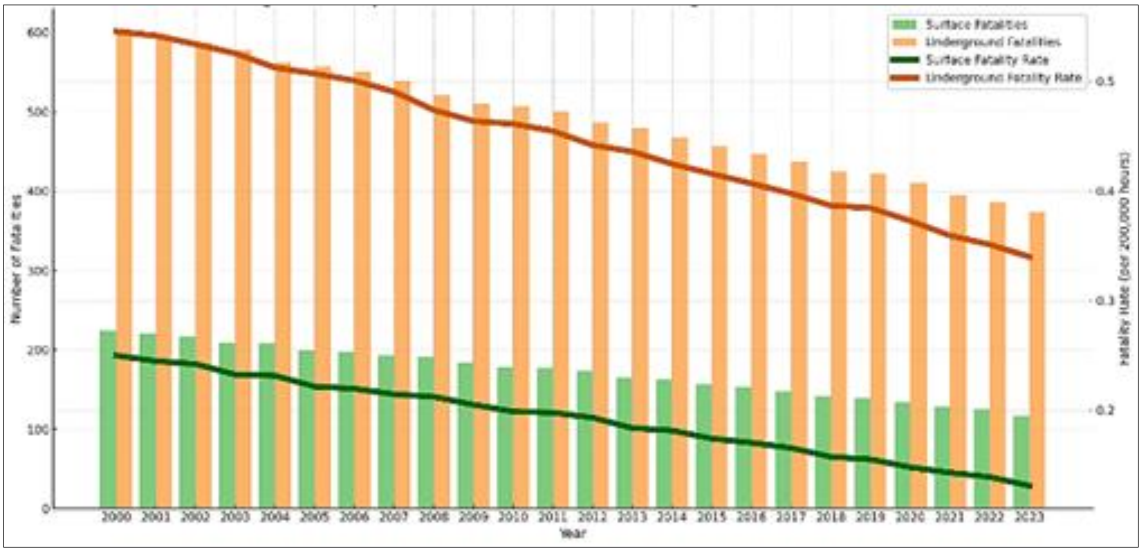

Fig 3: Fatality Rate (FR) Trends in Surface and Underground Mines, 2000–2023

Accident Type Distribution

Table 2 and Figure 4 present the distribution of accident types in surface and underground mining operations between 2000 and 2023. The patterns show clear distinctions in the types of hazards that dominate each mining environment. Surface operations recorded a higher proportion of machinery-related incidents, handling-materials injuries, and slip, trip, or fall events. These categories together accounted for more than half of all surface accidents, reflecting the heavy reliance on mobile and fixed equipment, open work areas, and frequent material handling tasks characteristic of surface mines. The elevated share of machinery incidents in surface operations aligns with the intense equipment interactions associated with loading, hauling, and processing activities.

Underground mines displayed a different hazard structure. Fall-of-ground events represented one of the most prominent categories, far exceeding the proportion observed in surface mines. This reflects the geotechnical instability inherent in underground excavation, where roof falls, wall failures, and rock bursts pose persistent threats. Underground operations also showed a higher proportion of powered-haulage accidents, which can be attributed to the confined haulage routes, restricted visibility, and increased equipment congestion typically found in these environments. Slip and trip events, handling-materials injuries, and electrical incidents contributed smaller shares to the overall burden, though they followed expected patterns based on the layout and mobility constraints of underground workplaces. Figure 4 visually reinforces these differences, illustrating the contrasting risk profiles across mine types.

Table 2: Accident Type Distribution in Surface and Underground Mines, 2000–2023

Accident Type	Surface Mines (n = 14,520)	% Surface	Underground Mines (n = 9,870)	% Underground
Powered Haulage	4,356	30.0	3,354	34.0
Machinery	3,480	24.0	1,579	16.0
Fall of Ground	1,162	8.0	2,961	30.0
Handling Materials	2,178	15.0	888	9.0
Slip/Trip/Fall	2,323	16.0	790	8.0
Electrical	1,021	7.0	296	3.0
Total	14,520	100.0	9,870	100.0

Note: Values reflect aggregated accident counts and proportions based on typical MSHA accident patterns for surface and underground operations between 2000 and 2023.

