



Characterisation of emission and exposure to diesel engine exhaust from trackless mobile machinery in underground South African Platinum Mines: *Evaluating strategies to prevent and control exposure*

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Executive summary

Background: Mining remains one of the major economic drivers in South Africa, as is evident through continued focus on long-term investments in mining and the mechanisation of mining operations. Mechanisation uses diesel-powered machinery; such machinery offers greater versatility than electric and battery-operated vehicles due to their ability to cover greater distances and move between different working sections (1). Diesel powered machines are most preferred because of their high energy efficiency and low carbon monoxide and carbon dioxide emissions compared to gasoline equipment (2). Using diesel-powered machines in mechanised mining has introduced a new risk to mine workers working in confined spaces underground.

Diesel engine exhaust (DEE) can increase significantly due to wear or breakdown of the engine components and after-treatment systems. The impact on emissions varies depending on the engine type, age, and state of wear and tear (3). Significant evidence demonstrates a correlation between DEE exposure and respiratory outcomes in mine workers.

DEE is a known carcinogen. In 2012, the International Agency for Research on Cancer (IARC) classified DEE as being carcinogenic to humans (class I) when inhaled, based on sufficient evidence that exposure is associated with an increased risk for lung cancer (4). There has been an incredible drive to manage diesel Particulate matter (DPM) in the South African mining industry (SAMI). The approach, however, has been focused on monitoring personal exposure to DPM rather than a multifaceted approach that includes eliminating or reducing the pollutant at the source. Efforts should be made to ensure that management plans for engineered solutions and risk-based approaches are in place when monitoring DPM (5). As a result, research in the mining domain has focused on developing integrated control strategies/solutions to prevent exposure to diesel engine exhaust.

South Africa shares the same concern with other countries regarding the DPM challenges in mining operations. The South African legal framework requires the employer to conduct a risk assessment and implement measures to prevent employees from overexposure to harmful airborne pollutants (MHSA 1996). Therefore, without local guidelines and regulations, SAMI can use the available scientific knowledge to control the exposure of DPM to employees and to ensure continuous monitoring of employees while working at the mines.

Currently, no specific systems guide sets standards or limits for personal or occupational exposure or tailpipe emissions of DPM (6,7). Further, even though enough knowledge is

available from international and local sources, DPM regulation still needs to be implemented in SAMI.

The Occupational Cancer Research Centre Report published in 2017 presented different control strategies for DPM following the hierarchy of control principles (8). These ranged from the proactive (most effective) to reactive (less effective) controls and included the following controls: elimination using alternative energy such as electric or battery-powered machines, substitution such as replacing, repowering, or engine rebuilds, and this would typically include retrofitting the engines with engine after-treatment systems; Engineering controls which may include retrofitting the engines with after-treatment technologies, improving general ventilation systems, idling technologies, installation of protective cabs; Administrative controls which may include preventative maintenance, idling policies, operator training and planned schedule for the site such as planning the number of machines required to operate in a working place; and lastly the use of personal protective equipment such as respirators. These controls can be implemented in a multifaceted approach to reduce or prevent employees from being overly exposed (3,8,9).

Diesel emission is a complex mixture and may require multiple control strategies to minimise employee exposure. In the study conducted by Bugarski et al, 2009, they highlighted different monitoring and control strategies ranging from emissions monitoring, including undiluted emissions measurements, i.e., Both ‘tailpipe output’ and ‘engine out’ (upstream of after-treatment systems), and the installation of after-treatment strategies and higher tier standard engine emissions. The control strategies can help identify and distinguish between engine maintenance issues and emission control device failures and assist in estimating ventilation requirements (10). In addition, in a study by Hines in 2019, significant improvements were achieved in reducing tailpipe emissions (reduction at source) by implementing an emission-based maintenance (EBM) program. This has resulted in a reduction of Carbon Monoxide (CO) by more than 80% and DPM by more than 47% on personal exposure, showing the direct impact the EBM has on reducing exposure of DPM to employees working underground. The study successfully reduced tailpipe emissions by introducing the EBM program at the mines. Further, fuel usage was also reduced by 7-20%, showing that when machines are well maintained, there are improvements in efficiencies and even utilisation and availability of machines for production (11).

Objective: The overarching aim of the research project was to determine the characteristics of diesel engine exhaust emissions at the source (aerodynamic size fractions) and evaluate how maintenance, maintenance plus installation of diesel particulate filters (DPF), and ventilation will impact the levels of DEE at the source and in the workplace.

Methods: A quantitative, quasi-experimental study, designed with an intervention component, was conducted in two Platinum underground mines in South Africa. DEE was measured at the source, and DPM was personally exposed to employees. DPM dispersion modelling was conducted underground, and different control strategies were evaluated to determine their role in reducing the pollutant underground.

Results: The concentration of median particles significantly decreased post the interventions, achieving an efficacy of 90-96% and 20-40% (p-value=0.001) for the machines that underwent maintenance plus installation of the DPF and machines that underwent maintenance only, respectively. Most particles emitted were in the ultrafine aerodynamic range, with a diameter between $\geq 0.01 < 0.1 \mu\text{m}$ and an aerodynamic fine size of $\geq 0.1 < 1 \mu\text{m}$.

Conclusion: A combination of control strategies (maintenance, retrofitting of machines with DPF, and ventilation) has shown great potential to reduce DEE in underground mines. Therefore, focused effort is required to implement integrated strategies to prevent or minimise exposure to DEE. Future studies to link dispersion models with real-time monitors are recommended to improve DEE's risk-based management.

Declaration

I, AMUKELANI PORTIA MANYIKE-MODAU, declare this thesis in my original work (except where acknowledgments indicate otherwise). It is submitted for the degree of PHD in Public Health at the University of Witwatersrand, Johannesburg. It has yet to be submitted for any other degree or examination at any other University. I empower the University to reproduce the research contents in any manner whatsoever.

