# Comprehensive analysis of diesel engine emissions and occupational air quality in underground mines

Soyibjon Akhmedov

*Navoi State University of Mining and Technologies, Navoi, Uzbekistan*

*Corresponding author:* axmedovs623@gmail.com

**Abstract.** Diesel-powered equipment is widely used in underground mining operations, significantly increasing productivity but simultaneously causing serious deterioration of mine air quality. This study presents a comprehensive assessment of underground air pollution caused by diesel engine emissions using a multi-component and integrated methodological approach. Experimental measurements, mathematical calculations, and modeling were used to evaluate gaseous pollutants ($NO_2$, NO, CO) and particulate components, including diesel particulate matter (DPM), elemental carbon (EC), total suspended particles (TSP), and polycyclic aromatic hydrocarbons (PAHs). Comparison with theoretical ventilation-emission models showed good agreement between measured and calculated concentrations, validating the applied modeling framework. The findings indicate that source-based emission control strategies, including advanced engine technologies and filtration systems, are more effective than ventilation-only approaches. The integration of real-time monitoring with laboratory-based analytical methods provides a robust and reliable framework for diesel emission management in underground mines.

## INTRODUCTION

The processes of underground mining are impossible to imagine without mining machines and transport equipment with diesel engines. Although these technologies provide high productivity and reliability, they are one of the main sources of mine atmospheric pollution. High concentrations of harmful gases and diesel particles sharply deteriorate the quality of mine air, negatively affecting occupational safety, worker health, and overall reliability of mining operations. Therefore, the development of scientifically based methods for assessing and controlling air pollution in underground mines is one of the urgent tasks of the modern mining industry [1-4;10-32].

The safety of mining operations and the stability of technological processes largely depend on the effectiveness of the ventilation system and the correct choice of measures aimed at reducing harmful emissions. Diesel engine exhaust gases contain nitrogen oxides ($NO_2$), carbon monoxide (CO), sulfur compounds, as well as diesel particles (Diesel Particulate Matter - DPM), the main part of which consists of elementary carbon (EC), organic carbon (OC), and polycyclic aromatic hydrocarbons (PAH). These substances accumulate especially in the face, loading and transport corridors, in areas with limited ventilation capabilities [5-8;15-32].

Numerous scientific studies show that even when the concentration of certain pollutants is within permissible limits, their combined and synergistic effects can pose a serious threat to the health of workers. The ability of diesel particles, especially their ultrafine fractions, to penetrate deep layers of the respiratory system makes them one of the most dangerous pollutants. In this regard, diesel fuel emissions are classified by international organizations as group 1 carcinogens [9,10,11-32].

The technical effectiveness of mine air quality management systems largely depends on the accuracy of measurements and the perfection of the assessment methods used. While initial studies mainly focused on gas components such as $NO_2$ and CO, modern scientific works consider diesel particles and elementary carbon as the main indicator of diesel emissions. At the same time, it was found that approaches based only on increased ventilation do not always give the expected result due to high energy consumption [12,13,14].

In recent years, integrated approaches, taking into account the combined influence of gas and particle components, have become widely used in assessing the state of mine air. Studies conducted on the basis of experimental measurements, mathematical modeling, and generalized air quality indices allow for in-depth analysis of changes in the mine atmosphere in space and time. However, in existing scientific works, gaseous and particle pollutants are often considered separately, and the issue of their unification into a single assessment system is insufficiently covered [15,16,17-32].

Therefore, it is necessary to develop a multi-component, experimentally and theoretically substantiated integrated methodological approach to assessing atmospheric pollution of underground mines under the conditions of operation of diesel-powered machines. This approach serves to more reliably assess the quality of mine air, make effective management decisions, and ensure labor protection and environmental sustainability.