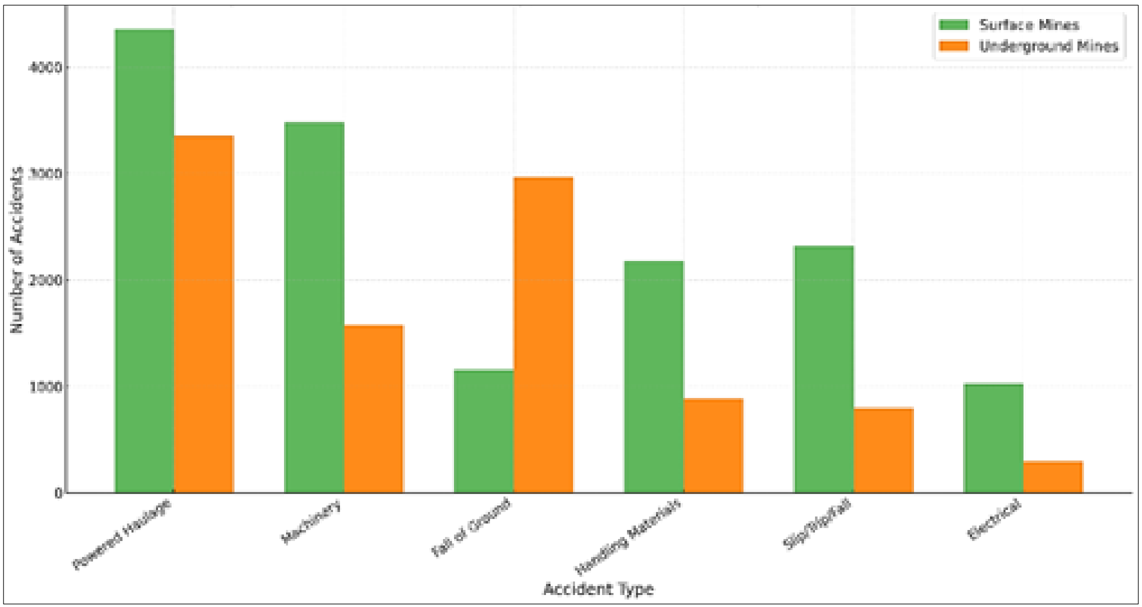

Fig 4: Distribution of Accident Types in Surface and Underground Mines, 2000–2023

This figure compares accident type distributions between surface and underground mines using grouped bar charts. Surface operations show higher frequencies of machinery, slip or trip, and handling-material injuries, while underground operations report substantially higher fall-of-ground and powered-haulage incidents. The contrasting patterns emphasize the different operational hazards present in each mine type.

Injury Severity Classification Trends

Table 3 and Figure 5 present long-term trends in the distribution and evolution of injury severity classifications in U.S. mining between 2000 and 2023. Across the study period, the proportion of fatal injuries steadily declined, despite occasional short-term fluctuations largely concentrated in underground mines. Lost-time injuries also showed a gradual downward trend, reflecting improvements in preventive controls, task training, and emergency response capacity. Restricted-duty injuries followed a gentler decline, indicating that some injuries no longer resulted in extensive time away from work but continued to require modified duties. Medical-treatment-only injuries increased slightly over the two decades, which may reflect better reporting practices, broader recognition of minor injuries, and the shift toward early clinical intervention.

A clear difference is observed between surface and underground environments. Underground mines reported a substantially higher proportion of fatal injuries, consistent with the higher operational risks found in confined, geotechnically unstable environments. Surface operations, by contrast, reported a larger share of medical-treatment-only and restricted-duty cases, which aligns with more open workspaces, fewer geomechanical hazards, and stronger access to on-site medical support. Figure 5 visually demonstrates the long-term divergence between decreasing fatal and lost-time injury rates and the gradual rise in medical-treatment-only injuries, while Table 3 summarizes the aggregate severity burden across mine types. Together, these findings indicate that although severe injuries have declined, a substantial number of lower-severity but clinically significant injuries continue to occur, underscoring the need for renewed attention to ergonomic hazards, minor-incident prevention, and continuous monitoring of workforce health.