A handwritten signature in black ink, appearing to read 'AMUKELANI PORTIA MANYIKE-MODAU', followed by a horizontal line and the letters 'ke'.

Signature of Candidate

Day 30 May 2024 in Johannesburg

Dedication

I want to thank God, the Almighty, who carried me through this exciting yet challenging journey to completion. His Grace is indeed sufficient for all of us, and his Power is made perfect in our weakness, as said in 2 Corinthians 12:9.

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List of Publications

1. Lebaka L, Manyike-Modau A, Brouwer D. Effectiveness of retrofitted diesel particulate filters on diesel particulate emissions: a small-scale intervention study. *Occup Health Southern Afr.* 2023; 29(1)1-7.

List of Presentations

1. **Burden of Air Pollution from Diesel Exhaust Emissions (DEE) in underground South African Mines:** *Implementing a risk-based monitoring system to manage over-exposure. Health and Safety Symposium, Wits University; 24 February 2023.*
2. **Characterisation of emission and exposure to diesel engine exhaust from trackless mobile machinery in underground South African Platinum Mines:** *Evaluating strategies to prevent and control exposure. Wits Research Day, Wits University; 14 September 2023.*
3. **Characterisation of emission and exposure to diesel engine exhaust from trackless mobile machinery in underground South African Platinum Mines:** *Evaluating strategies to prevent and control exposure. Limpopo Tripartite Eastern Limb; 28 September 2023.*

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Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AIOH	Australian Institute of Occupational Hygienists
AM	Arithmetic Mean
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CO	Carbon Monoxide
CO₂	Carbon Dioxide
CRT	Continuous Generation Technology
DE	Diesel Exhaust
DI	Direct Injection
DEE	Diesel Engine Exhaust
DEF	Diesel Exhaust Fluid
DEP	Diesel Exhaust Particle
DEEP	Diesel Emissions Evaluations Program
DFE	Disposable Filter Element
DMRE	Department of Minerals Resource and Energy
DPFs	Diesel Particulate Filters
DPM	Diesel Particulate Matter
DOC	Diesel Oxidation Catalyst
DOCC	Diesel Oxidations Catalytic Convectors
DS	Dynamic State
EC	Elemental Carbon
EFD	Experimental Fluid Dynamics
EGR	Exhaust Gas Reticulation
EPA	Environmental Protection Agency
ER	Emission Rate
GM	Geometric Mean
GSD	Geometric Standard Deviation
HC	Hydrocarbons
HoC	Hierarchy of Controls
IC	Internal Combustion

IARC	International Agency for Research on Cancer
kW	Kilowatt
LHD	Load, Haul, Dump
MHSA	Mine Health and Safety Administration
MHSC	Mine Health and Safety Council
MSIR	Mine Safety Inspection Regulation
M³	meters cubed
m³/s	meters cubed per second
m³/s/kW	meters cubed per second per rated kilowatt
mg/m³	milligram/cubic meter
N	Number
Nm	Nanometre
NIOSH	National Institute for Occupational Safety and Health
NO	Nitric Oxide
NO₂	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
OC	Organic Carbon
OEL	Occupational Exposure Limit
OEM	Original Equipment Manufacturer
PM	Particulate Matter
PNC	Particle Number Concentration
PMC	Particle Mass Concentration
PMO	Planned maintenance order
PPM	parts per million
SAMI	South African Mining Industry
SD	Standard Deviation
SOF	Soluble Organic Matter
SANAS	South African National Accreditation System
SS	Steady state
TMM	Trackless Mobile Machinery
TDC	Top dead centre
TLV	Threshold Limit Values
TWA	Time Weighted Average
RCTM	Real-time condition monitoring

STEL	Short Term Exposure Limit
UG	Underground
µg	Microgram
µm	micrometre
ULSD	Ultralow Sulfur Diesel

Thesis layout

The thesis structure is as follows: Chapter 1 details the introduction to the study, a high-level summary, the research problem statement, study objectives, and objectives. Chapters 2-5 provide pertinent details from the literature review and objective findings presented as a monograph. Chapter 6 concludes the study.

Chapter 1: Introduces diesel engine exhaust as a health concern in underground Platinum mines in South Africa, where mechanised mining design entails diesel-powered equipment to load and haul the blasted ore to the surface/underground. A problem statement is formulated from the evidence presented, which includes setting out the study's aim, objectives, and hypothesis. Justification of the study is given, and the general approach to the study is outlined in the form of a conceptual framework.

Chapter 2: The findings from the literature review are presented. Diesel engine exhaust and their constituents are defined, including detailed particle composition where particle number concentration, mass concentration, and size distribution are reviewed. Monitoring methods used in the mining industry are reviewed, and surrogate markers employed to assess exposure to DPM, such as Elemental carbon (EC), are reviewed. Flue gasses Exhaust gasses are evaluated, including CO, NO, NO₂, and NO_x. Finally, the mine ventilation requirements are reviewed and assessed in line with those of the mine under study. The information provided in this section helps understand the impact of the current situation, providing essential criteria for improving emission control strategies for diesel engine exhaust.

Chapter 3: Presents the sampling and analysis methodology for the stated objectives. Characterisation of the study population is defined, followed by the sampling methodology for the point source tailpipe emissions. This section also provides the statistical analysis methods employed, formulae relating to the environment, procedures relating to environmental DEE loads (the process of quantifying the level of stress by level of pollutant concentration in the environment when DEE is released upon the underground environment), and cost evaluation formulae for the interventions.

Chapter 4: The chapter presents the results and findings per objective. Comparative results are given for the different interventions. Tailpipe emissions are presented as total particle number concentration and mass concentration. Results are presented from the pre-intervention and post-intervention, and the efficacy calculations based on the type of intervention are also shown. In addition, personal sampling results before and after the intervention are compared.

The DPM dispersion and resulting workplace concentrations are estimated by dispersion modelling, and the cost economics of implementing control strategies, including maintenance, retrofitted diesel particulate filters, and the effects of ventilation to reduce the pollutants, are compared.

