Determining airflow requirements for dilution mine dust and DPM in underground mine drilling horizon

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Thesis submitted to the School of Mining and Geosciences of Nazarbayev University in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mining Engineering

Nazarbayev University
21st April 2025

ORIGINALITY STATEMENT

I, Merey Jumabekova, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

Signed on 01.04.2025

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Abstract

The mining sector poses enormous health risks owing to diesel-powered machinery and blasting due to Diesel Particulate Matter (DPM) and mine dust. These pollutants are associated with respiratory conditions such as silicosis and pneumoconiosis. In this thesis, I work on the problem of optimizing airflow to lower DPM and dust levels in underground mines, specifically at the drilling horizon.

An underground mine was modelled using VentSim Design 5.4 software to create a simulation model of an underground mine for the purposes of comparing original and optimized ventilation strategies. The results show that increasing the air supply diminishes DPM and dust levels in the most affected areas. Nonetheless, excessive airflow velocities are likely to generate conditions for dust resuspension, emphasizing the balance of ventilation necessity.

The results support the need to improve miners' health and safety, optimizing ventilation systems to limit particulate exposure.

Dedication

This thesis is dedicated to my family, whose constant encouragement, insightful conversations, and unwavering support made this work possible.

ACKNOWLEDGMENT

This study was supported by the Nazarbayev University Grant Program.

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1. Introduction: Context and Problem Definition

1.1 Background

The mining industry is a vital part of the global economy, providing raw materials essential for various sectors. However, it also produces substantial amounts of dust and aerosol emissions that pose significant health risks to miners. These emissions primarily include particulate matter (PM), dust and Diesel Particulate Matter (DPM), which are generated by blasting, diesel-powered machinery, and material handling activities. Respiratory diseases, such as silicosis and pneumoconiosis (black lung disease), are the leading health concerns associated with dust exposure in mining environments.

1.2 Problem Definition

Despite the increasing recognition of the dangers posed by ultrafine particles, dust and DPM, the mining industry still primarily relies on traditional mass-based measurements, such as PM10 and PM2.5, to monitor dust exposure. These methods fail to account for the hazardous properties of ultrafine particles, leading to an incomplete understanding of the exposure risks. The gap in monitoring methods is particularly problematic in environments where these particles are prevalent, such as underground mining operations.

1.3 Objectives of the Thesis

Mine aim is to determine the airflow requirements needed for effective dilution of mine dust and diesel particulate matter (DPM) in the underground mine drilling horizon using VentSim software.

This thesis objectives are to:

- Review existing methodologies for measuring dust and aerosols in underground mining environments.

- Investigate the factors contributing to elevated DPM and dust concentrations, particularly in high-risk zones such as loading faces and drilling horizons.

- Use VentSim software to model airflow patterns and calculate the necessary ventilation rates to control DPM and dust concentrations in underground mining conditions.

- Compare the simulated airflow results with available field measurements or reported benchmarks to assess the accuracy and reliability of the modeling approach.
- Propose a recommended airflow rate under specific underground mining conditions that ensures safe and effective reduction of dust and DPM exposure for mine workers.

1.4 Scope of Work

The study will focus on underground mining operations, where high-risk activities such as drilling, diesel equipment, blasting, conveyor belt operation, and maintenance work create substantial levels of dust and aerosol emissions. The research will involve:

- A comprehensive review of existing methodologies for measuring DPM and dust, and other relevant metrics.
- Modeling airflow and dust in an underground hard rock mine using VentSim Design software
- Base on a case study metal mine produce ventilation modelling

1.5 Practical Importance

The practical implications of this research are significant for improving occupational health and safety in mining. By introducing DPM and dust into air quality monitoring systems, this research could:

- Provide real-time data on harmful particle concentrations, enabling quick intervention when exposure limits are exceeded.
- Enhance the effectiveness of ventilation and dust control strategies by identifying areas with the highest particle concentrations.
- Reduce the incidence of respiratory diseases and other health conditions among miners by focusing on the ultrafine particles that are the most biologically active and harmful.

1.6 Justification of Research and Development

Respiratory diseases related to dust exposure are a major concern in mining, and the traditional monitoring methods fail to provide a complete assessment of the risks. Ultrafine particles, often overlooked by conventional methods, are known to penetrate deep into the lungs, causing severe damage over time. By focusing on DPM and dust, this research aims to address this gap, offering a more accurate and reliable metric for assessing dust exposure. The adoption of real-time LDSA monitoring could transform occupational health practices, providing a safer environment for miners and reducing the long-term health risks associated with dust exposure.

2. Literature review

Due to the use of diesel-powered equipment, geological disturbances, and restricted ventilation routes, underground mining operations have a one-of-a-kind environment for aerial generation. In such environments, aerosols, including diesel particulate matter (DPM), are predominantly sourced from incomplete fuel combustion of LHD vehicles drilling rigs, and haulage trucks operating within poorly ventilated stopes and development headings (Barrett et al., 2019; Lutz et al., 2014). To some extent DPM's mass comes from total carbon (carbon = EC + OC), which more or less has worked in enforcement as a stand-in for exposing limits of diesel. Nevertheless, it does not capture the reactive surface area and deposition of ultrafine particles (Lepistö et al., 2023). Particles greater than 1 µm in size constitute less than 10% of total DPM mass but may still cause some degree of mechanical respiratory irritation (Saarikoski et al., 2019a). In addition, the high surface area-to-volume ratio of ultrafine particles increases their biological reactivity, making them more harmful.

2.1 Health Effects of Aerosol and LDSA Exposure

Noll et al. (2013) explains that in most of the underground mining environments, operators with a very high changing concentration of diesel smoke associated with working parts of the machinery experience a sharp reduction of comfort, work output and increased usage of PPE. A range of toxicology studies proposes that biological response is more strongly determined by surface area of the particles rather than their mass or count, particularly in the case of ultrafine particles. Smaller and lighter particles which have higher surface area caused more intense lung inflammation and systemic impact in animal models as compared to bulkier or heavier particles. In the case of mining settings, where diesel emissions are almost entirely composed of particles <100 nm, monitoring LDSA can help bridge the gap between exposure and health effects. (Lu et al. 2014) Additionally, high surface-to-volume ratio of ultrafine particles increases their adsorption of toxic substances such as PAHs and heavy metals, making them more reactive. According to the analysis of Bugarski and coworkers, as well as Lutz and coworkers, people are capable of further ROS and pro-inflammatory cytokines production, which is in turn helps in the undermining of epithelial cells, long-term tissue remodeling, as well as DNA damage. (Bugarski et al., 2009; Lutz et al., 2014). Given the aging workforce in many mining operations and the prevalence of comorbidities such as hypertension, LDSA-relevant exposures could significantly elevate cardiovascular disease risk in this population. (Lepistö et al., 2023)

2.2 Aerosol Behavior in Underground Mines

Since underground mines are enclosed and compartmentalized, aerosol dynamics in this regard are quite distinct from surface or open-pit environments. The efficiency of these systems is largely governed by local airflow patterns (Salo et al., 2021; Afshar-Mohajer et al., 2019). In a more detailed study, Sabanov et al. (2025) looked at how black carbon (BC) levels — used as stand-ins for diesel particulate matter (DPM) — relate to lung-deposited surface area (LDSA) in underground metal mines. They studied how tiny particles from diesel engines behave under different ventilation setups, using real-time tools like the Partector 2, DustTrak, and MicroAeth. Their work showed that even when extra ventilation systems were running as required by law, particles were still unevenly spread, forming areas with high and low concentrations inside the mine tunnels (Sabanov et al., 2025). Computational fluid dynamics (CFD) simulations by Noll et al. (2013) along with Lepistö et al. (2023) have proved that aerosol distribution in underground drifts is non-uniform and responsive to changes in the configuration of tunnels and the layout of equipment. CFD predictions also show that in zones where tools are stationed, increased airflow turbulence can reintroduce previously settled particles, increasing exposure risk even with ventilation. During peak load activities, like loading ore into the shuttle trucks or hauling through the inclined drifts, emissions have a unique pattern of spatial dispersion which changes over time. As a result, LDSA levels increase sharply within active zones and after a certain distance or time when ventilation enables dispersion, levels gradually decrease (Noll et al., 2013; Bugarski et al., 2009). Additionally, the synchronized diesel engine utilization timing of multiple machines connected to the same ventilation loop can result in spatial overlap of plumes and enhanced aggregate exposure impact (Kimball et al., 2012).

The vicinity of diesel engines gives rise to steerable thermal jets, which change the intended paths of aerosols. The flow of warm air emanating from engine casings and exhaust systems has the potential to carry ultrafine particles upward where it becomes increasingly stagnant, especially in tunnels characterized by low airflow velocity or low ceiling height. These horizontal flows can alter pours which would have otherwise been stable and reliable, making the tracking of aerosols in real-time much more difficult (Lepistö et al., 2023).

The particle size is of greater importance, among other things. For example, coarse particles like rock dust or blasting residue greater than a micron settle due to gravity within meters of their emission source. This leveling off region of ultrafine particles with < 100nm diameter which contributes most of the LDSA profile, exhibit Brownian motion and remain suspended for much longer periods. They are more likely to follow convective air paths, which is the reason why LDSA can show significant values far from the immediate source of emission (Salo et al 2021; Lepisto et al 2023). These particles can further extend their reach by penetrating into cracks, niches, and irregular wall textures, becoming reintroduced into the airstream when air turbulence or human activity stirs the air.

Blasting, mucking, and shaft hoisting are examples of operational cycles that influence aerosol behaviour. For example, blasting increases the need for ventilation while simultaneously generating high amounts of coarse dust. Alongside that, Supersedes Fine Coal Dust: The World’s Worst Pollutant Permits Blasting Not only does it increase the rough dung sand, their need for ventilation increases and for simultaneous airflow changes, all of someone’s dust pioneered previously ceases is blown away by a sharp wind. During quasi-static changes is when safety constraints are invoked, systems are slowed down or shut altogether, which leads to backflows, or stagnation, DPM overall leads to remaining longer than intended in almost always dusty working areas (Harris et al 2014).

The field measurements also support that aerosol concentrations which include LDSA are temporally variable with pronounced spikes during early shift equipment start-up and post diesel-intensive activities. These variations are not always captured by shift-average sampling methods, indicating that peak exposure periods may be largely underestimated without real-time or high-frequency monitoring (Noll et al., 2013; Afshar-Mohajer et al., 2019).

To optimize aerosol transport studies on modern mining work are increasingly relying on hybrid approaches which combine empirical measurements and models. Lepistö et al. (2023) explains an approach that integrates CFD modeling with a ventilation network solver which enhances the accuracy of maintaining the spatial distribution and geometrical fidelity of the models while significantly reducing the simulation time. Operators now can pinpoint areas in their domain where LDSA accumulation may pose high risks and assess how varying ventilation design or operational changes would affect those zones (Saarikoski et al., 2018).

