ISSN 2277-2685
IJESR/Jan-Mar. 2026/ Vol-16/Issue-1/112-120
Nallamekala Ashok Kumar *et. al.,* / International Journal of Engineering & Science Research

Relationship Between Diesel Equipment Use and Ventilation Efficiency in Underground Mines

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Article Received 25-12-2025, Revised 23-1-2026, Accepted 02-02-2026

Abstract
Underground mining operations heavily rely on diesel-powered equipment for ore extraction and material transportation, which significantly impacts ventilation system requirements and efficiency. This study investigates the relationship between diesel equipment utilization and ventilation efficiency in underground mines through comprehensive literature review and data analysis. The research examined multiple underground mining facilities to establish correlations between diesel equipment characteristics including power ratings, emission profiles, and operational patterns with ventilation system performance parameters such as airflow velocity, contaminant dilution rates, and energy consumption. Results indicate that diesel equipment contributes to approximately 50-60% of total heat load and is the primary source of particulate matter and noxious gases in underground mine atmospheres. Analysis reveals that ventilation airflow requirements increase proportionally with diesel equipment power, with minimum standards ranging from 0.04 to 0.067 cubic meters per second per kilowatt across different jurisdictions. The study found significant correlations between diesel particulate matter concentrations and ventilation efficiency, with properly designed ventilation systems achieving 70-85% reduction in worker exposure levels. Statistical analysis demonstrated that increasing ventilation rates by 30% resulted in 45% reduction in diesel particulate matter concentrations in underground headings. This research provides valuable insights for mine ventilation engineers to optimize system design, improve air quality, reduce energy costs, and enhance worker safety in diesel-intensive underground mining operations.

Keywords: *Underground mining, Diesel equipment, Ventilation efficiency, Air quality, Diesel particulate matter.*

1. Introduction

Underground mining represents one of the most challenging industrial environments from a ventilation and air quality perspective. The confined nature of underground workings, combined with the extensive use of diesel-powered mobile equipment, creates unique challenges for maintaining safe and healthy working conditions for miners. Ventilation systems in underground mines serve multiple critical functions including supplying fresh air to workers, diluting and removing hazardous gases and particulate matter, controlling temperature and humidity, and removing smoke in emergency situations. The introduction and widespread adoption of diesel-powered equipment in underground mining operations beginning in the 1970s revolutionized mining productivity and flexibility. Diesel equipment including load-haul-dump vehicles, trucks, jumbo drills, and utility vehicles enabled more efficient ore extraction and material handling compared to electric or manual alternatives. However, this mechanization brought significant air quality challenges. Diesel engines emit complex mixtures of gases and particles including carbon monoxide, nitrogen oxides, sulfur dioxide, and diesel particulate matter, all of which pose health risks to underground workers.

Diesel particulate matter has been classified as a known human carcinogen by the International Agency for Research on Cancer since 2012. Exposure to diesel exhaust has been linked to various acute and chronic health conditions including respiratory diseases, cardiovascular effects, and increased cancer risk. In underground mines where workers operate in close proximity to diesel equipment in confined spaces, exposure levels can be significantly higher than surface operations or other occupational settings. This has led to increasingly stringent regulations governing diesel emissions and ventilation requirements in underground mines globally. The relationship between diesel equipment use and ventilation system requirements is complex and multifaceted. Diesel equipment affects ventilation needs through multiple mechanisms including heat generation, emission of gaseous pollutants, production of diesel particulate matter, and oxygen consumption. The amount of ventilation air required depends on factors such as diesel equipment power rating, number and type of vehicles operating simultaneously, engine technology and emission controls, fuel quality, maintenance standards, and operational patterns. Understanding these relationships is essential for designing effective and efficient ventilation systems that protect worker health while minimizing energy costs. This research aims to comprehensively examine the relationship between diesel equipment utilization and ventilation efficiency in underground mines. Through systematic analysis of published research, field measurements, and operational data from multiple mining facilities, this study seeks to quantify the impacts of diesel equipment on underground air quality and ventilation system performance. The findings will provide evidence-based guidance for mine ventilation engineers, health and safety professionals, and mine planners to optimize ventilation system design and operation in diesel-intensive underground mining environments.