Chapter 5: This chapter provides a summary of the study's main findings. A synthesis of the results is presented logically to demonstrate the validity of the hypothesis. The originality and significance of the findings are discussed, together with recommendations for further investigations to address outstanding issues identified within the study. Study limitations are outlined, policy is recommended, and contributions to the scientific community are presented.

Chapter 6: This chapter concludes the study piece of work based on the set objectives.

CHAPTER 1 - INTRODUCTION

This chapter introduces an overview of the characteristics of diesel engine exhaust, their link to underground mine workers' health, and the challenges of using diesel-powered machines and mining mechanisation. The following topics are introduced and described in detail throughout the section: Mining methods, diesel engine exhaust, related legislation, exposure monitoring, and ventilation strategies, including technology. The problem statement and the domain of the study are specified, and the scope and the specific research objectives are presented, together with the justification of the study.

1. Introduction

1.1 Mining

Mining remains one of the major economic drivers in South Africa, resulting in a continual focus on long-term investments in mining and the mechanisation of mining operations. Traditional conventional mining, which employed winches and locomotives to clean and convey ore from mining faces to processing plants on the surface, is becoming less common. Instead, there is a growing trend towards the mechanisation of mining operations as a more economically viable solution. However, the shift towards industrialisation also presents an inherent burden of introducing hazardous underground environmental pollution from the exhaust emissions of machines employed.

Mechanisation makes use of diesel-powered machinery. Such machinery offers greater versatility than electric and battery-operated vehicles due to their ability to cover greater distances and move between different working sections(1). Diesel-powered machines are most preferred because of their high energy efficiency and low carbon dioxide (CO₂) emissions, ease of maintenance, and durability compared to gasoline equipment (2). However, they are a significant source of underground pollution, as diesel engines emit diesel combustion products containing toxic gases and particulate matter (12,13).

Particulate Matter (PM) is a mixture of solid and liquid particles suspended in the air. Particulate Matter health indicators refer to the mass concentration of particles with aerodynamic D₅₀ equal to 10 µm (PM₁₀), 2.5 µm (PM_{2.5}), and 1.0 µm (PM₁). PM₁ is called fine particulate and comprises ultrafine particles with a diameter of less than 0.1 µm. These particles are liberated into the air streams and are a source of exposure to employees working underground (14).

The major contributors to the total particle mass emitted by diesel engines include elemental carbon (EC), organic carbon (OC), inorganic ions such as sulfates, nitrates, ammonia, sodium, chloride ions, and trace metallic compounds (1). EC, and OC emissions make up what is known as total carbon (TC). It is the most significant fraction of aerosols emitted by diesel engines, typically accounting for 70–90% of DPM. On average, elemental carbon comprises 50–70% of TC and greater than 45% of ‘total engine-out PM emissions. In contrast, the engine-out organic carbon makes up between 10 and 80% of total carbon (1).

The EC fraction of DPM is a product of the pyrolysis of the fuel and the lubricating oil in the combustion chamber. The OC fraction of exhaust emissions from a diesel engine is a complex mixture of burned and unburned lubricating oil and fuel compounds (1). Additionally, DPM is a highly dynamic physical and chemical system that exhibits extreme spatial and temporal dependency in composition (15).

DPM particles are tiny and are subdivided into three size categories: nano-particles or ultrafine particles less than 100 nm in diameter, and fine particles less than 2.5 μm in diameter (4,16). PM₁₀ and PM_{2.5} include particles that are small enough to penetrate the thoracic region of the respiratory system. The health effects of inhalable PM due to exposure over both short (hours, days) and long term (months, years) include respiratory and cardiovascular morbidity, aggravation of asthma, respiratory symptoms, mortality from cardiovascular and respiratory diseases, and lung cancer (4).

The composition of DPM is influenced by several factors, such as fuel type, engine-rated power, the level of dilution and its subsequent atmospheric processing after being emitted from the tailpipe, the engine operating conditions (e.g., speed/load, injection timing, and strategy), the presence of after-treatment devices (such as a diesel catalytic convertors or particulate filter), engine maintenance status and the type of fuel and lubricants used (1,12,17). When DPM is emitted into the environment, workers may be exposed to the pollutants during their shifts, making them prone to short and long-term health effects.

In addition to DPM and other diesel exhaust (DEE) constituents, the underground environment consists of several airborne pollutants from mining activities, such as dust and gases. The risk of developing disease from exposure to mining activities depends on the degree of inhaled pollutants, particulate size, ventilation, duration of exposure, and individual physiological factors (18). Exposure to DE in an underground occupational setting is of great concern because of the underground mining design. Some areas are more confined and require auxiliary fans

for proper ventilation to dilute and remove the particulate matter (19). Underground mine workers are exposed to some of the highest levels of diesel exhaust since they work alongside diesel-powered equipment in confined spaces (20,21).

Ore cleaning is a critical process in the mining cycle. Trackless mobile machinery is scheduled daily to load and haul the ore from the working phases to the conveyor belts. To effectively manage the diesel-driven Trackless Mobile Machinery (TMM), the mine needs to have established a planned maintenance program for the TMM fleet. This will ensure that the machines are serviced at certain intervals, and critical spares are always held in-store, contributing to an acceptable operational availability of equipment of 80% at any given shift. Proper engine maintenance programs contribute to managing engine health, reducing breakdowns, and increasing employee productivity (11,22).

Diesel emissions can increase significantly due to wear or breakdown of the engine components of after-treatment systems. The impact on emissions will vary depending on the engine type and the state of wear and tear. One report for the Diesel Emissions Evaluation Program (DEEP) found that in 7 test situations, depending on the engine design technology and condition, maintenance decreased particulate matter emissions by up to 55% of particulate matter and 65% of gases (13,23). TMMs are designed with specific engine requirements, influencing the inherent risk of generating diesel emissions at the workplace. Most maintenance programs focus on the engine's mechanical functionality and are not emission-based.