The fuel type used has also affected the fleet composition's spatial dwell of LDSA. LDSA is greatly amplified at mines utilizing older diesel engines outfitted with low-efficiency aftertreatment systems due to erratic engine loads and degraded filtration systems. In a field study carried out in an oil shale underground mine, Sabanov et al. (2024) evaluated DPM exposure using diesel-powered equipment. They found that diesel was the major contributor to increased DPM concentrations during loading and dumping activities, while also remarking that DPM area concentrations increased significantly with engine load and DPM exposure was cyclical based on equipment tasking. Peak DPM occurs intermittently while loaders and haulers were engaged in loading, dumping or on-road transport activities. The authors were able to demonstrate DPM does not blast uniformly throughout the mine, rather contaminant is likely to be concentrated in specific microenvironments, notably where local ventilation was limited or restricted airflow patterns were present. These findings support previous studies that have concluded that pollutants in underground environments will not occur uniformly, but there are hotspots likely due to local ventilation deficiencies (Bugarski et al., 2009; Noll et al., 2013). Sabanov et al. (2024) also noted spatial and temporal variability in DPM concentrations even in the same task area, suggesting that static mass-based sampling may miss peak exposures. Their findings indicate that it is necessary to consider mechanized vehicle positioning, vehicle task timing and how diesel emissions interact with ventilation flows to better understand exposure risks we discussed in the underground mining context Sabanov et al. (2024). The effects of pre-generation factors on aerosol dispersion and concentration patterns need to be considered, especially when understanding the behavior of LDSA in sophisticated mine settings. These effects will be discussed in later sections of the document (Kimball et al., 2012).

It can be concluded that aerosol behavior underground is impacted by a number of factors which often do not align with expectations, and so integrated assessment tools alongside continuous monitoring are essential to capture exposure risks. This informs the discussion regarding the monitoring systems characterizing DPM and LDSA levels in operational mines (Saarikoski et al., 2018).

2.3 Monitoring of Aerosols and DPM in Underground Mines

The more refined approaches to particle measurement tends to focus on situ detection and quantification, especially through the use of DPM, which marks an advancement in constituents of toxicological ultrafine particles relevance. The lung deposits surface area is a more representative exposure indicator because it suggests active impact surface area of particles posited to interact with lung tissue as opposed to their mass or numerical value. This section looks at the various types of monitoring technologies employed in underground mines and evaluates their effectiveness (Lepistö et al., 2023).

2.3.1 Real-Time Monitoring

Measuring devices used in non-ferrous and metal mines are able to capture diesel emissions almost live, thanks to Noll et al (2013) using laser photometry and filtration techniques to assess carbon concentrations during DPM monitoring. With these devices, instantaneous recognition of exposure spikes and high concentration zones is possible, enabling nicer control over operational and ventilation adjustments in active mining regions. Nonetheless, real-time equipment comes with its disadvantages. Routine maintenance and recalibration are often prerequisites, and so are favorable conditions of an environment for precision - severe humidity, changing aerosol makeup, or any of the many factors can render real-time equipment inaccurate(Lutz et al., 2014). An example: the DustTrak’s response is known to be untrustworthy in environments composed of mixed aerosols - such as dust rock from non-combustion activities, or blasting fume explosions (Lutz et al., 2014). Moreover, to gain comprehensive exposure diagnostic capabilities, new equipment which is fully LDSA integral must be added as real-time devices which measure LDSA directly are scarce.

2.3.2 Measuring Tool – Naneos Partector 2

The Naneos Partector 2 represents a state-of-the-art device built for monitoring purposes specific to LDSA. Unlike traditional sensors based on mass, it employs a unipolar diffusion charging technique which approximates the area of particles that may deposit on the surface of the human respiratory tract. It has been noticed that this device works particularly well in field operations where the tracking of ultrafine particles is essential (Salo et al., 2021). In subterranean mining activities, Partector 2 has been employed in monitoring LDSA exposure across different mining sites: near active diesel engines, at exhaust discharge locations, and in the rest zones. Results frequently reveal sharp contrasts between LDSA levels even in short spatial distance highlighting the microenvironmental risk identification potential (Salo et al., 2021; Lepistö et al., 2023). Moreover, the compact size and unobtrusive quiet performance allows data collection for many hours and makes the device usable for both fixed-station monitoring and personal exposure assessment. The greatest asset of the device lies in its ability to track the movement of ultrafine particles, which methods reliant on mass or numbers would miss, as is often the case with other devices. Since the LDSA is an indication of the actual deposition surface area within lungs, it is particularly valuable for identifying zones of high oxidative stress potential, informing health risk assessments, and tailoring engineering controls accordingly (Salo et al., 2021).

2.3.3 Other Measurement Tools

Other than the Partector 2, additional instruments have also been employed to monitor aerosol levels in mines. The TSI DustTrak DRX is a widely used instrument in general dust monitoring, even though it is not specific to LDSA. The instrument measures mass concentrations of PM1, PM2.5, PM10, and Total PM which allows estimation about the partitioning of particles though not their deposition behavior. The DustTrak is easy to operate, produces data quickly, and is bolstered by the instrument's high user friendliness that tends to outweigh the instrument's shortcomings; the measurements can be inaccurate at higher humidity or interference levels (Lutz et al., 2014). The device MicroAeth AE51 is most notable for its estimation of black carbon concentrations through light absorption, previously unencountered in diesel exposure scenarios. Although not a directly measuring LDSA instrument, it can be called a proxy for EC exposure and track enhancements of combustion particles that dominate among other ultrafine particles. Nonetheless, it is extremely sensitive to calibration along with correction for filter loading effects, contaminated environments, and removal of real-time pollution-free surroundings. (Lutz et al., 2017). Such tools are recommended for initial characterization and hazard mapping. However, these do not appear to be highly effective compared to particle measuring devices specifically configured for LDSA when measuring acute exposure risk or determining health effects due to ultrafine particles, especially via inhalation. Thus, a tiered monitoring approach is recommended—using LDSA monitors like the Partector 2 for high-resolution exposure tracking, supported by real-time EC or PM data for contextual understanding (Bugarski et al., 2009).

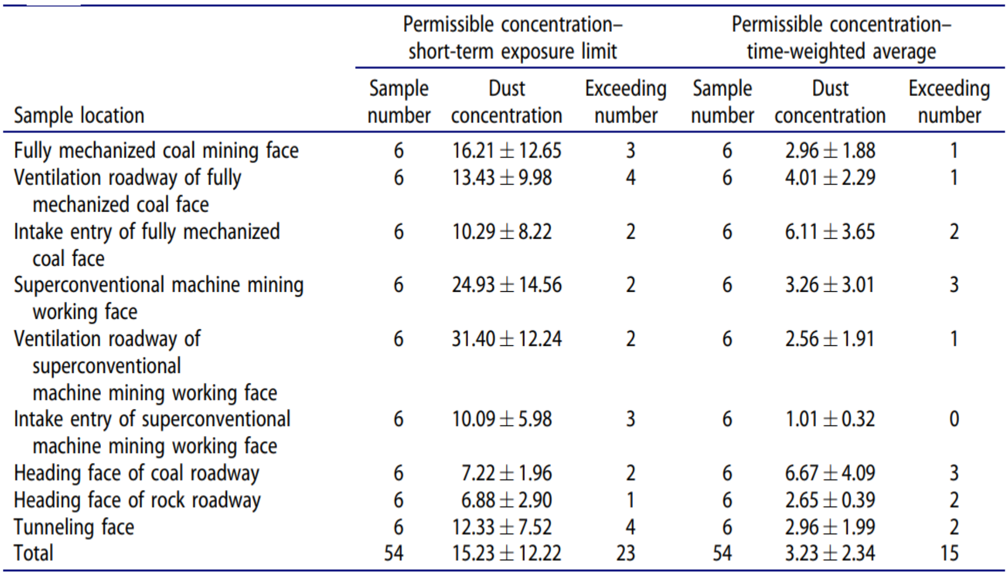
To sum up, the change from mass-based to LDSA monitoring alignment indicates a deeper change in occupational hygiene—towards more biologically relevant metrics. While every tool has its merits in specific scenarios, adoption of LDSA monitoring in underground mining is decisively positive in advancing miner health protection and scientifically managing their exposure (Salo et al., 2021).

2.4 Aerosol and DPM Management Strategies

A holistic construction of engineering control, administrative control, and environmental control designed to lower the creation and buildup of pollutants is crucial for the effective control of aerosol exposure in underground mining. Since ultrafine particles have increased biological hazard potential due to deep lung deposition and high surface reactivity, the management of the Lung Deposited Surface Area (LDSA) requires much more than mass emission reduction strategies with ventilation targets; it necessitates multiple strategies and an LDSA-sensitive approach (Salo et al., 2021). First line of defense strategies usually revolve around source reduction, especially the use of cleaner diesel engines, alternative fuel technology adoption, and emission control system implementation. Simultaneously, control of aerosol dispersion depends much on the design and optimization of mine ventilation systems. A main tool for simulating airflow and forecasting areas of high aerosol accumulation is computational fluid dynamics (CFD) modeling. Additionally possible with CFD is scenario-based planning—that is, analyzing how changes in equipment distribution or blasting cycles affect exposure profiles (Saarikoski et al., 2018). Minimizing localized diesel exhaust buildup requires auxiliary ventilation, particularly in development heads and blind stops. Airflow velocity has a direct impact on LDSA concentrations, according to studies by Saarikoski et al. (2018) and Huynh et al. (2018). Higher velocities shorten the residence period of ultrafine particles and facilitate more efficient clearance. However, even when the total particle mass is low, stagnant zones caused by inadequate auxiliary airflow can cause LDSA to peak. (Saarikoski et al., 2018)

Physically separating employees from emission sources is still a high-impact engineering solution. This can involve building environmental enclosures or pressurized cabs with filtered air supplies, automating drilling or mucking operations, and using remote-controlled equipment. Field data from mines using pressurized operator cabins show significant reductions in personal exposure, with LDSA levels inside enclosures often falling below background ambient levels (Barrett et al., 2019). Applications of surfactants and water sprays are also employed as dust suppression methods, especially for particles that are produced mechanically. These actions can assist stop particle resuspension, which indirectly lowers LDSA in disturbed areas, even if their primary goal is to manage coarse dust. But they usually don't work on fresh ultrafine diesel pollutants, which stay in the air and need to be mitigated by airflow. (Barrett et al., 2019)

Table 1. Dust concentrations in air in the Xinzhuangzi coal mine (Lu, Jiang,Tao, & Hu,2016)



	Permissible concentration–short-term exposure limit			Permissible concentration–time-weighted average		
Sample location	Sample number	Dust concentration	Exceeding number	Sample number	Dust concentration	Exceeding number
Fully mechanized coal mining face	6	16.21 ± 12.65	3	6	2.96 ± 1.88	1
Ventilation roadway of fully mechanized coal face	6	13.43 ± 9.98	4	6	4.01 ± 2.29	1
Intake entry of fully mechanized coal face	6	10.29 ± 8.22	2	6	6.11 ± 3.65	2
Superconventional machine mining working face	6	24.93 ± 14.56	2	6	3.26 ± 3.01	3
Ventilation roadway of superconventional machine mining working face	6	31.40 ± 12.24	2	6	2.56 ± 1.91	1
Intake entry of superconventional machine mining working face	6	10.09 ± 5.98	3	6	1.01 ± 0.32	0
Heading face of coal roadway	6	7.22 ± 1.96	2	6	6.67 ± 4.09	3
Heading face of rock roadway	6	6.88 ± 2.90	1	6	2.65 ± 0.39	2
Tunneling face	6	12.33 ± 7.52	4	6	2.96 ± 1.99	2
Total	54	15.23 ± 12.22	23	54	3.23 ± 2.34	15