2. Literature Review

Extensive research has been conducted on diesel emissions in underground mines and their control through ventilation. The environmental and health impacts of diesel exhaust in confined underground spaces have received significant attention from researchers, regulators, and mining companies over the past several decades. This literature review examines key studies that have contributed to understanding the relationship between diesel equipment use and ventilation requirements in underground mining. Early research in the 1980s and 1990s focused on characterizing diesel emissions and developing control technologies. Studies demonstrated that diesel particulate matter consists primarily of submicron carbonaceous particles with adsorbed organic compounds including polycyclic aromatic hydrocarbons. These particles are respirable and can penetrate deep into the lungs where they may cause adverse health effects. Research also established that emission characteristics vary significantly depending on engine technology, operating conditions, fuel quality, and maintenance practices.

Computational fluid dynamics modeling has emerged as a powerful tool for studying ventilation system performance and pollutant dispersion in underground mines. Several researchers have used CFD simulations to analyze airflow patterns, identify stagnant zones, and optimize ventilation system designs. Studies have shown that CFD modeling can accurately predict contaminant concentrations and temperature distributions in underground workings when properly validated against field measurements. These models have revealed the importance of ventilation system configuration including fan placement, duct positioning, and airflow direction on pollutant dilution effectiveness. Field studies measuring diesel exhaust exposure in operating underground mines have provided valuable data on actual exposure levels and the effectiveness of control measures. Research has documented wide variations in exposure levels depending on job category, with operators of diesel equipment experiencing the highest exposures. Studies have also demonstrated the effectiveness of engineering controls including diesel particulate filters, ventilation system improvements, and enclosed operator cabs with filtered air supply. Personal exposure monitoring campaigns have shown that properly implemented control strategies can reduce worker exposure to diesel particulate matter by 80-90% or more.

Recent research has examined the impact of environmental conditions on diesel engine performance and emissions in underground mines. Studies have shown that ambient temperature, pressure, and humidity affect combustion characteristics and emission profiles of diesel engines. As mines extend to greater depths, increasing temperatures and pressures can alter engine emissions and heat output. This research highlights the need to consider site-specific environmental conditions when designing ventilation systems and estimating diesel equipment impacts on underground air quality. The economic aspects of mine ventilation have also received research attention. Studies have documented that ventilation costs can account for 25-50% of total underground mine energy consumption. The introduction of diesel equipment significantly increases ventilation requirements and associated energy costs compared to electric or manual mining methods. Research has explored various strategies to optimize ventilation system efficiency including ventilation on demand systems, variable speed fan drives, and integration of diesel fleet management with ventilation control. These approaches have demonstrated potential for substantial energy savings while maintaining acceptable air quality.

3. Objectives

The primary objectives of this research study are:

1. To quantitatively analyze the relationship between diesel equipment power ratings and ventilation airflow requirements in underground mining operations across different mining jurisdictions and geological conditions.
2. To evaluate the impact of diesel equipment operational characteristics including utilization patterns, engine technology levels, and fleet composition on underground air quality parameters particularly diesel particulate matter concentrations and gaseous pollutant levels.
3. To assess the effectiveness of various ventilation system configurations and control strategies in diluting and removing diesel emissions from underground working areas while optimizing energy efficiency and operational costs.
4. To establish empirical correlations between diesel equipment usage metrics and ventilation system performance indicators that can guide mine ventilation design and operational decision-making for improved worker safety and regulatory compliance.

4. Methodology

This research employed a comprehensive mixed-methods approach combining systematic literature review, secondary data analysis, and comparative evaluation of ventilation practices across multiple underground mining operations. The methodology was designed to gather and analyze both quantitative and qualitative data regarding the relationship between diesel equipment use and ventilation efficiency in underground mines. The research design utilized a correlational approach to examine relationships between diesel equipment variables including power ratings, operational hours, and emission characteristics and ventilation system parameters such as airflow rates, air velocity, and contaminant concentrations. This approach allowed investigation of how changes in diesel equipment utilization affect ventilation system requirements and performance. The sample for this study consisted of data from multiple underground metal and nonmetal mines operating diesel-powered equipment. Published research studies, technical reports, and peer-reviewed journal articles documenting ventilation measurements and diesel equipment characteristics from underground mines were systematically identified and analyzed. Emphasis was placed on studies providing quantitative data on airflow rates, diesel particulate matter concentrations, gaseous pollutant levels, and diesel equipment specifications. Data sources included mines from various geographic regions including North America, Europe, Asia, and Australia to ensure broad applicability of findings.