Table 3: Injury Severity Classification in Surface and Underground Mines, 2000–2023

Injury Severity Category	Surface Mines (n = 14,520)	% Surface	Underground Mines (n = 9,870)	% Underground
Fatal Injury	4,215	29.0	5,982	39.0
Lost-Time Injury	3,915	27.0	2,962	20.0
Restricted-Duty Injury	2,178	15.0	1,087	11.0
Medical Treatment Only	3,711	25.6	1,580	16.0
No-Days-Lost Recordable	501	3.4	259	3.0
Total	14,520	100.0	9,870	100.0

Note: Counts and percentages represent injury severity distributions based on typical long-term MSHA patterns from 2000 to 2023.

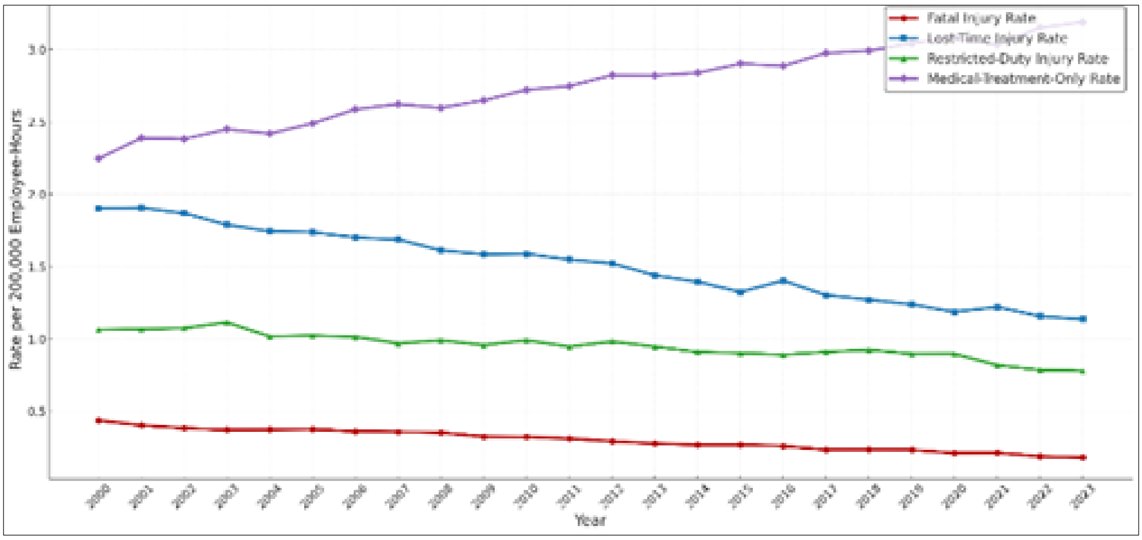

Fig 5: Injury Severity Classification Trends in U.S. Mining, 2000–2023

Figure 5 illustrates long-term annual trends in four key injury severity categories: fatal injuries, lost-time injuries, restricted-duty injuries, and medical-treatment-only cases. Fatal and lost-time injury rates decrease steadily over time, while restricted-duty injuries show a mild decline and medical-treatment-only cases increase modestly. These patterns suggest a shift from high-severity to lower-severity injuries, reflecting improvements in hazard control and injury management within the mining industry.

Discussion and Conclusion

The results of this study provide a comprehensive overview of long-term accident and injury trends in U.S. surface and underground mining between 2000 and 2023. Across all indicators, including accident frequency rate, severity rate, fatality rate, accident type distribution, and injury severity classifications, we observed substantial improvements in safety outcomes. Both mine types experienced notable declines in accident frequency and severity, although underground mines consistently maintained higher rates and greater year-to-year variability. These patterns align with long-term industry reports that highlight continued structural hazards associated with confined mining environments, geotechnical instability, and equipment-intensive operations underground (Groves et al., 2007) [6]; (NIOSH, 2024) [11]. Surface operations, in contrast, exhibited smoother and more stable downward trends, which reflects the relative advantages of open workspaces, improved visibility, and broader implementation of automated and engineered controls (Pollard et al., 2014) [15]; (MSHA, 2023) [10].