Fuel type is also an important influence on aerosol characteristics. Biodiesel versus conventional diesel comparisons have had mixed results in research studies. While biodiesel can reduce the total DPM mass, it can also change the size distribution to smaller particles, potentially resulting in an increase in LDSA (Lutz et al., 2014). Net benefit needs to be ensured through simultaneous LDSA assessments with any fuel-switching approach. Administrative controls that complement engineering controls consist of scheduling practices and minimization of exposure time. LDSA exposure can be reduced further during a shift by restricting the number of workers in high-emission locations during periods of intense machine use, rotating workers through lower-exposure tasks, or implementing rest periods in areas of clean air. Training for ventilation staff and operators of equipment further supports compliance with best practice. Most significantly, regular supervision should be offered to confirm that the handle actions are genuinely functioning. Measurements after pre and post-concentration due to changes in ventilation or engine modifications have been taken with LDSA capable analytics such as the Naneos Partector 2, which can provide an immediate feedback loop to target interventions. Since it enables evidence-based tuning of controls rather than guesswork, or surrogates based on masses, this feedback loop is a key part of modern exposure control. (Bugarski et al., 2022)

2.5 Control of Aerosols

To reduce aerosol emissions, one effective method is using modern diesel engines that follow strict environmental standards, like US EPA Tier 4 or Euro Stage V. These engines have features like diesel oxidation catalysts (DOCs), diesel particulate filters (DPFs), and advanced combustion control systems that help reduce emissions from the engine. A 2022 study by Bugarski and his team found that cars with diesel particulate filters (DPFs) had much lower levels of LDSA in underground iron ore mines (Bugarski et al., 2022). To keep engines working within allowed emission limits, it's crucial to regularly check, tune, and maintain the injection, turbocharger, and exhaust systems. These steps help ensure engines run efficiently and with fewer emissions (Barrett et al., 2019). Mines that follow strict preventative maintenance schedules often see lower diesel particulate matter (DPM) levels and more consistent lung-depositing surface area (LDSA) readings during work shifts. The choice of fuel also directly impacts aerosol production. While many companies still use regular petroleum diesel, there is increasing interest in alternative fuels like biodiesel blends, such as B20 and B50. Biodiesel typically has lower aromatic content and burns more completely, resulting in fewer particle emissions overall (Lutz et al., 2017). Barrett's research found that burning biodiesel can create more very small particles with a larger surface area, which can increase LDSA, even if the total mass of diesel particles decreases. Therefore, when choosing fuel, it's important to consider both the size and surface of these particles, along with how much emission they produce. (Barrett et al.2019)

Emission profiles are also influenced by the load, idle duration, and duty cycle of the engine. The load, idle time, and duty cycle of an engine also affect the emission profiles. However, many low-load conditions (idling or low-load operation) yield a greater proportion of ultrafine particles with high LDSA values, while high-load engines are major sources of larger particles with high mass. Mines with steep ramps or heavy haul routes need to consider engine type and operating strategy in developing emission control strategies because they may experience high-load continuous operation. (Noll et al., 2007)

The introduction of closed crankcase ventilation (CCV) systems and selective catalytic reduction (SCR) in heavy-duty trucks can reduce aerosol emissions. SCR reduces nitrogen oxide emissions that can form secondary aerosols, and by preventing blow-by gases from entering the mine atmosphere, CCV systems can help reduce aerosols as well (Barrett et al., 2019; Bugarski et al., 2009). These technologies come together to form a strong system for actively managing emissions. They offer instant feedback and help in mapping areas where exposure occurs. This is especially useful when paired with tools for real-time monitoring, like the Naneos Partector 2 (Saarikoski et al., 2018). To make sure pre-generation processes are accurate, it’s important to take detailed measurements and provide thorough feedback. Nowadays, there is a growing trend of using real-time LDSA monitors to assess how effective engine changes or fuel replacements are. This assessment takes place not just at the tailpipe but also in various sections of mines (Lepistö et al., 2023). Operators can find the best mix of engines, fuels, and aftertreatment systems to reduce risks for their money by watching how Lung Deposited Surface Area (LDSA) changes during controlled tests (Lutz et al., 2014; Bugarski et al., 2009). In the future, the way we control aerosols might change a lot when the mining industry starts using electric and hybrid vehicles more widely. However, for mines that still mainly use diesel, it is important to improve controls before engine use to manage LDSA and aerosol exposure.

These methods will be necessary until all vehicles in the fleet are fully updated to use newer systems (Kimbal et al., 2012).

2.6 Control at the Point of Generation

These controls remain especially significant in underground settings where airflow limitation and space restriction can result in localized diesel particulate matter (DPM) accumulation and high Lung Deposited Surface Area (LDSA) levels. These DPFs require frequent cleansing to prevent blockage, and if they are poorly managed, emit particle bursts throughout cleaning cycles. An alternative cost-efficient method is the use of enclosed or partially enclosed operator cabins with high-efficiency particulate air (HEPA) filters and pressure-positive systems. The cabins isolate miners from external air, substantially reducing the level of diesel particulate matter (DPM) that they are exposed to. Studies, such as one by Barrett et al. in 2019, have found LDSA levels to be considerably reduced compared to environmental levels even where active diesel is applied. (Kimbal et al., 2012)

Environmental enclosures and local ventilation regulate emissions where there is high pollution, such as loading bays, fuel stations, or crushers' chambers. As an example, diesel exhaust can be eliminated before it reaches the air where employees breathe by using canopy hoods and extraction fans over such points. By employing Computational Fluid Dynamics (CFD) models, these systems can be optimized to capture more particles while keeping less air recycled (Lepistö et al., 2021; Saarikoski et al., 2018).

Mobile extraction units are another method and are mounted on vehicles or trailers to ventilate isolated work areas or compartments that are more enclosed. They are applicable for short durations to carry out risky activities like drilling, preparing to blast, or keeping up with shafts. They capture sudden peaks of emissions effectively that could otherwise result in high levels of local air pollution if left unchecked (Barrett et al., 2019; Huynh et al., 2019).

The application of chemical suppressants and scrubbers is effective at eliminating airborne particles at source. These systems are primarily for large particles, but they can prevent even very small particles from getting re-suspended. Such systems are particularly effective where diesel and mineral aerosols are present. Calibration with real-time LDSA monitoring is essential to monitor the efficiency of such systems. Equipment such as the Partector 2 can be stationed near an engine or an emission point to visibly observe the outcome of the controls and detect leaks or faults. Such data enables us to continuously improve controls from the real-time data. (Noll et al., 2013)

2.7 Administrative Controls

Administrative controls augment engineering methods by addressing procedure, work organization, and behavior factors that affect aerosol exposure. These controls tend to be less expensive and flexible than technology interventions, so they make particular sense for smaller operations or as part of comprehensive exposure management efforts. Task-oriented scheduling is an important administrative method. By varying work sequences to limit the number of people present where high exposure occurs—i.e., equipment startup, blasting, or ore transfer—mines can mitigate cumulative LDSA exposure. Shift rotation and work-rest scheduling can similarly reduce exposures to different workers to avoid individual health risk (Noll et al., 2013).

Training and awareness are crucial for effective administrative control. When workers are educated about where aerosol pollution comes from, how ventilation systems work, and the areas with the highest exposure, they're more likely to take protective actions—like staying away from exhaust plumes, keeping cabin doors closed, or reporting ventilation issues. Ventilation officers and supervisors play an important role in ensuring these practices are followed by conducting daily briefings and inspections (Harris et al., 2014; Noll et al., 2013).

Their success depends on making sure equipment is used properly, well-maintained, and properly fit-tested, with regular training and compliance checks to back it up (Lutz et al., 2014; Lu et al., 2016). Administrative controls also include things like limiting equipment idle time, setting preventive maintenance schedules, and tracking DPM exposure over time. For example, cutting down on idle times doesn't just save fuel and reduce emissions; it also lowers worker exposure during times of minimal airflow (Barrett et al., 2019; Bugarski et al., 2009).

Finally, integrating monitoring data into administrative decisions improves the responsiveness of controls. For example, real-time LDSA trends can trigger operational actions, such as starting auxiliary ventilation or postponing high-emission tasks. Mines that use these dynamic response systems are better prepared to handle unpredictable exposure conditions and ensure a safer work environment. Point-of-generation and administrative controls play a crucial role in the aerosol exposure control hierarchy, bridging the gap between technological solutions and people-centered practices to support long-term risk reduction underground. (Noll et al., 2013)

2.8 Role of Ventilation in DPM and LDSA Management

Primary ventilation systems provide the necessary bulk airflow from surface intakes to underground work areas, ensuring good air quality in active drifts and development headings. However, the effectiveness of aerosol removal depends significantly on local airflow patterns and secondary ventilation systems, such as auxiliary fans, ducts, and regulators. If ventilation is poorly directed or inadequate, high-exposure microenvironments can form, even if overall airflow volumes meet regulatory standards (Salo et al., 2021).

In a number of mining jurisdictions, a regulatory framework prescribes ventilation requirements according to the engine power of the diesel-powered equipment which has a direct equivalence to DPM/TOXIC gas emissions. For example, airflow rates are usually prescribed at 0.06 m^3/s per kilowatt (kW) of engine power in Australia, Canada, and South Africa; Australia specifies between 0.05 and 0.06 m^3/s per kW; and Canadian provinces specify ventilation rates from 0.047 m^3/s to 0.092 m^3/s per kW (Halim, 2017). These limit conventionally prescribed ventilation rates were based predominantly on old tests done by the U.S. Bureau of Mines, and recently , have not had any identified scientific basis specifically in regard to DPM dilution. Furthermore, the prescribed limit ventilation rates were for dilution of toxic gases, such as carbon monoxide (CO) and nitrogen dioxide (NO_2) not for diesel particulate matter which was only first recognized as a human carcinogen in 2012. Additionally, the Government of Western Australia as recently as December 2020 recommended an airflow quantity six to eight times larger than the general convention of 0.05-0.06 m^3/s per kW distance travelled per kW of engine power to satisfy both toxic gas and DPM (Halim, 2017). This is an example of increasing levels of awareness of the inadequacy of old ventilation standards for modern diesels, and the need for validation to re-establish ventilation requirements for diesel exhaust emissions in underground mines.

Air velocity plays a key role in controlling DPM and LDSA levels. Low air speeds allow ultrafine particles to accumulate and remain suspended in the air, while higher velocities help disperse these particles, reducing the time they spend in the breathing zone. Studies have found that areas with stagnant airflow, like blind headings or shaft bottoms, often have much higher DPM concentrations than well-ventilated spaces, even when overall particulate matter levels are similar (Afshar-Mohajer et al., 2019)

Ventilation-on-demand (VoD) systems are a notable development in the dynamic control of LDSA. These systems adjust airflow in real-time by incorporating data from sensors, tracking personnel movements, and monitoring the status of equipment operations. Mines equipped with VoD systems can minimize energy waste by directing airflow only to the areas where Diesel Particulate Matter (DPM) is actively being produced. This not only helps reduce LDSA levels but also improves cost-effectiveness (Bugarski et al., 2009).