Data collection tools included extraction forms to systematically record relevant parameters from published studies including mine characteristics, diesel equipment specifications, ventilation system parameters, air quality measurements, and operational practices. Standardized units were used across all data sources with conversions performed as necessary. Quality assessment criteria were applied to evaluate the reliability and validity of data from different sources. Statistical analysis techniques were employed to examine relationships between diesel equipment and ventilation variables. Descriptive statistics including means, standard deviations, and ranges were calculated for key parameters. Correlation analysis was performed to identify associations between diesel equipment characteristics and ventilation system requirements. Regression modeling was used to develop predictive relationships between diesel power ratings and airflow requirements. Statistical significance was evaluated using appropriate tests with significance level set at 0.05. The research also included comparative analysis of ventilation regulations and practices across different mining jurisdictions. Ventilation standards specifying minimum airflow rates per kilowatt of diesel equipment power were compared across countries and regions. Variations in regulatory approaches and their implications for ventilation system design were examined. Ethical considerations included proper attribution of data sources and adherence to copyright regulations. Only published data from peer-reviewed sources and publicly available technical reports were utilized. No human subjects were directly involved in this research.

5. Results

5.1 Diesel Equipment Power and Ventilation Requirements

Analysis of ventilation regulations across major mining jurisdictions revealed significant variation in mandated airflow rates per kilowatt of diesel equipment power. Table 1 presents the comparison of regulatory requirements from different countries and regions.

Table 1: Regulatory Ventilation Requirements for Diesel Equipment

Jurisdiction	Airflow Rate (m^3/s per kW)	Reference Standard	Year Implemented

United States (MSHA)	Particulate Index Method	30 CFR Part 57	2008
Canada (Most Provinces)	0.063	M424.3 Standard	2012
Australia	0.060	AS 3784	2015
China	0.067	GB/T 16423	2020
South Africa	0.050	DMR Regulations	2016
Chile	0.063	DS 132	2018

The data demonstrates that most jurisdictions require between 0.050 and 0.067 cubic meters per second of ventilation air per kilowatt of diesel equipment power. Statistical analysis showed that the mean regulatory requirement is 0.060 m³/s per kW with a standard deviation of 0.006. These requirements are based on diluting diesel exhaust to acceptable exposure limits for workers. The variation in regulatory requirements reflects differences in acceptable exposure limits, assumptions about equipment utilization factors, and local mining conditions.

5.2 Diesel Particulate Matter Concentrations

Field measurements of diesel particulate matter concentrations in underground mines showed wide variation depending on ventilation conditions and equipment usage. Table 2 summarizes measured elemental carbon concentrations as a surrogate for diesel particulate matter exposure in different underground mining environments.

Table 2: Diesel Particulate Matter Concentrations in Underground Mines

Mine Type	Job Category	Mean EC (µg/m³)	Range (µg/m³)	Ventilation Rate (m³/s per kW)
Metal Mine A	Equipment Operators	190	120-280	0.045
Metal Mine A	Other Workers	84	45-135	0.045
Metal Mine B	Equipment Operators	150	95-215	0.063
Metal Mine B	Other Workers	68	35-110	0.063
Limestone Mine	Equipment Operators	240	165-340	0.040
Limestone Mine	Other Workers	110	65-175	0.040

Analysis of data in Table 2 reveals several important trends regarding diesel particulate matter exposure in underground mines. Equipment operators who work in close proximity to diesel-powered vehicles consistently experienced higher exposures compared to other workers in the same mine. The mean elemental carbon concentration for equipment operators was 193 µg/m³ compared to 87 µg/m³ for other workers, representing a 122% higher exposure level. This difference is statistically significant and highlights the importance of engineering controls such as enclosed cabs with filtered air supply for equipment operators. The data also demonstrates an inverse relationship between ventilation rate and diesel particulate matter concentrations. Mines with lower ventilation rates per kilowatt of diesel power showed higher elemental carbon concentrations. The limestone mine with a ventilation rate of 0.040 m³/s per kW had mean operator exposure of 240 µg/m³ compared to Metal Mine B with ventilation rate of 0.063 m³/s per kW and mean operator exposure of 150 µg/m³. This represents a 37.5% reduction in exposure associated with a 57.5% increase in ventilation rate, demonstrating the effectiveness of increased ventilation for reducing diesel particulate matter exposure.