Monitoring workplace pollution forms the basis of Occupational Hygiene programs at the mine. It is primarily implemented to characterise occupational health hazard risks, assess and evaluate their health effects, and develop exposure monitoring strategies. This includes measuring workplace and personal exposures and linkage to medical surveillance for potentially exposed employees. Although South Africa does not have regulated exposure limits for DPM, a personal sampling strategy has been partially implemented using the NIOSH 5040 methodology in most mines. The personal samples are sent to the laboratories for analysis. However, the results detailing the degree of exposure are not readily available, as highlighted in previous studies, raising concern about the effectiveness of this approach in preventing exposure (24,25).

The need for regulated standards in South Africa limits the overall management of DPM in South African mines. Some mines in South Africa have adopted the international best practice regarding ventilation design parameters for DPM and the Occupational exposure limit (OEL)

for EC and TC, depending on the company's response to risk assessment or risk appetite. Further to the adoption of OEL, another critical aspect of mine and ventilation design to improve workplace conditions would be incorporating the ventilation design criteria for DPM, having an integrated risk-based approach for preventative control strategies at source and effective risk-based monitoring and response/management strategies.

Over and above reducing DPM/DEE at the source and personal exposure monitoring of DPM in underground mines, effective workplace exposure management requires critical input parameters during the planning and design phase of the mining operations. This allows dilution and effective removal of pollutants once liberated in an underground environment. Ventilation parameters, for example, are used to determine the total ventilation infrastructure requirements, dilute airborne pollutants, and regulate heat underground (26). Through general ventilation, the reduction in diesel emission concentration in the mine atmosphere can be achieved using clean air directed to the working area. Increasing airflow can be achieved by using higher horsepower fans, adding more fans in parallel, and adding new ventilation shafts or airways (13). The design parameters dictate the quantity of airflow required to effectively ventilate a workplace and the number of machines needed to load and haul in a specific workplace to effectively dilute airborne pollutants. A well-designed and properly implemented ventilation system provides beneficial physiological and psychological side effects that enhance employee safety, comfort, health, and morale. Determining the quantity of air required to circulate to meet all health and safety standards underground is essential in planning a ventilation system during the design phase. Once the air volume requirement has been calculated, the correct shaft size, number of airways, and fans can be determined (27).

1.2 Problem statement and justification of the study

Traditionally, mining uses locomotives to clean the blasted ore from the face to the conveyor belts (28). The modern trackless mechanising mining method has introduced diesel-powered machines, generating diesel engine exhaust that presents hazardous conditions to the working environment. Exposure to DEE in underground occupational settings is of great concern due to the nature of the confined space underground, resulting in the possibility that it takes longer for the pollutant (DEE) to clear within the working environment. Other areas, such as development headings, require auxiliary ventilating fans to dilute workplace airborne pollutants optimally (13).

DEE is a known carcinogen. In 2012, the International Agency for Research on Cancer (IARC) classified DEE as being carcinogenic to humans (class I) when inhaled, based on sufficient evidence that exposure is associated with an increased risk for lung cancer (4,29). There has been an incredible drive to manage DPM at the mines. The approach, however, has been to monitor the effectiveness of preventative action. Efforts should be made to ensure that management plans for engineered solutions and risk-based approaches are in place when monitoring DPM to focus on eliminating or reducing the pollutant at source (5).

Managing DEE from an engineering perspective is critical during the mine design feasibility studies and setting off the mine. The planning process also considers the correct selection of the tramming machines, such as the size of machines, design tier, and size specifications, playing a role in determining the total exposure to DPM underground. The input parameters for designing a ventilation system aim to ensure that the correct air volumes are provided for the mine's needs (30). This includes the capacity for intake and return airways and haulage design to ensure that air volumes are delivered to where people work and travel. The goal is to provide the required air volumes to maintain safe and healthy working conditions. Although the design criteria consider the heat load, fire load, and gas re-entry requirements, a gap has been identified regarding the design criteria for airborne pollutants, including that of DPM.

When planning for ventilation requirements in mechanised mines, the ventilation design input must consider the DPM dilution factor by using the ventilation airflow rate of $0.06 \text{ m}^3/\text{s}/\text{kW}$ where diesel machines operate. This airflow rate ensures proper dilution and pollution removal from the workplace during the load and haul operation. In SAMI, clear guidance and regulations must be enforced for ventilation dilution rates where diesel-powered machines are used. Further, many mines use heat load factors to determine ventilation requirements, and this could underestimate the risk by having inadequate DPM dilution and effectiveness to remove workplace DPM, especially in shallow cooler mines where the heat load is very low. The Australia Work Health and Safety (WHS) Mines Act requires the volume of air in each place where a diesel engine operates to have a ventilating airflow rate factor of not less than $0.06 \text{ m}^3/\text{s}$ for each kilowatt of maximum output capacity of the engine, or $3.5 \text{ m}^3/\text{s}$ (1). The Ontario Occupational Health and Safety Act regulation also requires mechanical ventilation in underground mines to provide an airflow dilution factor of at least $0.06 \text{ m}^3/\text{s}$ per kilowatt of power of the diesel equipment operating in the mine (1).

As the introduction alluded, the most hazardous part of DEE is particulate matter, of which EC is the marker. Therefore, the particle size and distribution must be fully understood to address the pollution at the source. Previous studies have shown a very strong correlation between real-time monitoring of EC using the ICx monitor (Airtec) and personal sampling of EC using the NIOSH 5040 gravimetric methods. This requires some validation in the underground environment against other evaluated methods (31).

EC and OC emissions make up the most significant fraction of aerosols emitted by diesel engines. TC generally makes up about 70–90% of DPM. On average, elemental carbon comprises 50-70% of TC and greater than 45% of ‘total engine-out emissions’ (1,32).