Moreover, when it comes to ultrafine particle dilution, it's essential to reconsider the targets through the lens of LDSA rather than simply relying on mass-based thresholds. Since LDSA can rise independently of the overall particulate mass—especially in situations involving high engine loads or following regeneration cycles—ventilation design should factor in both LDSA monitoring and traditional particulate matter metrics (Noll et al., 2007).

Methodology

3.1 Research Design

This study takes a simulation-based approach to analyze how diesel particulate matter (DPM) and dust behave in the underground mining environments. The research is conducted using VentSim Design software, a tool tailored for modelling ventilation systems in mines and tunnels.

The aim is to explore how optimizing ventilation can help reduce DPM and dust concentrations in the chosen operational underground mine. The study is divided into two main phases:

1. **Initial Simulation**: This phase models the existing ventilation system with an airflow rate of 0.5 m^3/s. It helps us track how DPM and dust gather and spread throughout the mine.

2. **Optimized Ventilation Simulation**: For this phase, airflow is increased to 5 m^3/s, 8.4 m^3/s and 10 m^3/s along with improvements to the ventilation system. This allows us to observe how these changes affect the reduction of DPM and dust levels.

This study is based on an existing underground mine model in the VentSim software, simulating diesel emissions from mining machinery, especially in Drift 1(Drilling Horizon). Monitoring points are placed in both Drift 1 and the Shaft to track changes in emissions before and after improving the ventilation system.

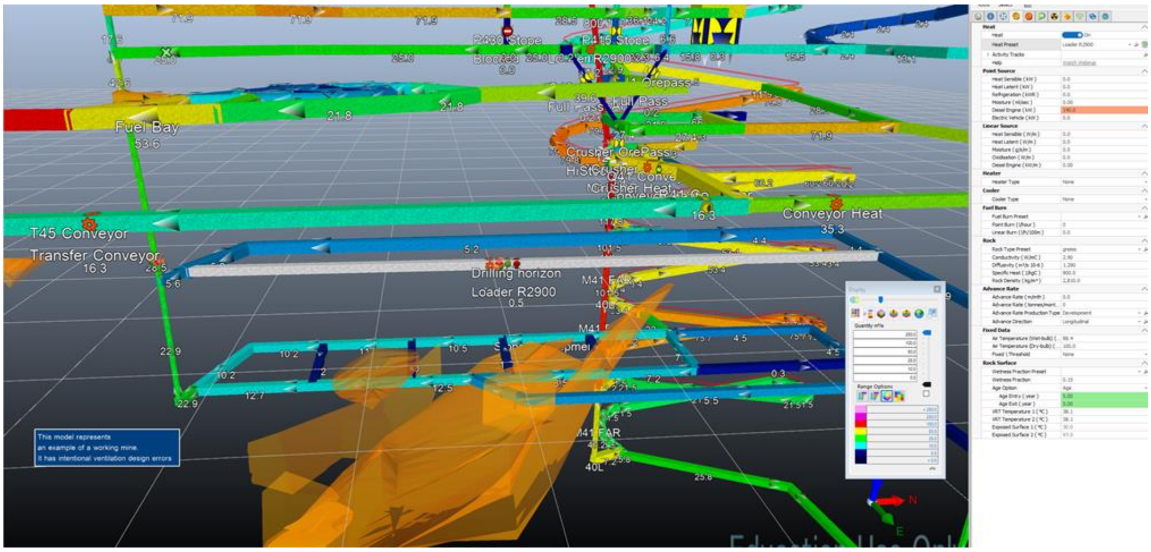
By using Ventsim modeling, the study looks at airflow and the movement of contaminants, removing the safety risks that come with on-site testing.

The main steps of the methodology are:

- Importing and adapting the existing mine model into VentSim.
- Defining diesel machinery and drilling jumbos as sources of emissions, along with particle release details.
- Setting up the mine’s ventilation network for both the initial and optimized conditions.
- Running dynamic simulations for both scenarios.
- Measuring DPM and dust levels at the monitoring points.
- Analyzing the results using received data for comparison.

This study uses a metal mine model to ensure that all input parameters, such as airflow and contaminant behavior, closely reflect real-world mining conditions. The main goal is to understand how changes to the mine's ventilation system can reduce miners' exposure to harmful particles. The Ventsim model represents a typical sublevel caving horizons. It reflects a typical mine situation with the use of diesel-powered equipment that can produce areas with higher diesel particulate matter (DPM) and dust concentrations at use of drilling equipment..

3.2 Simulation Model Description



This model represents
an example of a working mine.
It has intentional ventilation design errors

Figure 1. Metal Mine VentSim simulation used for this paper

Two airflow were used for simulation (Drift 1 and Shaft). Drift 1 was the major diesel and dust source, and Shaft was used to monitor the distribution of the aerosols. Diesel equipment (modelled as a DPM source) was added and modeled in Drift 1; ventilation flow through the drifts was sealed so that air was only flowing into the two drifts.

The modeled ventilation circuit had one primary intake airway, two primary exhaust routes, as well as other auxiliary branches, with a fan station at the return. In its initial configuration, airflow was restricted to rates shown in the dataset (rather than temperature or dilution) as it was limited to 0.5 m^3/s. The simulation could see the accumulation of aerosol, and delay in clearance from Drift 1.

It was determined that the airflow capacity of both drifts could be increased to 5 m^3/s (Scenario 1), 8.4 m^3/s (Scenario 2) and 10 m^3/s (Scenario 3) by adding auxiliary fans, and reducing airflow resistance in selected branches. Both of these changes are designed to to dilute DPM and dust faster.

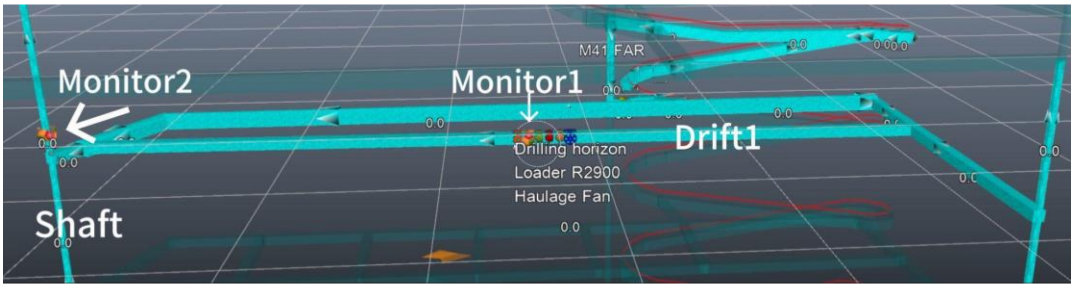


Figure 2. Metal Mine with 2 Monitors, Drift 1 and Shaft.

The model's geometry, airflow boundaries, and environmental conditions were configured based on the parameters of the model. These parameters included:

- Airflow: 0.5 m³/s
- Optimized airflow: 5 m³/s, 8.4 m³/s and 10 m³/s
- Monitoring time: 3 hours
- Fixed sensor locations Monitor 1 and Monitor 2

- Dust Concentration: 50.0 mg/m³

- Diesel Engine Power: 140.0 kW

- DPM: 500 µg/m³

- Machine used: Loader R2900 (Gross power - 409 HP, Operating weight - 29000 kg, payload capacity - 6500 kg, maximum speed - 18.5 km/h)

To understand the dust exposure levels in various mining environments, we compared the results from our research with data from several other mining operations. The following table provides dust concentration levels from a variety of mine sites, measured using different equipment and techniques:

Table 2. Comparing the existing dust concentration data

Mine Site	Drilling Equipment	Rock Type	Dust Concentration (mg/m³)	Measurement Method	Notes	Source
Coal mine	CFJD5 airflow velocity meter, JCB4 methane detection and alarm device, CC-20A mine dust sampler	Coal	Not specified	Field measurements, CFD simulation	Used airflow velocity meter and dust sampler for measuring respirable dust	Luo et al. (2016)
US coal mines	No specific equipment mentioned	Coal	1.5 mg/m³ (respirable dust in US coal mines, 30 CFR §70.100)	Regulatory limits, field measurements	Dust concentrations beyond 200 feet limited to 0.5 mg/m³	US regulatory standards (30 CFR §70.100)
El Aljibe Quarry	Personal sampling devices used during drilling and mucking	Chrome ore	3 mg/m³ (respirable dust in El Aljibe Quarry)	Personal dust sampling	All occupational concentrations below 3 mg/m³ respirable matter	TFM_Gonzalo_Morera_Vall_Gonzalez

Underground chrome mine (Kemi, Finland)	Soot Particle Aerosol Mass Spectrometer (SP-AMS), Nano Scanning Mobility Particle Sizer (SMPS), ELPI, Optical Particle Counter (OPC)	Chrome ore	PM_1 concentrations ranged from 19-360 µg/m^3, with $PM_{2.5}$ averaging around 0.1 mg/m^3	Measurement using dust samplers and field sampling	Heavy equipment used for sampling in the chrome mine, dust concentrations varied in different zones	Lüt1 (Outokumpu Kemi)
United Taconite Mine	DustTrak (Model 8520), PTrak (Model 8525)	Taconite	PM_1: 0.25-0.5 mg/m^3, with specific ranges depending on operational conditions	Field sampling, real-time monitoring	Heavy particulate concentrations during dry and wet processing in Taconite mine	United Taconite Mining Operations
Underground mine	Diesel generator Tier-4 (Kubota D1703-M-BG-ET01), Marple chamber for controlling DPM	Not specified	Variable: High, medium, low DPM concentrations: 600 µg/m^3, 300 µg/m^3, 100 µg/m^3	Field measurement	Measured DPM in three ranges with a focus on vehicle and drilling equipment emissions	Lüt3 (DPM in underground mines)

Mesabi Iron Range	Nano-MOUDI II, APS Model 3321	Granite, Talc-carbonate	$PM_{2.5}$: 29.9 ± 32.3 mg/m^3, $PM_{0.5}$-10: 9.6 ± 11.2 mg/m^3, Black Carbon (BC) concentration doubled in June	Real-time measurement, field sampling	Notable rise in BC concentrations in June	Mesabi Iron Range Study
Metal mine	DustTrak (Model 8520), PTrak (Model 8525)	Chrome ore	DPM: 600 µg/m^3 (without DPF), 170 µg/m^3 (with ceramic DPF)	Lab analysis and field measurements	DPM concentration before and after DPF installation	Lüt5 (DPM control in metal mines)
Outokumpu Kemi	Soot Particle Aerosol Mass Spectrometer (SP-AMS), Nano Scanning Mobility Particle Sizer (SMPS), ELPI, Optical Particle Counter (OPC)	Granite	PM_1 concentrations ranged from 10-360 µg/m^3	Sampling in underground mine	Measured during peak mining operations	Outokumpu Kemi (Underground Chrome Mine)