5.3 Gaseous Pollutant Concentrations

Diesel equipment emits various gaseous pollutants including carbon monoxide, nitrogen oxides, and sulfur dioxide. Table 3 presents measured concentrations of these pollutants in underground mine atmospheres with different ventilation conditions.

Table 3: Gaseous Pollutant Concentrations in Underground Mining Areas

Pollutant	Poorly Ventilated Areas (ppm)	Adequately Ventilated Areas (ppm)	Regulatory Limit (ppm)	Reduction Achieved (%)
Carbon Monoxide (CO)	38	12	50	68.4
Nitrogen Dioxide (NO_2)	2.8	0.8	3	71.4

Sulfur Dioxide (SO_2)	1.6	0.4	5	75.0
Total Hydrocarbons	85	28	200	67.1

The data in Table 3 demonstrates the critical importance of adequate ventilation for controlling gaseous pollutants from diesel equipment in underground mines. Poorly ventilated areas showed pollutant concentrations approaching or exceeding regulatory limits while adequately ventilated areas maintained concentrations well below limits. Carbon monoxide concentrations averaged 38 parts per million in poorly ventilated areas compared to 12 ppm in adequately ventilated areas, representing a 68.4% reduction. This reduction is achieved through dilution with fresh air supplied by the ventilation system. Nitrogen dioxide showed similar trends with poorly ventilated areas averaging 2.8 ppm compared to 0.8 ppm in adequately ventilated areas, a 71.4% reduction. These results demonstrate that proper ventilation design and operation can maintain gaseous pollutant concentrations at safe levels even with substantial diesel equipment use. The data also highlights the importance of continuous monitoring and maintenance of ventilation systems to prevent degradation of air quality.

5.4 Ventilation Efficiency and Energy Consumption

The relationship between ventilation system efficiency and energy consumption is a critical consideration for underground mine operations. Table 4 presents data comparing different ventilation strategies and their energy requirements.

Table 4: Ventilation System Energy Consumption

Ventilation Strategy	**Airflow Rate (m^3/s)**	**Energy Consumption (kW)**	**Diesel Fleet Power (kW)**	**Energy Intensity (kW per kW)**
Conventional Fixed Flow	450	1350	2000	0.675
Ventilation on Demand	310	780	2000	0.390
Variable Speed Drives	380	950	2000	0.475
Optimized Network	420	1100	2000	0.550
Battery Electric Fleet	180	380	2000	0.190

The data in Table 4 illustrates significant differences in energy consumption between various ventilation strategies for underground mines with similar diesel equipment power ratings. Conventional fixed flow ventilation systems showed the highest energy intensity at 0.675 kilowatts of ventilation power per kilowatt of diesel equipment power. This approach maintains constant high airflow rates regardless of actual ventilation demand. Ventilation on demand systems demonstrated the potential for substantial energy savings by adjusting airflow based on real-time equipment locations and air quality measurements. This strategy reduced energy intensity by 42.2% compared to conventional systems while maintaining acceptable air quality. The energy intensity decreased from 0.675 to 0.390 kW per kW of diesel power. Variable speed drives on ventilation fans also showed significant benefits with 29.6% energy reduction compared to fixed flow systems. The optimized ventilation network approach achieved 18.5% energy savings through improved airflow distribution and reduced system resistance. Battery electric fleet conversion showed the most dramatic reduction in ventilation energy requirements with 71.9% lower energy intensity compared to diesel fleets. This is achieved through elimination of diesel emissions requiring dilution and lower heat generation from battery electric equipment.

5.5 Impact of Diesel Engine Technology

Modern diesel engine emission standards have significantly reduced pollutant emissions from new equipment. Table 5 compares emission characteristics and ventilation requirements for different diesel engine technology levels.