The widespread use of mining machines with diesel engines in underground mines, along with increasing production efficiency, creates serious environmental and hygienic problems associated with the pollution of the mine atmosphere. Exhaust gases and particles emitted from diesel engines - in particular, nitrogen oxides ($NO_2$), carbon monoxide (CO), diesel particles (Diesel Particulate Matter, DPM), elementary carbon (EC), as well as polycyclic aromatic hydrocarbons (PAH) - accumulate in hazardous concentrations in underground working zones, posing a direct threat to the health of mining workers. The classification of diesel fuel emissions as Group 1 carcinogens by international health organizations and the IARC further increases the relevance of this problem.

## EXPERIMENTAL RESEARCH

Exceeding the permissible levels of harmful gases and diesel particles in the mine atmosphere as a result of the operation of machines with diesel engines in underground mines leads to a sharp deterioration of air quality in the working zones. According to the results of scientific research, an increase in the concentration of nitrogen dioxide ($NO_2$), diesel particles (DPM), and elementary carbon (EC) in diesel fuel emissions exacerbates working conditions and poses a high risk to the health of workers. It has been established that in some cases, even when the concentration of individual pollutants is within the norm, their combined synergistic effect increases the overall environmental risk several times.

Therefore, one of the main conditions for ensuring the stable and safe operation of machines with diesel engines used in mining is the effective control of air quality in the mine atmosphere and the restriction of harmful emissions. Such conditions are achieved not only by optimizing ventilation systems, but also by applying technical and organizational measures aimed at reducing diesel emissions at the source.

Also, the process of ensuring the quality of mine air should not be limited to the operational stage, but also include the selection of diesel equipment, fuel quality control, maintenance, and the organization of real-time monitoring. As noted in scientific works, monitoring and evaluation systems based on an integrated approach allow for the timely detection of the accumulation of harmful substances and the prevention of dangerous situations.

Currently, various measurement and evaluation methods are used to control the mine atmosphere. They are divided into classical chemical methods for detecting gaseous pollutants, elementary carbon-based methods for assessing diesel particles, and integrated air quality indices that take into account the combined effect of several pollutants. The combined application of these methods allows for a more complete and reliable assessment of the real state of mine air [9-35].

The main task of control and assessment systems for mine air quality is to improve working conditions by limiting the concentration of harmful gases and diesel particles, reducing the occupational risk of workers, and ensuring industrial safety at mining enterprises. This indicates the need for a comprehensive assessment of diesel emissions and the development of scientifically based technical solutions aimed at their reduction.

## RESEARCH RESULTS

The issue of mine atmospheric pollution by diesel emissions has been covered in many scientific studies, in which special attention is paid mainly to reduction measures based on gaseous components, diesel particles, or ventilation. However, in most existing studies, these factors are considered separately, and not as a single system.

In recent years, diesel particles and elementary carbon have been widely studied as the main indicator of diesel emissions, and the limited effectiveness of approaches based only on ventilation has been scientifically substantiated. At the same time, integrated assessment approaches, combining experimental measurements, real-time monitoring, and mathematical modeling, allow for more reliable determination of mine air quality. In the conditions of our country, the adaptation of these modern approaches to the real operating conditions of local deposits is an important scientific and practical task [9-35].

One of the main objectives of this article is to analyze the spatial and temporal distribution of gaseous and particulate pollutants in underground mines using diesel engines, as well as to determine their combined impact using integrated assessment indicators. Within the framework of the study, the results of experimental measurements are compared with theoretical ventilation-emission models, and the main factors influencing the accumulation of harmful substances in the working zones are determined. The obtained results serve as a scientific basis for improving diesel waste management strategies in underground mines and increasing occupational safety and industrial safety [10-35].

The problem of air pollution during the operation of mine machines with diesel engines in underground mine workings has been systematically studied. The main focus is on methods for determining and controlling the concentration of the leading components of exhaust gases of diesel engines - high-toxic and carcinogenic compounds, such as nitrogen oxides (NO, NO2), carbon monoxide (CO), hydrocarbons, and especially 3,4-benz (a) pyrene. Research results show that exhaust gases from diesel engines can cause up to 60% of mine atmospheric pollution, which poses a serious threat from the point of view of occupational safety and industrial sanitation.