University of Arizona San Xavier Underground Mining Laboratory (SX)	2005 Wagner B10-203 load-haul-dump (LHD) vehicle	Not specified	PM_1: 16.21 ± 12.65 mg/m³ (fully mechanized coal face)	Field sampling, vehicle-based measurements	Measured using sampling devices and LHD vehicle-based analysis	Lutz et al. (2017)
Xinzhuangzi and Xiejiaji Mines, Huinan	No specific equipment mentioned	Chrome ore	PM_1: 16.21 ± 12.65 mg/m³, $PM_{2.5}$: 19.22 ± 7.89 mg/m³, Free Silica: 11.28 ± 7.79 mg/m³	Sampling from various mine operations and equipment	Detailed data on PM, silica, and microbial concentrations	Xinzhuangzi and Xiejiaji Mines, Huinan

In this research, I aimed to set dust concentration based on several international mining operations. From the papers and field data, the breathable dust levels limit is 1.5 mg/m³ in U.S. coal mines (within legal limits). Dust concentration overlimits can go over 16 mg/m³ in underground chrome and coal mines in China and Finland, with extreme peaks in some metal mining sites reaching as high as 29.9 mg/m³. Some mines during drilling operations demonstrated up to 600 mg/m³ of dust concentrations. My research, however, does not only look at the breathable parts but also studies how larger dust behaves under ventilation, especially in high-dust drilling areas, where levels can easily go over the usual workplace limits. Picking a reference value of 50 mg/m³ sets my study's scenario as tough but still realistic—allowing strong tests to check ventilation plans and look at the dust levels miners would likely face during long drilling work. This number allows solid study of places filled with dust while also looking at the need to study both dilution and dust being stirred back into the air in dusty conditions.

The software was set up to model contaminant dispersion using a dynamic airflow simulation. As the simulation progressed, the sensors in the model recorded DPM and dust readings. From the time-series plot of contaminant concentrations, we recorded key measurements every 5 minutes to assess the performance of the upgrade in ventilation.

Ambient parameters such as temperature and humidity were held constant between the two simulations to limit any confounding effects due to external changes in airflow. The intention of the simulation of contaminants focused on a comparison of air movement, particle deposition, and settling performance of the mine site, before and after the optimized ventilation.

This simulation allows for the controlled observation of contaminant behavior under realistic conditions and forms the basis for all measurements, comparisons, and analysis of data for the research.

3.3 Simulation Procedure and Data Acquisition

Each simulation chronicles the extent to which exposure to DPM and dust can be reduced through ventilation optimization. The methods follow two main phases of the simulation, an initial scenario and an optimized scenario. The simulation model encompasses the entire range of functions in a mining operation; drilling, ore extraction, material handling, and ventilation, which include the integration of all systems & equipment for operational safety and efficiency.

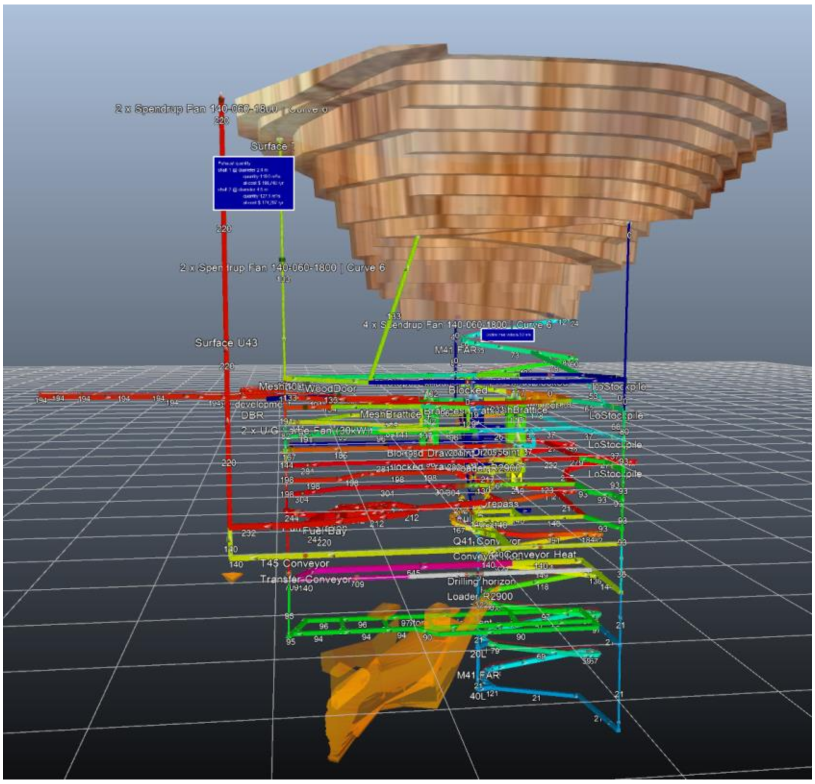


Figure 3 . VentSim Metal mine simulation

Ventilation Model Components:

- Backfilling
- Crusher & Crusher Room
- Drilling Horizon
- Fan Recirculation Problem
- Fuel Bay
- M41 FAR (Fan Airflow Regulation)
- New Development Areas: P400, P415, P430 Stope
- Conveyors: Q41, R41, T45
- Orepasses: Q41, Q42
- Workshop Area

Mining process description:

1) Drilling Horizon and Stope Development

Extraction mining starts at the drilling horizon when the drill accesses to the orebody via various drills. This is followed by the stope development, which begins to create tunnels and chambers allowing for the removal of valuable minerals, extraction. Blasting is used to break the rocks to obtain ores.

Figure 4. Drilling horizon with working Loader R2900

2) Loading and Transport

Once fragmentation is completed the loaders go and take the fragmented material to the conveyors taking it to crushers or orepasses:

- The loaders also go to the R41 Conveyor and Q41 Conveyor and take the ore from there.
- Ores are moved to the surface using skip hoists through orepasses: Q41 and Q42.

3) Crushing and Ore Handling

The ore is crushed prior to moving or processing, each volume is reduced gradually as it goes through the crushers. There are storage or hoisting systems to hold the fuel.

4) Ventilation and DPM Control

The fans help reduce contamination like DPM - diesel particulate matter, pollution within the mine and also control the airflow for better air quality.

5) Material Storage and Transport

After the processing phase the ores can be placed into buffers until surface processing begins or stockpiled through ledges. Movement of the ores to the surface can be done using conveyors or skip hoists.

6) Backfilling

During this process the areas where ore has been mined will be backfilled with cement or sand to add stability for these areas.

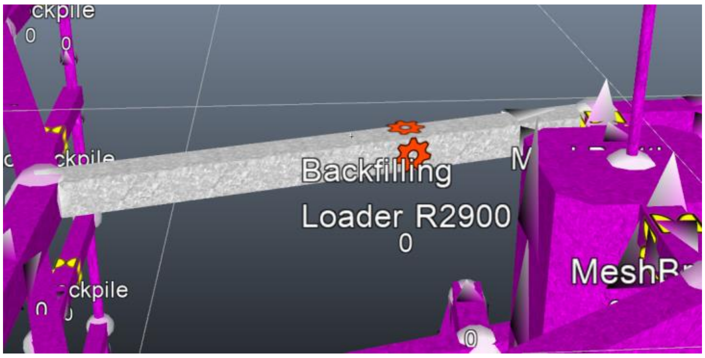


Figure 5. Backfilling process

The model captures fundamental components of mining, from drilling to handling mined ores and materials. It models mining processes in entirety, inclusive of system ventilation and backfill, so that all components of the mining operation can be simulated to improve air, DPM control, transport of materials, etc. airflow, DPM control, material transport

Results

4.1 Initial Ventilation Simulation

In the first simulation Drift 1 was modelled, with a diesel vehicle working. The ventilation airflow was defined as 0.5 m³/s, but this is not a good airflow, and could be considered poor airflow, as in actual mining scenarios, this lower airflow does not provide enough airflow to scour up aerosols, allowing it to build up in hazardous amounts.

Key setup parameters:

- Airflow: 0.5 m³/s

- Vehicle operation time: 3 hours

- DPM and dust measured every 5 minutes

- Monitor placement: midpoint of Drift 1 and downstream in Shaft

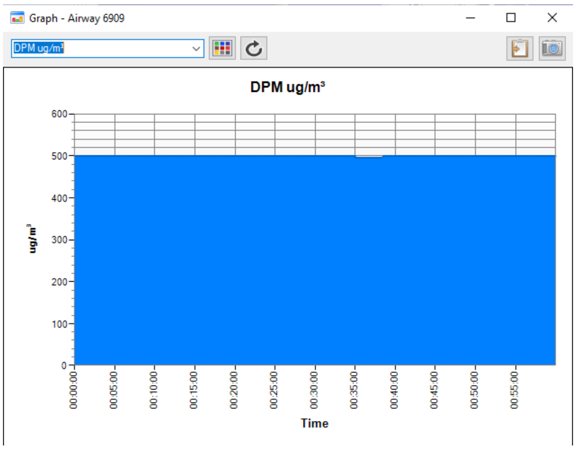


Figure 6. – Initial DPM Concentration (Drift 1)

At Monitor1, DPM concentration sharply increased to approximately 500 µg/m³ for the entire nearly one-hour monitoring period. Persistently high concentrations with little to no fluctuation are indicative of sustained diesel emissions in a stagnant or poorly circulated region. These conditions suggest sustained diesel activity without adequate control measures or ventilation technology to dilute or capture emissions.

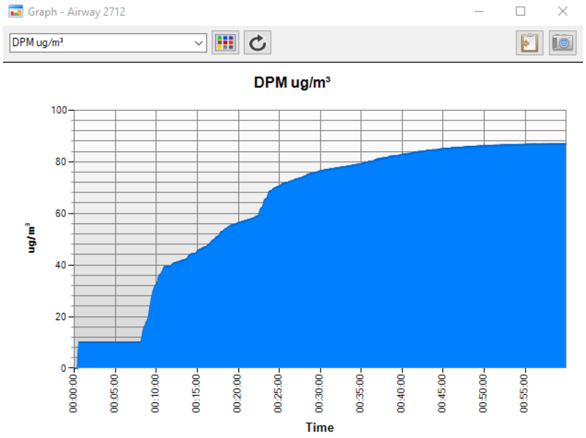


Figure 7 – Initial DPM Concentration (Shaft)

At Monitor 2, we observed the DPM (Diesel Particulate Matter) concentration levels to be below 10 µg/m³ for the first few minutes, but sharply increased to approximately 40 µg/m³ at the 10-minute mark. The concentration remained at 90 µg/m³ for the remainder of the monitoring period and showed a steady increase throughout the 45 minutes of monitoring.

With no sign of leveling off, we can definitively conclude that diesel emissions were active and rapidly increasing over this period. This could be caused by greater use of diesel-powered equipment alongside a build-up of exhaust in an enclosed space or diminished ventilation efficacy. Such an increase in concentration in the primary airway, which serves to supply fresh air and enables the effective clearing of dangerous contaminants, poses a serious risk.