Currently, the monitoring system in the underground mines for the EC uses personal gravimetric sampling (33). However, this method has some limitations, as it only gives daily averages, whereas exposure profile patterns over time can only be achieved through real-time monitoring systems. Computational Fluid Dynamics (CFD) and Ventilation dynamic simulation through software have shown that if CFD and ventilation simulations are applied correctly, proactive decisions can be taken to manage the immediate risk (34). For this study, a fluid dynamic simulation was conducted to predict the cumulative concentration of diesel engine exhaust in the workplace. This was done to formulate recommendations to implement a risk-based method to identify, monitor, and respond to DPM exposure to prevent and reduce exposure for mine workers.

The option to use a network ventilation fluid dynamics tool such as (VentSim) was possible, as the mine under study already has an established system and ventilation network for designing and planning mine ventilation, which includes design predictions for airflow, heat, gases, and fires. VentSim Design is a complete integrated mine and tunnel ventilation software package that enables the design and testing of ventilation circuits, including airflow, pressure, heat, gases, power, radon, fire, and many other types of ventilation information. A new module, VentSim CONTROL, utilises intelligent software connected to hardware devices to remotely monitor, control, and automate airflow, heating, and cooling to deliver safer, more productive, and lower-cost ventilation for the mine (26,36).

Consequently, mine management can make quick decisions to prevent overexposure to DPM and latent health effects on the mine workers, future liability costs towards paying occupational disease compensation, and, most importantly, have a healthy workforce. Implementing emission-based maintenance will also assist the mine management in effectively prolonging

the life of their machines, employing good cost-effectiveness. A literature review conducted by the Mine Health and Safety Council South Africa in 2019 through the Chamber of Mines GEE committee (CoM), currently known as the Mineral Council, has shown that DEE emissions increase when poorly maintained machines become prone to mechanical breakdown. These factors directly affect the productivity of employees, as well as the operating cost of the mine, due to poor production output (36).

Currently, when planning mine design and occupational hygiene strategies, more focus is given to assessing unhealthy working conditions and their consequences than preventative approaches as documented in occupational health research, studies, and publications. A radical shift is required from focusing on DPM exposure monitoring to focusing on systems that will assist in preventative strategies (36). This research contributes to the detailed understanding of DEE characterisation in the mining environment. It will include profiling the concentration of diesel particle emission based on the number of workplace diesel-powered machines used and the actual underground environmental conditions based on the ventilation design or layout requirements. This information will be analysed to determine the workplace DEE dilution process requirements and evaluate how multifaceted control strategies can be best applied to reduce exposure to DPM underground. Further, the research outcome aims to formulate effective and risk-based DEE early response control strategies based on the risk hierarchy of control framework.

1.3 Research Question

South African Mining industry has been moving towards mechanisation from traditional conventional mining methods. The traditional method used winches (battery-powered equipment) to clean the ore and convey it to the surface post-blasting. The mechanised method uses diesel-powered machines to clean and haul the ore from the working face, which presents a challenge to increased air pollution at the underground workings due to diesel emission generation. South Africa does not have mandatory legislation nor implementable guidelines to enforce specific compliance by mines to prevent exposure to diesel emissions.

Although the South African Mine Health and Safety Council (a statutory body created by the Mine Health and Safety Act (Act 29 of 1996) has conducted several studies to understand the potential risks and health effects of DPM and exposure concentration levels for DPM personal sampling at underground mines and have provided recommendations regarding the phased-in approach to deal with DPM, there is a slow uptake regarding implementing systems as there

are no enforceable DPM regulations. This research aims to understand diesel emission characterisation and to evaluate specific emission interventions, including maintenance and engine retrofitting with diesel particulate filters. The results contributed to developing dynamic simulations with possible improvement scenarios in line with technology, explicitly implementing integrated preventative control strategies to ensure employees are not exposed to DEE underground.

1.4 Study aims and objectives.

The overarching aim of this research project was to determine characteristics of diesel engine exhaust emission at source during the operation of trackless mobile machinery and to evaluate specific control strategies to prevent and control workplace exposure to DEE in underground Platinum Mines. The following research objectives were conditional:

1. To evaluate the efficacy for reduction of engine exhaust emission of diesel-powered trackless mobile machinery by 1) the introduction of the OEM maintenance program; 2) the introduction of the OEM maintenance plus retrofitting of machines with diesel particulate filters
2. To evaluate the effectiveness of interventions mentioned above to reduce the diesel engine exhaust-related concentrations in the underground work environment by measuring personal exposure to Elemental Carbon (EC) and CO concentrations
3. To model diesel engine exhaust dispersion patterns to predict the spatial and temporal risk of over-exposure to diesel particulate matter (DPM) in underground workplaces using fluid flow dynamic systems
4. To evaluate the impact of different control strategies to prevent and control exposure to diesel exhaust

Figure 1.1 shows the overall framework applied in this research, aiming to develop prevention and control strategies to minimise employees' exposure to diesel engine exhaust. The approach was first to understand and characterise diesel engine exhaust at the source (tailpipe), which included determining the total particle concentration and size and measuring exhaust gases.

Two maintenance interventions were conducted to determine the effectiveness of the maintenance systems. The consequential particulate information was used as input to develop ventilation simulation and dispersion dynamics to understand better dispersion, accumulation over time, and the possible application of controls that would prevent or reduce workers' exposure to DEE during the shift.