The concentration of harmful substances in mine air is generally expressed by the following dependence:

$$C = \frac{G}{Q_v} \cdot \eta^{-1} \tag{1}$$

where: C - concentration of the harmful substance, mg/m$^3$; G - mass flow rate of the substance exiting the diesel engine, mg/s; $Q_v$ - ventilation air flow rate, m$^3$/s; η - mixing and absorption coefficient

Maximum allowable concentration condition for nitrogen dioxide:

$$C_{NO_2} \leq C_{PDK} \tag{2}$$

$C_{NO_2} > C_{PDK}$ If: it is necessary to optimize the ventilation or engine mode, and for 3,4-benzene (a) pyrene, since the risk is high even at minimal concentrations, the assessment is carried out more as a indirect indicator.

In the process of systematically studying the problem of air pollution during the operation of mine machines with diesel engines in underground mine workings, graphs of the dependence of the influence of mining machines involved in the technological process and their direct involvement on the concentration of $NO_2$ and the concentration of CO in the mine air are presented graphically in Figures 1 and 2 below.

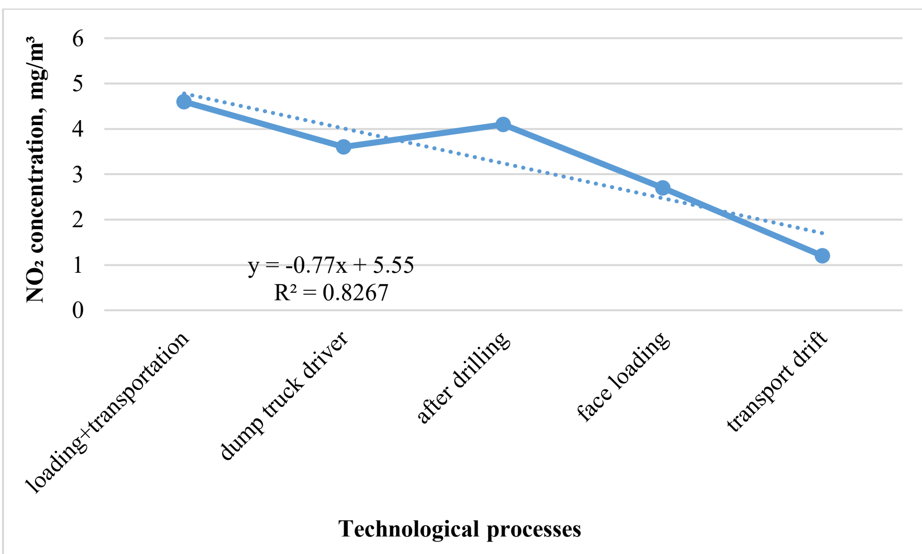


**FIGURE 1.** Dependence of $NO_2$ concentration on the technological process

The results of the analysis of the graphs presented in Fig. 1 and 2 show that the concentration of nitrogen dioxide and carbon monoxide in technological processes using mine machines with diesel engines strongly depends on the type of process. The most dangerous zones are the stages of work after loading and drilling, where values close to or exceeding the maximum permissible concentration are observed. In transport drifts, the concentration of harmful gases is significantly reduced due to the effectiveness of ventilation.