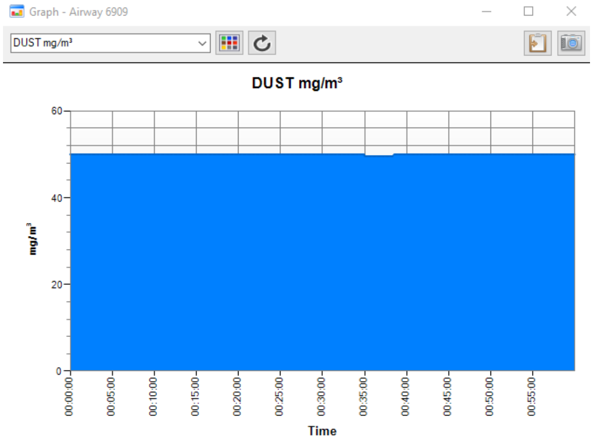


Figure 8. Dust concentration over Time (Drift 1)

In Figure 8, the concentration of dust went up immediately and maintained a stable value of about 50 mg/m³ for the rest of the monitoring period for nearly one hour. The concentration of airborne particles monitored micron after micron did not increase or decrease, suggesting there was a drastic, steady amount of airborne dust particles. This is likely caused by continuous drilling, blasting, or material handling in a confined space with poor ventilation.

The distal regions of a scrubbed, clean, rotating fresh air system, which is supposed to distribute fresh air into the workplace, shows signs of persistent harsh dust saturation around particulates airborne suggests the utter failure of sophisticate dust controlling measures like vents spraying water or scrubbers and absence of sufficient exhausts serving the purpose of capturing and removing dust constituting particles.

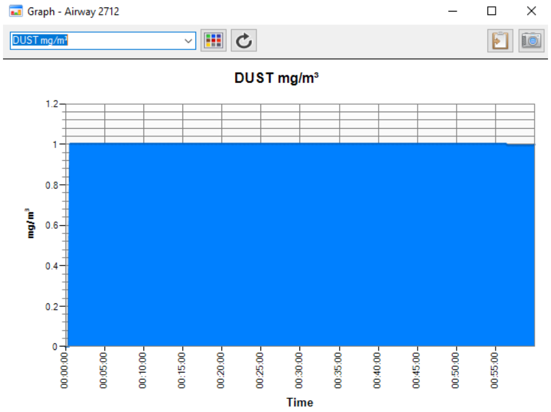


Figure 9. Dust concentration over Time (Shaft)

At Figure 9, the dust concentration quickly reached about 1 mg/m³ and stayed at that level for the whole monitoring period of almost one hour. The steady concentration shows a constant source of dust in the area, most likely because of ongoing activities such as moving raw materials, running machines, breaking up surfaces, or not having good enough ventilation and dust control systems in place.

4.2 Optimized Ventilation Simulation

In phase two, the ventilation system was increased; airflow was increased to 5 m³/s, 8.4 m³/s and then 10 m³/s, with air flows was increased by including auxiliary fan systems and altering resistance paths to flush potential contamination flows better. The commonly used standard of **0.06 m³/s per kW diesel engine** power for ventilation in underground mines is reported in mining guidelines across Australia, Canada, and South Africa, but its origin can be traced back to practices derived from historical U.S. Bureau of Mines testing (Halim, 2017).

So, according to standard, the values for airflow for Loader R2900 working in drilling horizon would be:

140.0 kW * 0.06 m³**/s = 8.4 m³/s**

Key setup parameters:

- Airflow: 5 m³/s, 8.4 m³/s and 10 m³/s

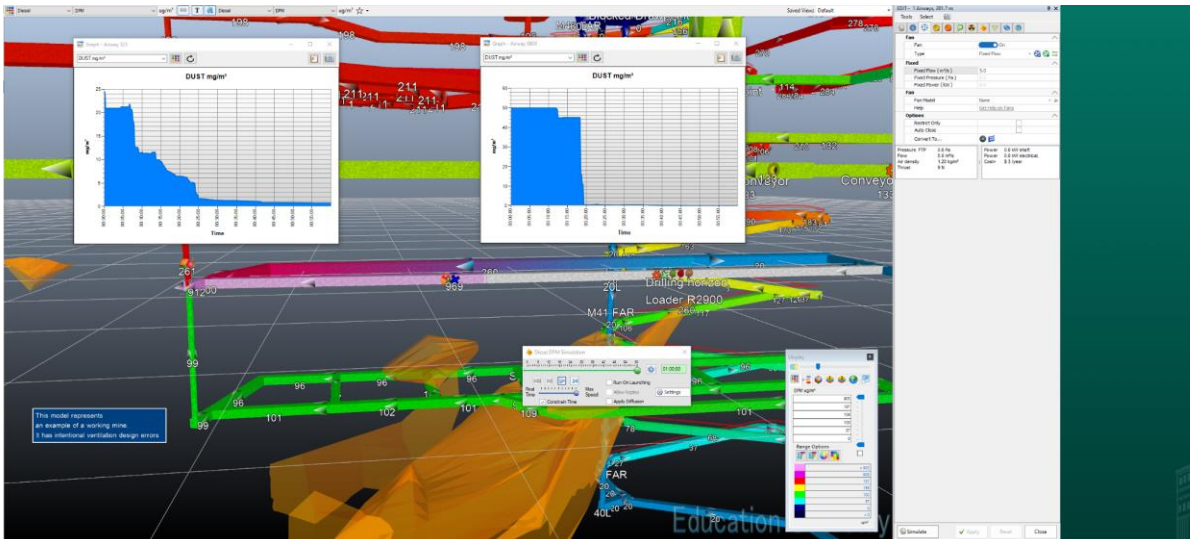
- Same vehicle operation and emission rate

- Same sensor locations

- Same parameters

After optimizing the airflow simulation illustrated that there were visual differences in contaminant dispersal and clearance. DPM concentrations reached much lower peaks and declined faster while dust values did increase.

With regards to 5 m³/s original level representing rupture typical airflow in more life-preserving parts of the mine with no dust suspended. Saarikoski et al. (2018) argue that the airflow in question is adequate for air circulation and DPM dilution without disturbing settled dust. On the other hand, 10 m³/s was chosen to depict increased ventilation strategies usually employed in highly polluted zones such as drilling or crushing stations because at this speed DPM dilution is effective, although it can cause dust resuspension (Barrett et al., 2019). Exploring the effect of the aforementioned velocities on the simulation provides insight into the relation of DPM dilution and dust resuspension, exposing the balance between controlling particulate emission and dust exposure.

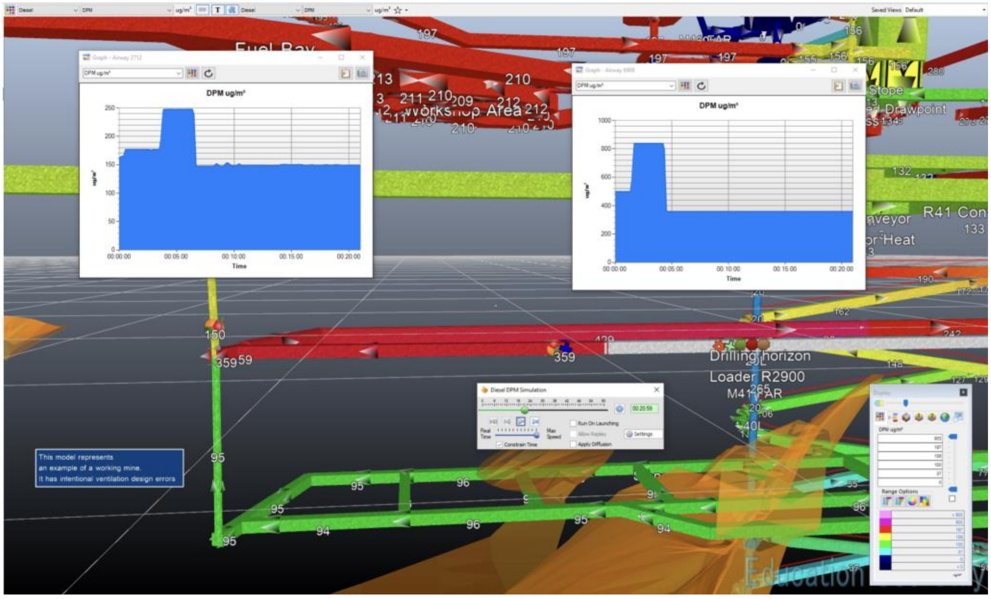


This model represents
an example of a working mine.
It has intentional ventilation design errors

Figure 10 – Optimized Dust Concentration with 5 m^3/s (Drift 1 and Shaft)

At Monitor 2, the dust concentration quickly shot up to around 25 mg/m³ and stayed at that high level for the first few minutes before beginning a sharp decline. Over the course of the next 25 minutes, the concentration steadily dropped and eventually leveled off close to zero, where it remained for the rest of the one-hour monitoring period. This sharp early drop suggests that either the dust-generating activity stopped, or the ventilation system effectively cleared the air after the initial buildup.

At Monitor 1, the dust concentration started even higher, at about 50 mg/m³, holding steady for roughly the first 20 minutes before it too sharply dropped off, hitting nearly zero and staying low for the rest of the hour. This pattern similarly suggests that a strong dust source was active early on, but something — likely the end of a dust-producing task or a sudden improvement in ventilation — allowed the concentration to quickly fall.

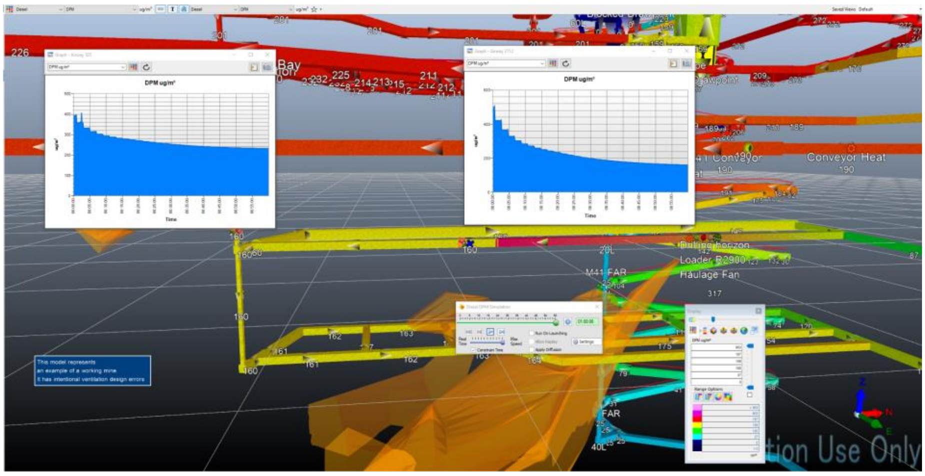


This model represents
an example of a working mine.
It has intentional ventilation design errors

Figure 11. Optimized DPM Concentration with 5 m3/s (Drift 1 and Shaft)

At Shaft, Diesel Particulate Matter (DPM) concentrations started at approximately 170 µg/m³ and ranged higher for the first few minutes, spiking briefly, then ending at about 140 µg/m³. The step-like profile shows an initial spike in diesel emissions or an initial piece of activity, which decreased and tapered off—likely as a result of either decreased machinery use, or ventilation, while still resulting in a concentration above permissible limits for prolonged exposure, indicating this area may therefore still pose a health hazard if ventilation is not further enforced.