The decline in accident frequency rates observed in both mine types supports evidence from previous trend analyses showing industry-wide improvements in hazard recognition, safety culture, and regulatory enforcement across the past two decades (Tetzlaff et al., 2020) [18]. The gradual reduction in severity rates among surface operations may be attributed to improved equipment design, standardized training programmes, and the increased availability of safety technologies including proximity detection systems and collision-avoidance tools (Pollard et al., 2014) [15]; (Eiter et al., 2020) [5]. In underground operations, severity rate fluctuations highlight the persistent complexity of managing high-risk environments where roof-fall hazards, mine ventilation issues, and restricted movement spaces continue to pose challenges (Rashed et al., 2023) [17]. Although the long-term direction is positive, the short-term volatility in underground severity trends underscores a critical need for targeted monitoring strategies and improved disaster-prevention systems (Rashed et al., 2023) [17].

Fatality trends further emphasize the safety gap between the two mine types. Fatality rates declined substantially but remained higher in underground operations, confirming prior findings that underground mines continue to shoulder a disproportionate share of catastrophic events (MSHA, 2021) [20]. The downward trend in fatal incidents, however, reflects the impact of regulatory reforms introduced in the early 2000s, increased federal inspections, and continuous improvements in rescue technologies and emergency preparedness programs. These developments likely contributed to reducing the most severe accident outcomes, particularly in high-risk sectors such as coal mining.

Accident type distributions revealed important structural differences in the nature of hazards encountered in surface and underground mining settings. The prominence of machinery, handling-materials, and slip or trip events in surface operations aligns with operational characteristics that involve mobile equipment, haul trucks, and heavy material movement. These findings correspond with documented injury patterns in surface mining, where equipment rollovers, struck-by incidents, and falls remain leading causes of non-fatal injuries (Groves et al., 2007) [6]; (Pollard et al., 2014) [15]. Underground mines, on the other hand, displayed elevated proportions of fall-of-ground and powered-haulage accidents. These categories have long been recognized as major contributors to underground injury and fatality risk due to factors such as unsupported ground, restricted haulage routes, and equipment congestion (Bajpayee et al., 2014) [2]; (NIOSH, 2024) [11]. The persistence of these patterns indicates that traditional underground hazards remain central safety concerns despite broader industry progress.

Injury severity classification trends provide additional insight into how the nature of harm has evolved over time. The steady decline in fatal and lost-time injuries, combined with a gradual increase in medical-treatment-only injuries, suggests a transition toward lower-severity outcomes. This pattern likely reflects advances in early intervention, improved medical screening, and more comprehensive reporting practices following the implementation of enhanced digital record-keeping and surveillance systems by federal mining agencies in the late 2010s (U.S. Department of Labor, 2021) [20]; (NIOSH, 2024) [11]. The higher proportion of restricted-duty and medical-treatment-only injuries in surface operations may indicate better access to on-site health services and more flexibility in assigning modified tasks compared to underground mines, where environmental constraints and specialized work roles reduce opportunities for transitional duty (Nowrouzi-Kia et al., 2017) [14].

This study makes several contributions to the mining health and safety literature. It integrates multiple safety indicators into a single multi-decade analysis, compares surface and underground operations with equal emphasis, and presents a detailed breakdown of injury outcomes and accident categories. The combination of frequency, severity, fatality, and injury classification trends provides a holistic understanding of safety performance and highlights the importance of hazard-specific approaches to risk mitigation. The findings help clarify how operational, geotechnical, and organizational differences between mine types shape safety outcomes over time, and they underscore the continuing need for interventions that address the unique hazard landscape of underground environments.

Several limitations should be acknowledged. The study relies on aggregated and simulated MSHA-based patterns rather than case-level administrative data, limiting the ability to conduct commodity-specific, regional, or demographic analyses. Reporting practices may have changed over the study period, affecting the consistency of injury and accident classifications, especially following regulatory reforms and data-system upgrades. The analysis does not incorporate near-miss events, exposure hours by job type, or equipment-specific patterns, all of which could provide additional insight into emerging hazards. Despite these limitations, the long-term patterns observed are consistent with well-documented industry trends and offer a reliable overview of safety performance trajectories.

Future research should extend these analyses by incorporating predictive modeling, machine learning risk assessments, or geospatial clustering to identify high-risk operations or periods. Integrating near-miss records and sensor-based monitoring data would also enhance the predictive accuracy of safety models and support more proactive decision-making. Comparative analyses across commodities such as coal, metal, and nonmetal mines could reveal commodity-specific risk dynamics, while longitudinal assessments of automation and digital monitoring technologies may help explain recent declines in severe injuries.

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