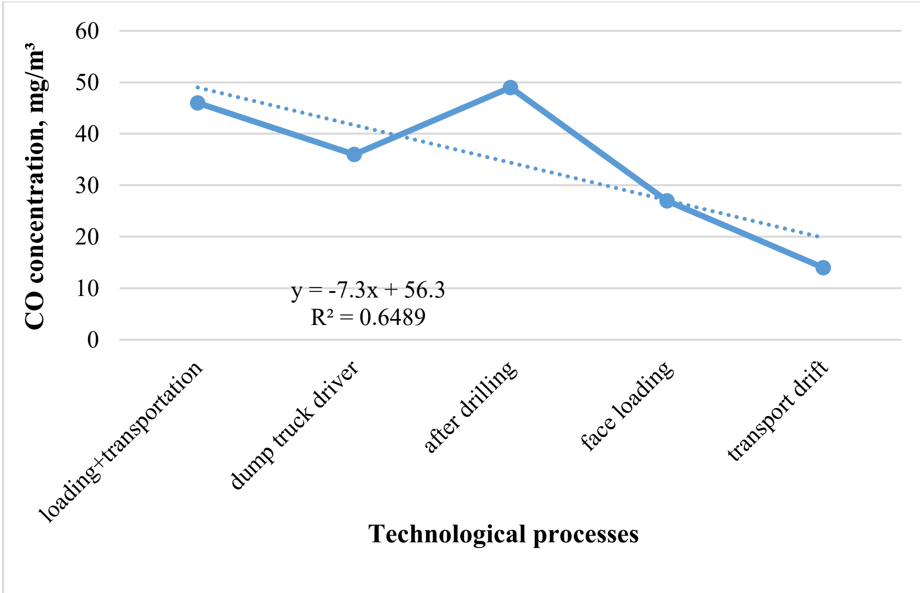


**FIGURE 2.** Dependence of CO concentration on the technological process

Studies were conducted on the basis of a comprehensive (multi-methodical) approach to determining the composition of exhaust gases of diesel-powered machines under underground mine conditions. The main goal of this approach is to determine the leading components of the gas mixture ($NO_2$, CO, hydrocarbons, 3,4-benz (a) pyrene) with maximum reliability under real operating conditions.

The indicator tube method - the CO and $NO_2$ in the gas are determined, that is, the reagent located inside the tubes enters into a chemical reaction with the gas, causing a color change.

$$l = k \cdot C \tag{3}$$

where: l - color change length; C - gas concentration; k - calibration coefficient.

Indicator tubes are suitable for operational control, but with lower accuracy (±20-25%), high humidity and mixed gases cause errors.

Vacuum Container Method - mine air is collected in special vacuum glass containers and then chemically analyzed in the laboratory. With the help of this method, the content of NO, $NO_2$, and CO was determined.

$$C = \frac{m}{V} \tag{4}$$

where: m - mass of absorbed substance; V - volume of air taken.

This method is useful for control measurements, but is limited to errors due to NO → $NO_2$ oxidation, changes in composition due to time delay, and dynamic processes.

Method based on solid sorbents - a gas mixture is passed through a special solid sorbent, and $NO_2$ and other components are absorbed. Then they are determined by desorption in the laboratory.

$$m_{ads} = K \cdot C \cdot t \tag{5}$$

where: mads - mass of absorbed substance; C - concentration; t - sampling time; K - sorption coefficient.

The method allows determining the highest accuracy and lowest concentrations, but requires laboratory processing and is methodologically complex.

Method for determining 3,4-benzene (a) pyrene - adsorbed on the surface of solid particles, collected through a filter or sorbent, extracted using a solution, determined by the spectrophotometric method.

$$A = \varepsilon \cdot l \cdot C \tag{6}$$

This is the Beer-Lambert law: A - optical density (absorption), ε - molar absorption coefficient, I - optical path length, C - concentration

Due to the complexity of mine conditions, it was shown that one universal measurement method is insufficient, and methods of operational control, laboratory analysis, and high-precision sorption-analytical methods were used in a complementary manner. While indicator tubes are effective for operational evaluation, vacuum tubes provide control measurements. The method based on solid sorbents is distinguished as the most reliable method for determining low concentrations, and spectrophotometric determination of 3,4-benz (a) pyrene plays an important role in assessing environmental risk. In general, the selected set of methods makes it possible to accurately, reliably, and scientifically substantiatedly assess the composition of diesel exhaust gases under real operating conditions.

Diesel particle material (DPM), formed as a result of the use of diesel engine equipment in underground mines, is mainly ultramavel particles based on elementary carbon (EC), reaching the deepest part of the respiratory tract due to their size of ~100 nm and posing a high carcinogenic risk to the body. The IARC classification of diesel emissions as group 1 carcinogens further increases the relevance of this problem.