Conceptual Framework for the research:

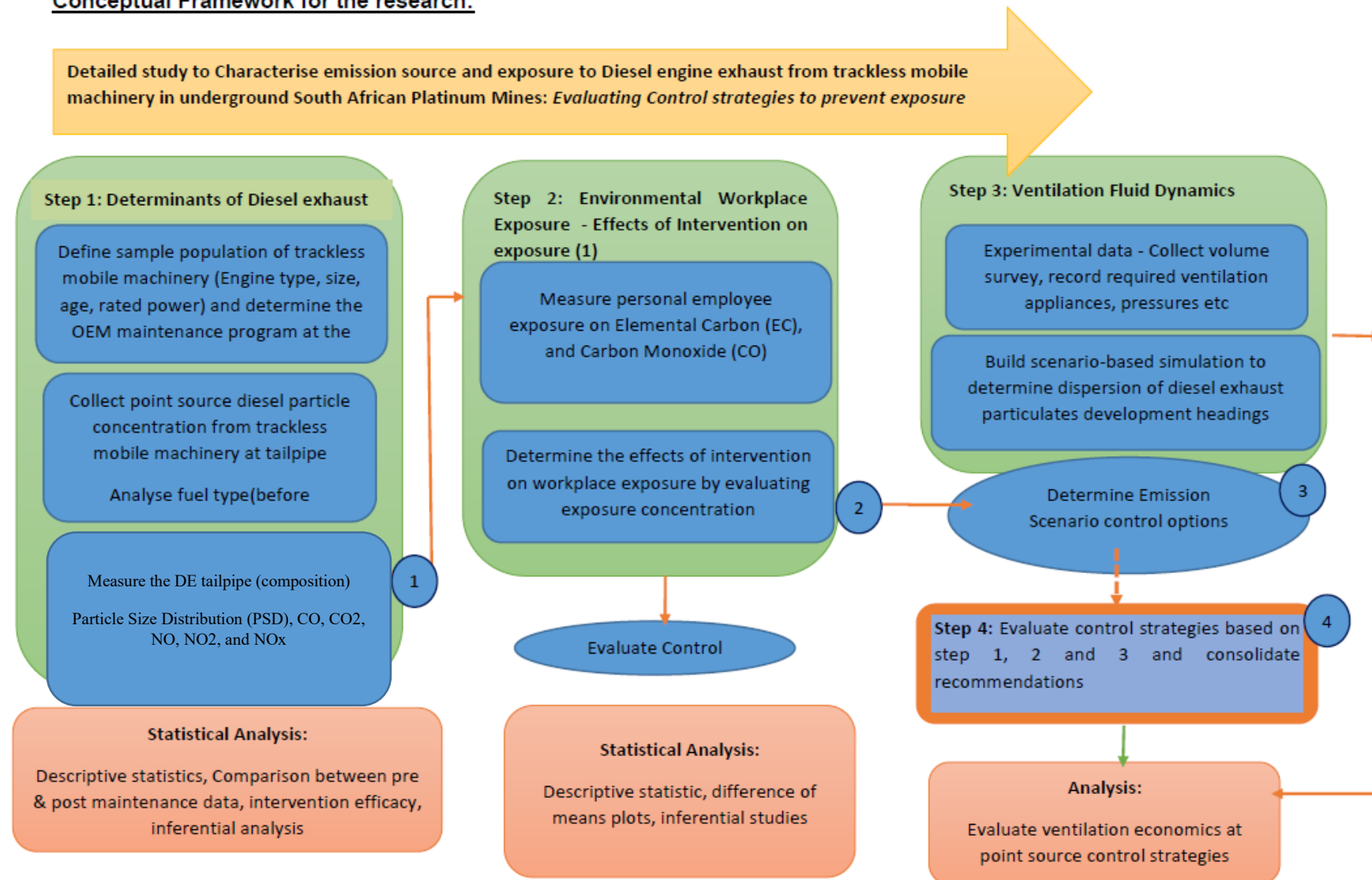


Figure 1.1: Conceptual framework

CHAPTER 2

This chapter reports the literature review on diesel engine exhausts in underground platinum mines from a legislative, economic, and health perspective. It considers a multifaceted approach to managing the exposure levels at the point source and various research outputs on computational simulation dynamics. The reported research output on the maintenance of diesel-powered machines and engineering controls was assessed to support the study objectives.

2. Literature Review

2.1 Diesel Engine Exhaust

Diesel engine exhaust (DEE) is a complex mixture of gases and particulates produced from unburned fuel, lubricating oil, and the combustion of diesel fuel (38). Gaseous compounds include carbon dioxide, water vapour, oxygen, sulfur and nitrogen compounds, carbon monoxide, and low molecular weight hydrocarbons and their derivatives (39). DEE consists of diesel particulate matter (DPM), which contains elemental carbon (EC) at the core and adsorbed organic compounds (OC), including polycyclic aromatic hydrocarbons, or PAHs, metals, and other trace compounds (8,40).

The particles produced by the engine are generally divided into four categories according to their particle diameter: (1) large particles $>10\ \mu\text{m}$, (2) coarse particles $2.5\text{--}10\ \mu\text{m}$ (PM₁₀), (3) fine particles $0.1\text{--}2.5\ \mu\text{m}$ (PM_{2.5}), and (4) ultra-fine or nanoparticles below $100\ \text{nm}$ ($0.1\ \mu\text{m}$) (PM_{0.1}) (40). Ultrafine particles are dominant in the particle number size distribution in contrast to the mass size distribution (2). The composition of diesel engine exhaust (DEE) depends on how the engine is operated. Typical compositions of DEE for a heavy-duty diesel engine tested in a heavy-duty transient cycle are described as follows: inorganic carbonaceous substances, named EC, constitute about 40% of the total PM mass. A study by Morla et al. (1) also indicated that elemental carbon comprises 50-70% of TC and greater than 45% of total engine-out PM emissions. The engine-out organic carbon makes up between 10 and 80% of total carbon (11).