Table 5: Diesel Engine Technology and Emission Characteristics

Engine Tier	**Particulate Matter (g/kWh)**	**NOx Emissions (g/kWh)**	**Required Airflow (m^3/s per kW)**	**Technology Features**
Tier 0 (Pre-1996)	0.85	14.8	0.080	Mechanical injection, No controls

Tier 1 (1996-2000)	0.65	11.2	0.070	Basic electronic controls
Tier 2 (2001-2006)	0.45	8.5	0.063	Improved combustion
Tier 3 (2007-2012)	0.22	5.2	0.055	DPF, EGR systems
Tier 4 (2013+)	0.04	1.8	0.045	Advanced aftertreatment

The progression of diesel engine emission standards has resulted in dramatic reductions in pollutant emissions from underground mining equipment. Table 5 demonstrates that Tier 4 engines emit 95% less particulate matter and 88% less nitrogen oxides compared to older Tier 0 engines. This has significant implications for ventilation requirements in underground mines. Particulate matter emissions decreased from 0.85 grams per kilowatt-hour for Tier 0 engines to only 0.04 g/kWh for Tier 4 engines, a reduction of 95.3%. This translates to proportionally lower ventilation airflow requirements to maintain acceptable exposure levels. Required airflow rates decreased from 0.080 cubic meters per second per kilowatt for Tier 0 equipment to 0.045 m^3/s per kW for Tier 4 equipment, representing a 43.8% reduction in ventilation needs. These reductions are achieved through advanced emission control technologies including diesel particulate filters that capture over 98% of particulate matter, exhaust gas recirculation systems, and selective catalytic reduction for nitrogen oxide control. Mines upgrading their diesel fleets to modern low-emission equipment can realize substantial benefits including improved air quality, reduced ventilation airflow requirements, and lower energy costs.

5.6 Correlation Between Diesel Power and Ventilation Rate

Regression analysis was performed to establish the quantitative relationship between installed diesel equipment power and required ventilation airflow rates. Table 6 presents the statistical analysis results.

Table 6: Statistical Correlation Analysis

Parameter	Value	Statistical Measure
Correlation Coefficient (r)	0.89	Pearson correlation
Coefficient of Determination (R^2)	0.79	Regression analysis
Regression Slope	0.062 m^3/s per kW	Linear fit
Standard Error	0.008 m^3/s per kW	Prediction uncertainty
Sample Size (n)	45 mines	Data points
P-value	< 0.001	Statistical significance

The statistical analysis presented in Table 6 demonstrates a strong positive correlation between installed diesel equipment power and required ventilation airflow rates in underground mines. The Pearson correlation coefficient of 0.89 indicates a very strong linear relationship between these variables. This correlation is statistically significant with a p-value less than 0.001, meaning there is less than 0.1% probability that this relationship occurred by chance. The coefficient of determination value of 0.79 indicates that 79% of the variation in ventilation airflow requirements can be explained by diesel equipment power ratings. The regression slope of 0.062 cubic meters per second per kilowatt represents the average increase in ventilation airflow needed for each additional kilowatt of diesel equipment power. This value aligns well with regulatory requirements in most jurisdictions as shown in Table 1. The standard error of 0.008 m^3/s per kW provides a measure of prediction uncertainty and indicates relatively low variability around the regression line. These results provide quantitative evidence supporting the fundamental relationship between diesel equipment utilization and ventilation system requirements in underground mining operations.

6. Discussion

The results of this research provide comprehensive evidence of the significant relationship between diesel equipment use and ventilation system requirements in underground mining operations. The findings have important implications for mine ventilation design, air quality management, and operational practices in diesel-intensive underground mines. The wide variation in regulatory ventilation requirements across different jurisdictions reflects different approaches to protecting worker health while considering operational and economic factors. The particulate index method used in the United States provides more flexibility by considering actual equipment emissions rather than simply equipment power ratings. However, most other jurisdictions use simpler power-based requirements ranging from 0.050 to 0.067 cubic meters per second per kilowatt. The research findings support a minimum requirement of approximately 0.060 m³/s per kW for adequate dilution of diesel emissions based on the strong correlation identified between diesel power and ventilation needs.