General model of diesel particle concentration:

$$C_{DPM} = \frac{E_{EC}}{Q_v \cdot \eta} \quad (7)$$

where: CDPM - concentration of diesel particulate matter (EC), mg/m$^3$; EEC - elementary carbon emissions emitted by the engine, mg/s; Qv - ventilation air consumption, m$^3$/s; - filtration and elimination efficiency (DPF, DOC, SCR).

This study is devoted to the analysis of current international regulatory requirements for diesel particles (DPM) emitted by mining machines with diesel engines, as well as the effectiveness of their control strategies. The results of comparing the maximum permissible concentrations (MPC) established for medical institutions based on various standards showed that regulatory approaches differ significantly across countries, and in recent years there has been a steady trend towards their tightening. In particular, the requirements of SafeWork Australia, which are planned to be implemented from 2026, reflect an advanced sanitary and hygienic approach to working environment air protection.

Analysis of the graphs presented in Fig. 3 and 4 showed that reducing LPM only through ventilation requires high air consumption and high energy costs. At the same time, it was found that comprehensive control strategies based on the use of diesel particle filtration systems (DPF) and high-class engines (Tier 4) reduce ventilation requirements by almost two times. The obtained results confirm that the implementation of an integrated environmental and technical approach in underground mines is the most optimal solution for increasing the safety of the working environment and ensuring energy efficiency.

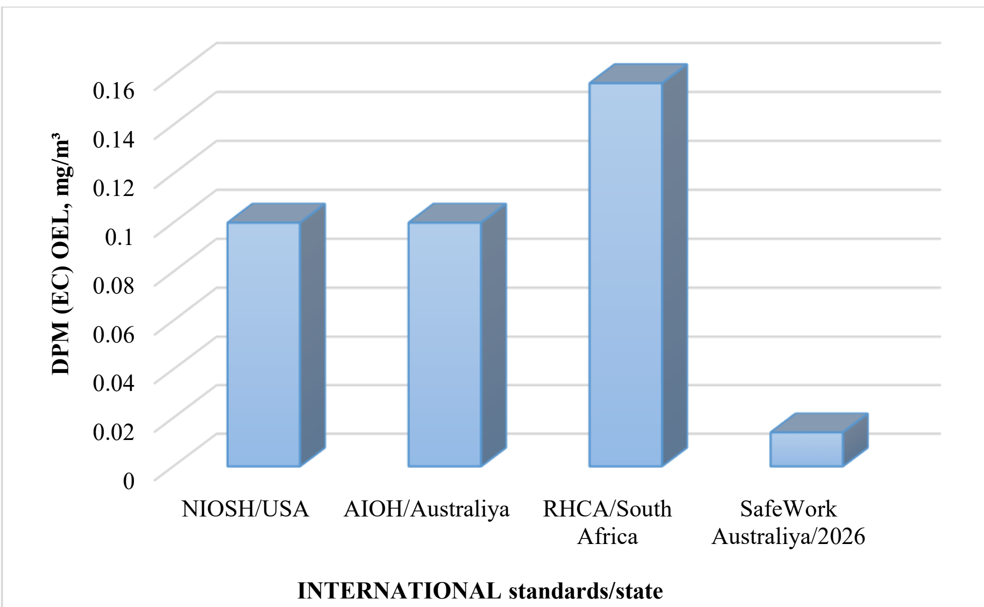


**FIGURE 3.** Comparative analysis of DPM (EC) OEL according to different standards

The results of this study confirm that the pollution of the mine atmosphere under the conditions of operation of machines with diesel engines in underground mines is a multi-component and complex process. As a result of experimental measurements and comparison of theoretical ventilation-emission models, an uneven spatial and temporal distribution of concentrations of harmful gases (NO, $NO_2$, CO) and particulate pollutants (DPM, EC, PAH) was determined. The observation of high peak concentrations, especially in the loading and face zones, made it possible to identify these zones as the most hazardous working zones.