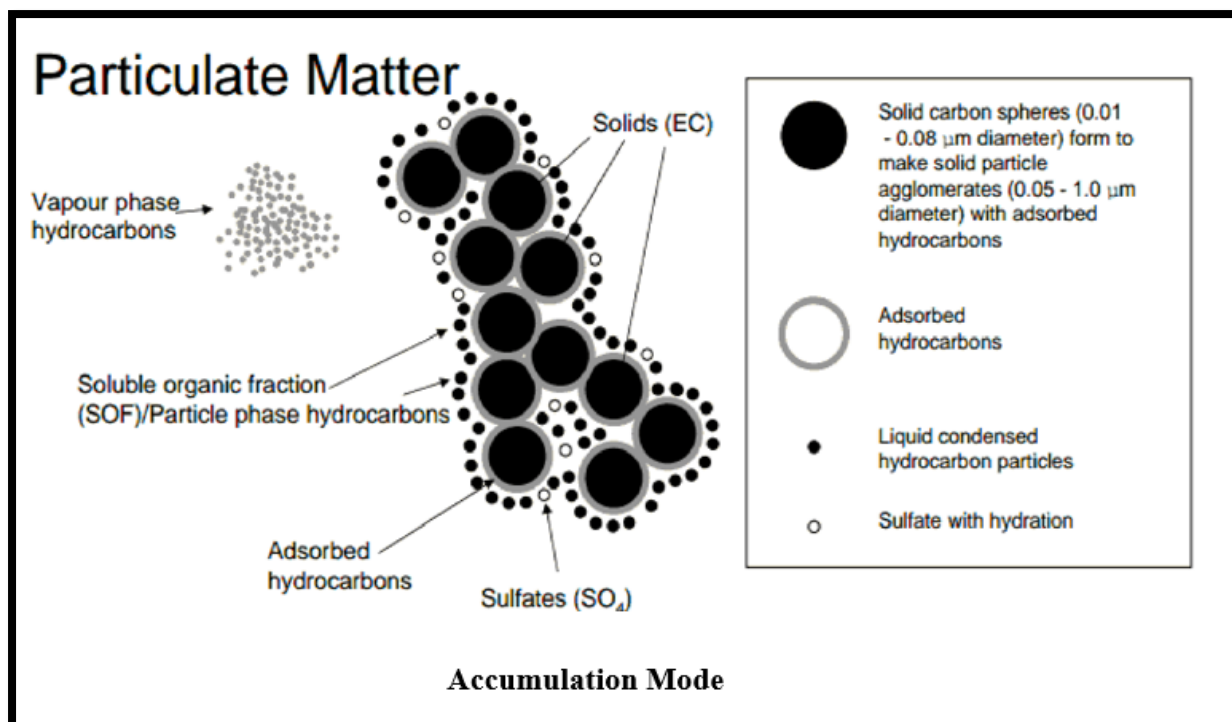


Figure 2.1: Structure and physio-chemical composition of diesel particular matter (Adapted from Dong et al.) (41).

Figure 1.1 shows the structure and physio-chemical composition of DPM, consisting of a solid carbon sphere (0.01 – 0.08 μm diameter) to form a solid particle agglomerate (0.05 – 1.0 μm diameter) with adsorbed hydrocarbons (40). Although the exact composition of diesel nanoparticles is unknown, it is believed that they are composed primarily of condensates (hydrocarbons, water, sulfuric acid), making up the nucleation mode of the DPM. In addition to the physio-chemical composition of DPM, another critical factor relates to the physical mixing status of the various DPM constituents. An internal mixing process of the various DPM constituents carbonaceous portion agglomerate, with other adsorbed or condensed species such as organics, sulphates, or metal oxides, mix to form a single, incorporated particle. This situation is called external mixing. Therefore, DPM's structure or mixing state is another crucial aspect to consider when assessing the respiratory health effects of this pollutant (14,38,41).

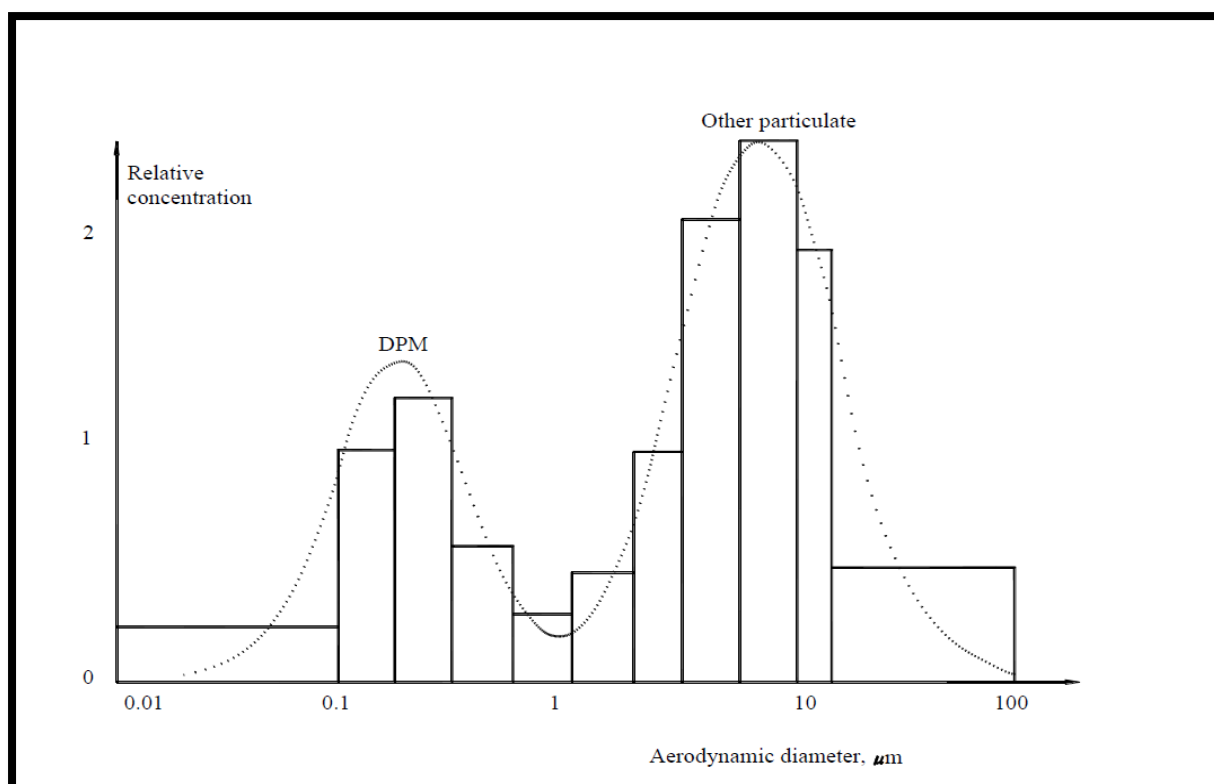


Figure 2.2: Distribution of DPM Versus other Mining Particles (Adapted from Dong et al. 2011) (41).