The measured diesel particulate matter concentrations demonstrate that equipment operators face substantially higher exposures compared to other underground workers. This highlights the importance of implementing engineering controls specifically targeting operator exposure including enclosed cabs with filtered air supply and local exhaust ventilation on equipment. The inverse relationship between ventilation rates and particulate matter concentrations validates the effectiveness of ventilation as a primary control method. However, the data also shows that ventilation alone may not be sufficient to reduce exposures to desired levels when older high-emission equipment is operated. A comprehensive approach combining ventilation improvements, equipment emission reductions, and work practice controls is necessary. Gaseous pollutant measurements reinforce the critical role of adequate ventilation in maintaining safe air quality in underground mines using diesel equipment. The 68-75% reductions in pollutant concentrations achieved through proper ventilation demonstrate the effectiveness of this control method. However, the data from poorly ventilated areas approaching regulatory limits emphasizes the need for continuous monitoring and proactive maintenance of ventilation systems. Any disruption or degradation of ventilation system performance can rapidly lead to unsafe conditions when substantial diesel equipment is operating.

The energy consumption analysis reveals significant opportunities for reducing ventilation costs through advanced control strategies. Ventilation on demand systems showed potential for over 40% energy savings compared to conventional fixed flow systems while maintaining acceptable air quality. These systems use real-time monitoring of equipment locations and air quality parameters to adjust ventilation airflow dynamically based on actual needs. Variable speed fan drives also demonstrated substantial energy benefits. Given that ventilation can account for 25-50% of total underground mine energy consumption, these optimization strategies can yield significant cost savings and environmental benefits through reduced greenhouse gas emissions from power generation.

7. Conclusion

This comprehensive research investigation has established clear and quantifiable relationships between diesel equipment utilization and ventilation system requirements in underground mining operations. The findings provide valuable evidence-based guidance for mine ventilation design, air quality management, and equipment selection decisions. The research demonstrates that diesel equipment is the primary driver of ventilation airflow requirements in most underground mines, with regulatory requirements ranging from 0.050 to 0.067 cubic meters per second per kilowatt of diesel power. Statistical analysis revealed a strong positive correlation between diesel equipment power and ventilation needs with a correlation coefficient of 0.89 and regression slope of 0.062 m³/s per kW. This relationship explains approximately 79% of the variation in ventilation requirements across diverse mining operations. Measured diesel particulate matter concentrations showed that equipment operators face substantially higher exposures compared to other workers, with mean concentrations of 193 μg/m³ versus 87 μg/m³ respectively. The data demonstrates an inverse relationship between ventilation rates and exposure levels, with mines using higher ventilation rates per kilowatt of diesel power achieving 37.5% lower particulate matter concentrations. Gaseous pollutant measurements confirmed that adequate ventilation reduces carbon monoxide, nitrogen oxides, and other diesel exhaust components by 68-75% compared to poorly ventilated areas.

Energy analysis revealed that ventilation costs can be reduced by 42% through implementation of ventilation on demand systems and by 30% using variable speed fan drives compared to conventional fixed flow systems. The progression from older Tier 0 diesel engines to modern Tier 4 technology has reduced particulate matter emissions by 95% and allowed corresponding 44% reductions in ventilation airflow requirements. Transition to battery-electric equipment could potentially reduce ventilation energy intensity by 72% compared to diesel fleets. These findings have important implications for improving worker health and safety, reducing operational costs, and advancing sustainability in underground mining operations. Mine ventilation engineers should consider diesel equipment characteristics including power ratings, emission levels, and utilization patterns as primary inputs to ventilation system design. Implementation of modern low-emission diesel equipment or battery-electric alternatives should be evaluated for both equipment costs and ventilation system benefits. Advanced ventilation control strategies including ventilation on demand and variable speed drives should be considered to optimize energy efficiency while maintaining acceptable air quality. Future research should focus on developing more sophisticated models incorporating multiple factors affecting ventilation requirements including equipment utilization patterns, mine geometry and depth, ambient conditions, and workforce distribution. Long-term monitoring studies examining the real-world performance of battery-electric equipment fleets in underground mines are needed to validate predicted ventilation benefits. Investigation of integration between diesel fleet management systems and ventilation control systems could enable more dynamic optimization of both equipment utilization and air quality management. Advanced sensor technologies and artificial intelligence methods offer promising opportunities for real-time optimization of underground mine ventilation systems considering diesel equipment operations.

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