The obtained results are consistent with the classical studies presented in the literature, but in some important aspects complement them. In particular, while previous studies often assessed individual pollutants (for example, only $NO_2$ or CO), in this study, the combined synergistic effect of gaseous and particulate substances was considered based on an integrated approach. This situation showed that even if some pollutants are within permissible limits, their combined action can worsen the quality of mine air to dangerous levels.

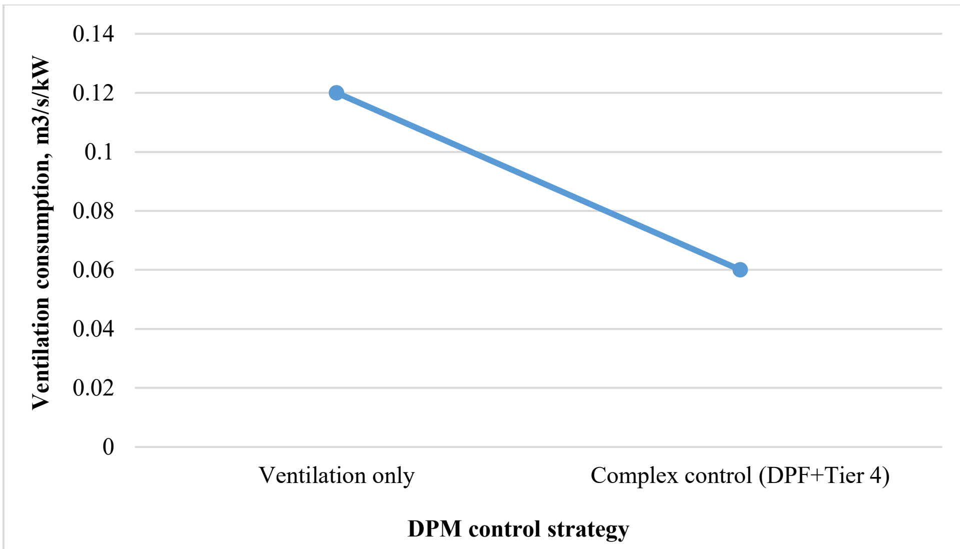


**FIGURE 4.** Ventilation requirement dependent on the healthcare facility is monitoring system

The study once again confirmed that elementary carbon (EC) is the most stable and reliable indicator for diesel particles. A strong correlation between EC and $NO_2$ indicates the expediency of using these indicators together when assessing the overall emission characteristics of diesel engine exhaust. At the same time, the relatively unstable and complex behavior of PAH concentrations confirms the toxicologically complex nature of diesel fuel emissions. This indicates that assessment approaches based on only one indicator are insufficient.

The results of the discussion also showed that strategies based solely on increased ventilation are not always effective due to high energy consumption. Theoretical and experimental analysis showed that the greatest environmental and economic efficiency is achieved when reducing diesel emissions at the source (high-class engines, DPF, DOC, SCR systems) in combination with ventilation. This conclusion fully corresponds to the concept of integrated management, put forward in modern scientific works.

In general, this study scientifically substantiated the need to introduce multi-component, integrated, and adapted to real operating conditions approaches to assessing and managing the quality of mine air in underground mines. The obtained results serve as an important methodological basis for improving occupational safety and industrial safety in practical mining conditions.

## CONCLUSIONS

The conducted studies showed that the use of machines with diesel engines in underground mines leads to a significant deterioration of the mine atmosphere with gaseous and particulate pollutants. The results of experimental measurements and theoretical modeling confirmed the formation of the highest concentrations of harmful substances in the loading and face zones. The research results showed that elemental carbon is a reliable indicator for diesel particles and has a strong association with $NO_2$.

The obtained results confirm that only ventilation-based approaches have limited effectiveness, and the optimal solution is an integrated management strategy that includes reducing diesel emissions at the source, modern filtration systems, and real-time monitoring. These scientific conclusions are of practical importance for ensuring occupational safety, industrial safety, and environmental sustainability in underground mines and will create a solid scientific basis for the development of technical solutions suitable for local mining conditions in the future.

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