At Drift 1, DPM levels began substantially higher around 500 µg/m³ and peaked to just below 800 µg/m³ shortly into the simulation. While the concentration decreased in value, overall the DPM concentration stabilized to around 350 µg/m³ above permissible limits. This pattern indicates an intense diesel activity or machinery use, which successfully overwhelmed the ventilation system. There was likely some dilution, but it appears there was little to no mixing of the DPM which is similar to poor dispersion, if any dispersion occurred. The DPM levels in the last portion of the simulation expresses significant air quality concerns for workers in this zone.



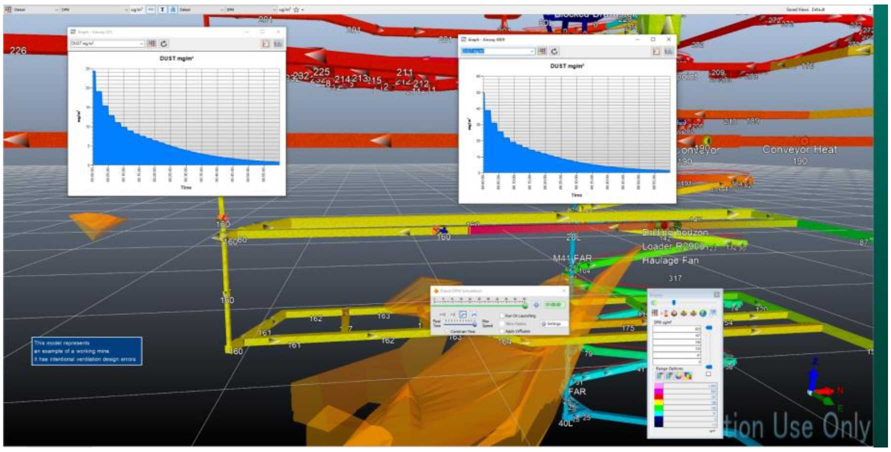
This model represents an example of a working mine. It has intentional ventilation design errors

Figure 12. – Optimized DPM Concentration with 8.4 m³/s (Drift 1 and Shaft)

Monitor 1 and 2

At Airway 325, the DPM (diesel particulate matter) concentration started high at around 400 µg/m³ but then steadily dropped over the first 10 minutes, continuing to slowly decrease across the one-hour monitoring period, leveling off at about 250 µg/m³. This downward trend suggests that either diesel activities were reduced over time, or that the ventilation system gradually cleared out the emissions, helping to lower the airborne DPM levels.

At Airway 2712, the DPM concentration was even higher at the start — peaking near 500 µg/m³ — but followed a similar downward curve, steadily dropping over the hour and settling near 200 µg/m³. This pattern also points to either a cutback in diesel equipment use or improving airflow that allowed pollutants to disperse or be vented out over time.

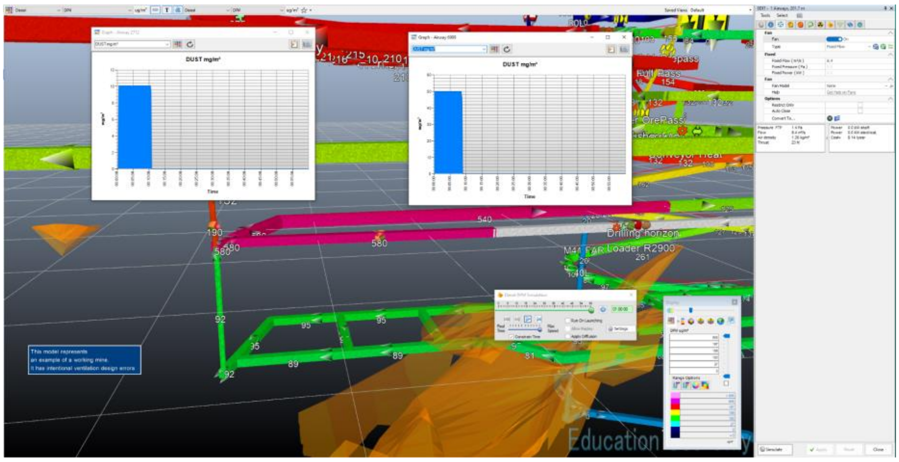


This model represents
an example of a working mine.
It has intentional ventilation design errors

Figure 13. Optimized Dust Concentration with 8.4 m³/s (Drift 1 and Shaft)

At Monitor 2 (Shaft) , the starting concentration of dust was approximately 25 mg/m³, which decreased significantly over the first 10 minutes and continued to drop throughout the monitoring period until it levelled off just above 2 mg/m³. This constant decrease could mean that there was a reduction in dust-producing activities, or that ventilation gradually improved over time by removing suspended particles, enhancing the air quality within that airway.

At Monitor 1 (Drift 1) , the situation was even more pronounced as the concentration of dust began at almost 50 mg/m³, following the same trend – dramatically declining within the first 15 minutes and then continuing to decrease throughout the hour and finishing under 5 mg/m³. This further demonstrates the ability to control dust sources while improving ventilation effectiveness in that area.



This model represents
an example of a working mine.
It has intentional ventilation design errors

Figure 14. Optimized Dust Concentration with 10 m3/s (Drift 1 and Shaft)

The second Monitor recorded a dust concentration level of around 10 mg/m³ almost instantly (in the first 2-3 minutes) of monitoring, but then dropped off to zero by approximately 10 minutes of monitoring and stayed at this level throughout the remainder of the 1-hour monitoring event. This rapid drop indicates that the ventilation system successfully removed the dust and kept the air clean.

The first Monitor recorded an even bigger dust concentration almost instantly. Dust levels for the first Monitor shot up to about 50 mg/m³ in the first 2-3 minutes. Similar to the second Monitor, dust levels were at zero by the 10-minute point, and stayed there for the rest of the monitoring period. This indicates that after a quick flash of dust getting released, the system took care of the dust fast, and there was no greater exposure moving forward.

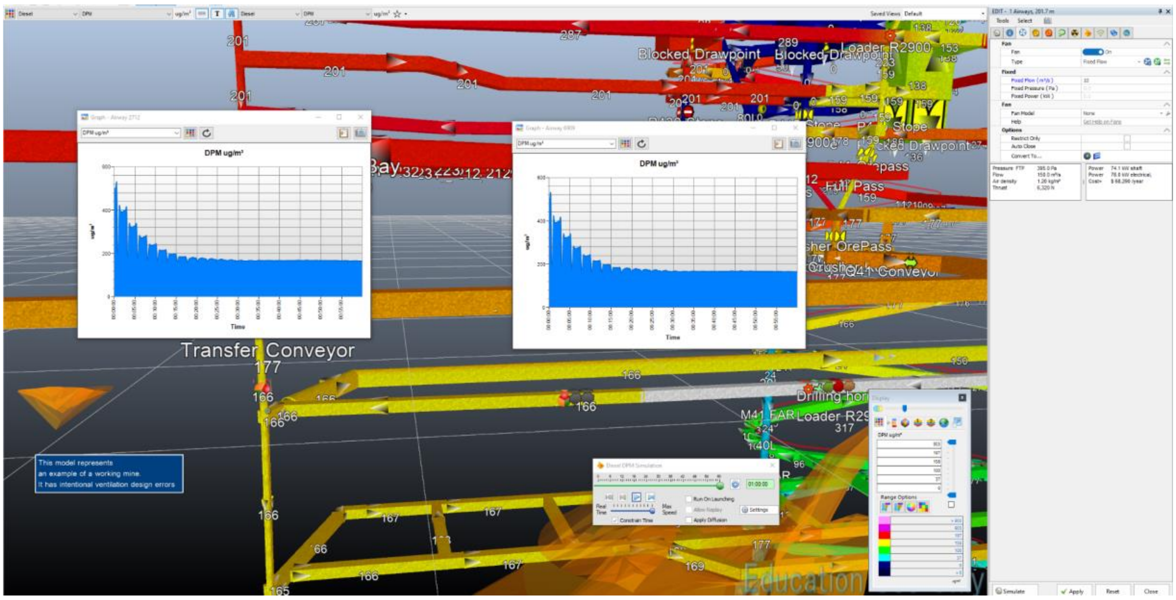

This model represents
an example of a working mine.
It has intentional ventilation design errors

Figure 15. Optimized DPM Concentration with 10 m3/s (Drift 1 and Shaft)

Shaft had a very high starting concentration of DPM just above 600 µg/m³ and consistently displayed a steep downward trajectory over time. By 10 minutes it was already below 300 µg/m³ and eventually stabilized around 160 µg/m³. This sort of profile indicates there was an initial strong diesel emission followed by either a decrease in activity from the source of emissions or improved ventiation to remove DPM from the unit. The steep initial drop indicates that the ventilation system was appending to clearing the area, but settling around 160 µg/m³ does indicate that air in the working area hasn't yet returned to completely diesel particulate free.

Drift 1's DPM profile showed a very similar trend. Starting near 500 µg/m³, like the neighbouring location, it resulted in a strong downward slope over time and stabilized at just short of 160 µg/m³ by the end of the one hour simulation. The progression between the two airways implied a common ventiliation pathway or common emission source. While it is like beneficial, even though the concentration is decaying over time, in terms of ideal levels, the thresholds of the final concentrations are still lower than the ideal levels even for short-term employee exposure. Further ventiation or source control are at Quebee's directed possible mitigated to prevent long-term potential exposure levels.

4.3 Comparative Analysis

Table 2. – DPM and Dust Concentrations: Initial vs Optimized

Airflow (m^3/s)	**DPM Peak (µg/m^3)**	**DPM Stabilized (µg/m^3)**	**Dust Peak (mg/m^3)**	**Dust Stabilized (mg/m^3)**
Initial (0.5 m^3/s)	500	500	50	50
5 m^3/s	500	350	50	4
8.4m^3/s	500	220	50	2
10 m^3/s	500	160	50	1

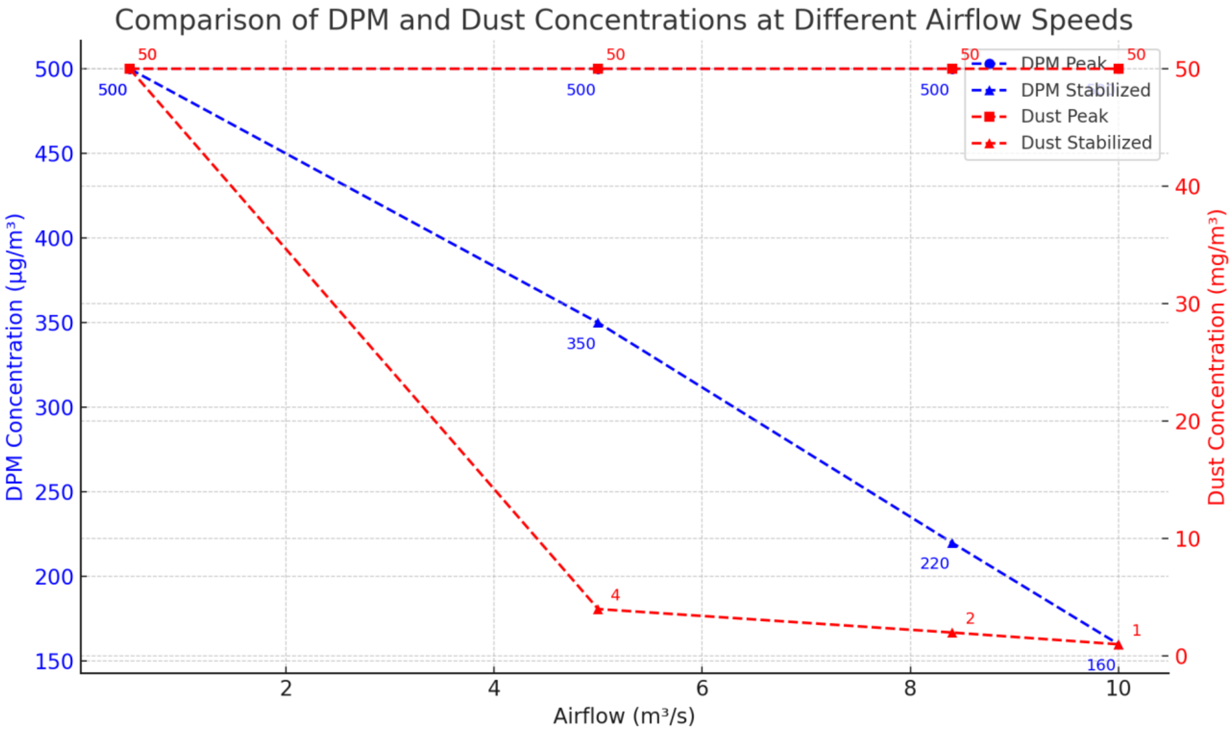


Figure 14. Comparison of DPM and Dust Concentrations over Time at Different Airflow Speeds

From the table and graph I can make a comparison between airflow values like this:

Performance at 5 m³/s

At 5 m³/s, the DPM peak concentration held steady at 500 µg/m³ and the stabilized level improved to 350 µg/m³, which was a modest improvement but not an extreme improvement. Dust levels improved more significantly from 50 mg/m³ to 4 mg/m³. While 5 m³/s airflow improved the DPM concentration, it did not really offer significant long-term gains. Ultimately, five m³/s was not a drastic improvement compared to the greater flow rates.

Airflow at 8.4 m³/s (Industry Calculated Value)

At 8.4 m³/s, again the DPM peak concentration held steady at 500 µg/m³, but the stabilized level improved to 220 µg/m³, less than half of the original concentration. Dust levels stabilized at 2 mg/m³ and were much improved than the 5 m³/s levels, which demonstrated more effective particulate removal. This situation also showed greater consistency in reducing particulates than 5 m³/s, which indicated that airflow in this range allowed for a reasonable amount of dilution while limiting potential turbulence. While it was an improvement in air quality overall, it did not outperform 10 m³/s.

Performance at 10 m³/s

DPM peaks consistently remained at 500 µg/m³, however the stabilized DPM exposure was measured at a much lower concentration at 160 µg/m³, the lowest recorded stabilized concentration of all the different scenarios, representing a 64% reduction of the DPM concentration of the scenario with the second highest level of DPM (220 µg/m³) allowed at an airflow rate of 8.4 m³/s. Dust concentrations decreased to 1 mg/m³, the lowest recorded value, an indication that airborne particulates were essentially cleared. This scenario exhibited both the most rapid and most absolute improvement in both DPM and dust concentrations, reinforcing the fact that higher airflow rates result in significantly more effective dilution of contaminants and reduce the likelihood of them re-accumulating. Therefore, in this study, 10 m³/s demonstrated optimum performance of both with immediate improvement and longer term improvement of air quality.

Conclusions and Recommendations

- The stabilized DPM concentration at 10 m³/s was 160 µg/m³, the lowest sum of all scenarios. The DPM concentration was reduced from 250 µg/m³ at 8.4 m³/s and 350 µg/m³ at 5 m³/s, making the overall performance from a DPM reduction much better as well.
- The dust concentration also dropped the most in this scenario when comparing all scenarios, with the highest magnitude of change occurring in the first 10 minutes of ventilation. The dust concentrations dropped from 50 mg/m³ to 1 mg/m³ at maximum flow rates of 10 m³/s, from 2 mg/m³ at 8.4 m³/s, and from 4 mg/m³ at 5 m³/s, therefore higher airflow was far more effective clearing dust from the environment, or did in this case allow for a near complete reduction of airborne particulates.
- 10m³/s airflow provided the most rapid and most complete clearance of airborne particulates, allowing for an acceptable standard of air quality throughout both monitored zones with zero delay. The airflow of 10 m³/s provided for rapid and sustained improvement in ventilation, so was the best option for air quality management in dangerous underground locality.

Where 5 m³/s allowed for moderate clearance of dust and little magnitude of reduction of DPM, and 8.4 m³/s allowed for a more balanced/holistic performance, the speed and consistency of contaminant clearing at 10 m³/s is of paramount importance in high-diesel emission zones, like drilling bumps. **Characteristically, 10 m³/s airflow presents the optimal configuration of efficient and effective low DPM and dust potential ion for ensuring safe breathable air quality in underground conditions, and chiefly in periods of high intensity diesel activity.** Even if this requires more air power for ventilation, the perceived human health wellness effect and immediate return of air quality was warranted and beneficial, and certainly in perhaps the most consequential occurrence of a mining activity.

Auxiliary Fans: The use of auxiliary fans in heavily polluted areas improved airflow in zones where natural ventilation did not reach. Auxiliary fans are appropriate for targeted DPM dilution ventilation, which is the case in some parts of the mine where DPM is mitigated while other areas are protected from contaminant buildups. As Ventsim Manual (2022) explains, auxiliary fans are useful for localized ventilation improvement.

Future systems could have a localized ventilation system with options to divert the airflow. If risk is imminent, auxiliary fans or local extraction systems could help reduce dust resuspension, while also diluting the concentration of DPM. " (Saarikoski et al., 2018; Barrett et al., 2019).

Discussion

5. Limitations of the Simulation Approach

Sources of diesel machinery emissions, such as the Caterpillar R2900 unit, were manually obtained using established predetermined industry benchmarks, and general operational data was used in scan mode, but the benchmarks did not model the optionality realism of emission profiles, which would be limited by fuel type, engine load and specific machinery characteristics. During idling or low power operation, emissions could potentially bias concentrations either positively or negatively and are non-negligible. (Noll et al 2007)

In modeling, the environmental parameters were constant. The ventilation flows were modeled under uniform assumptions of temperature, pressure, and humidity, and did not account for local thermal stratification, or seasonal variation. The model also did not account for environmental gradients that occur in the real-world setting, which can affect airflow, and buoyant behavior of the particles. (Kimbal et al., 2012)

Operational dynamics represent another limitation. Issues with worker behavior, equipment movement, traffic, random interruptions (fan failure or closure events), etc, which can have a strong impact on localised airflow and pollutant characteristics, were excluded from the model. This is also significant in confined or intersecting drifts, and the model included a more stable and idealised view of aerosol transport, which may not always reflect actual conditions (Noll et al. 2007).

The model run time was improved by simplifying mine drifts to completely regular shapes with uniform dimensions, omitting structural complexities such as cable, ventilation curtains, supports, and alcoves. These smaller structures may better promote uneven airflow, and accumulation of airborne dust within the drift. This study has its limitations, which indicates caution in using the study simulation data for mine ventilation planning. The study was able to demonstrate the influence of ventilation on DPM and dust concentration.

5.1 Conclusions and Recommendations

1. This research project was aimed to optimize DPM and dust concentration levels in an underground mining tunnel through modifying the ventilation settings using the VentSim Design software program. It began with initial airflow data of 0.5 m^3/s and analysis of three airflow modification levels of 5.0 m^3/s, 8.4 m^3/s and 10.0 m^3/s. With the first forecasting of the air quality conditions (in terms of contaminant dilution and concentration reduction) increasing the airflow from the original 0.5 to 5.0, to 8.4, then 10.0 m^3/s the study demonstrated there to be a threshold of improving DPM and ensuring good air quality.

2. Air quality from a dust and DPM level consideration could be considered to be reasonably diluted even at the industry-standard airflow of 0.06 m^3/s per kW and 8.4 m^3/s it was not as abrupt as in that scenario of the 10.0 m^3/s was significantly better in performance. Indeed, the 10.0 m^3/s airflow would demonstrate much better speed and reduction of contaminants levels versus other airflow settings.

3. The DPM levels measured in a span of 10 minutes had a concentration of approximately 160 $\mu g/m^3$ at airflows of 10.0 m^3/s, when compared to DPM concentration levels of 220 $\mu g/m^3$ at airflow at 8.4 m^3/s, and at 5 m^3/s the saturated concentration level of 350 $\mu g/m^3$.

4. From a dust concentration accounts the dust density levels decreased from a concentration level, ISP a to around 50 mg/m^3 in a period of 10-minute exposure monitoring with airflows of 10.0 m^3/s when comparing with airflows of 5 m^3/s and 8.4 m^3/s, and ultimately, the 10.0 m^3/s in air low density levels had decreased to nearly 1 mg/m^3 within 10 minutes of

measuring air quality, with no build of the dust at below a minute, and no 25 minutes or that concentrated dust permeate by a five minute delay in the other two studying airflows.

In summary, the data indicate that the 10.0 m³/s airflow level sampling conditions provided the most rapid reduction in pure form of DPM and dust concentration levels and improved the amount of preferential air quality, providing improvements in speed and amount preceding the other spanning ventilation settings of air flow.

Because air flow was purged rapidly, these results testify to the improvements made concerning energy consumption, thereby achieving optimal performance without excess power usage. These findings demonstrate that applying airflow rates aligned with diesel engine power is not only recommended, it practically achieves the fastest and most durable improvements in both DPM and dust levels.

In reference to the conclusions made, I recommend the following:

✅For the Loader R2900 and other similar diesel equipment, use approximately 10 m³/s of airflow after those pieces of equipment have operated to reduce DPM and dust.

✅Add additional fans, to take care of areas where DPM is generated, to closely manage problem areas without adding more airflow to the entire mine.

✅Install real-time in-situ air quality monitors that measure the particulate levels of DPM and dust, and allow for more timely adjustments of airflow.

✅Utilize additional dust-lowering techniques such as water sprays or dust suppressants where the potential exists for strong airflow to disturb settled dust.

In conclusion, this research contributes to overall knowledge of clean mine air and demonstrates the benefits of a simulation tool or construct that can be used to plan better ventilation systems and ventilation practices. Safety and health practices will continue to be improved with the continued audits and updates to the ventilation planning simulation tools at mine sites, which will lead to better decisions affecting worker health and safety underground.

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