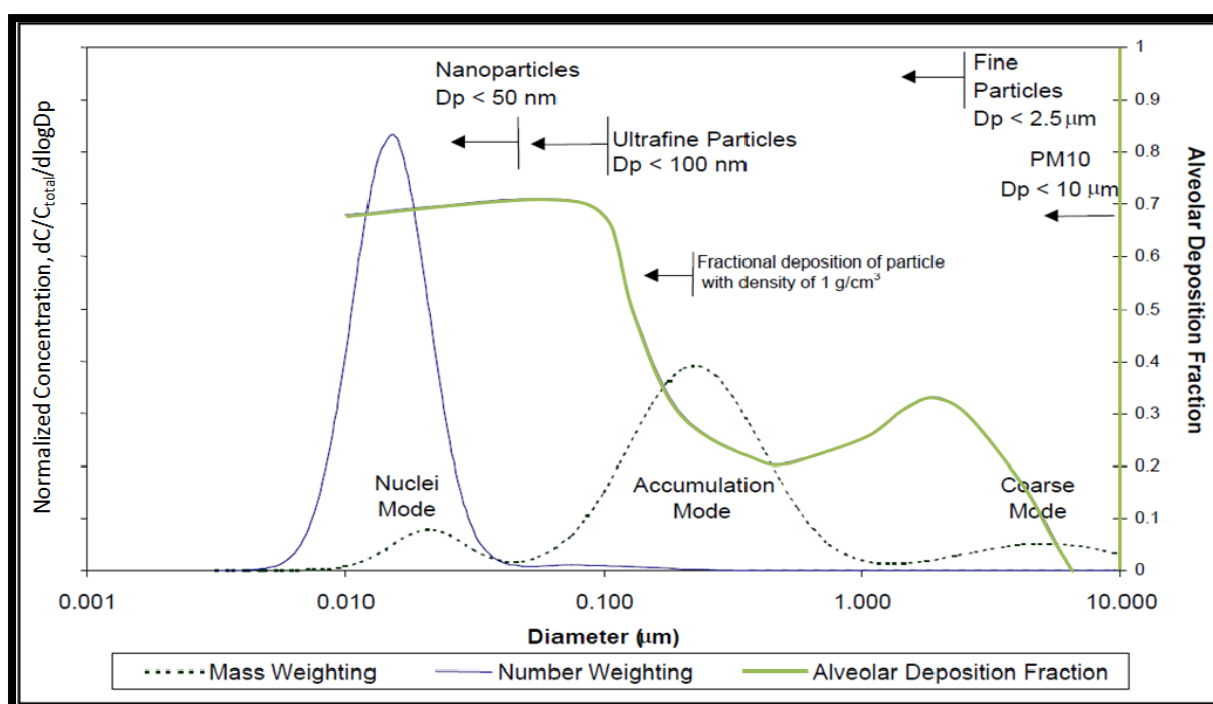


Figure 2.3: A graph showing a particle size distribution relationship between various diesel particulate matter particle metrics (number, surface, and mass) and the deposition of particles in the tracheobronchial and alveolar regions of the human lung (Adapted from Myung 2012) (42).

Figures 2.2 and 2.3 show how DPM particles behave at a deposit in the respiratory system, which is controlled by their aerodynamic particle size and mass. Particle mass concentration is

the mass of particles per unit of air volume, being the most straightforward and commonly used metric in air pollution studies. Particle mass emissions are referred to as PM emissions in the air pollution literature, where it is common for investigators to collect PM below a specified aerodynamic diameter that acts as a cut-point to provide a size-resolved PM sample. Particle number concentration and particle surface area concentration represent the surface area and number of particles emitted per unit air volume (41,42).

Figure 2.3, adapted from Myung and Park 2011, shows particle mass, surface, and number size distributions plotted concerning particle diameter. The modal value of each parameter shifts to larger particle diameters as the order of the dependence on particle diameter increases (viz; as the particles agglomerate). The particle number has a zero-order dependence on the particle diameter and has the smallest modal diameter of about 10 nm (42). Similarly, the particle surface area has a second-order dependence on particle diameter and the next largest modal diameter of around 150 nm. PM emissions (volume/mass) have a third-order (cubic) dependence on particle diameter and display the most significant mode of over 200 nm. The location modes are critical because if a different particle metric is chosen to explore respiratory health effects, then this metric is found in another part of the size distribution (42).

The literature review shows that diesel engine exhausts have a bimodal distribution, including small nuclei and larger accumulation mode particles. However, most particle numbers can be found in the nuclei mode, with ultrafine particles (aerodynamic diameter of 0.1 μm to 1 μm) (8,43). There are different methods to measure and control exposure to DPM. In studies done by de Jesus et al. (2019) in urban areas, diesel emission exposure was evaluated to determine whether air quality control strategies to reduce particle mass directly impacted the reduction of ultrafine particles. They found that particle number concentration (PNC) was dominated by UFP and mainly affected by local sources, especially combustion processes, with a significant contribution from vehicular exhaust. In contrast, the particle mass was dominated primarily by fine particles. They found a non-significant relationship between the two metrics when they assessed the relationship between PNC and mass concentration (PM_{2.5}) (44). Therefore, PNC and PM_{2.5} measurements are not representative of each other, and regulating particle mass (PM_{2.5}) does affect the reduction of PNC. This highlights the need to establish regulatory approaches and control measures to address the impact of elevated UFP concentration (44). Further, control measures aiming to reduce PM_{2.5} do not automatically reduce particle number concentration (8,42).

2.2 Health Effects

2.2.1 Human Respiratory System

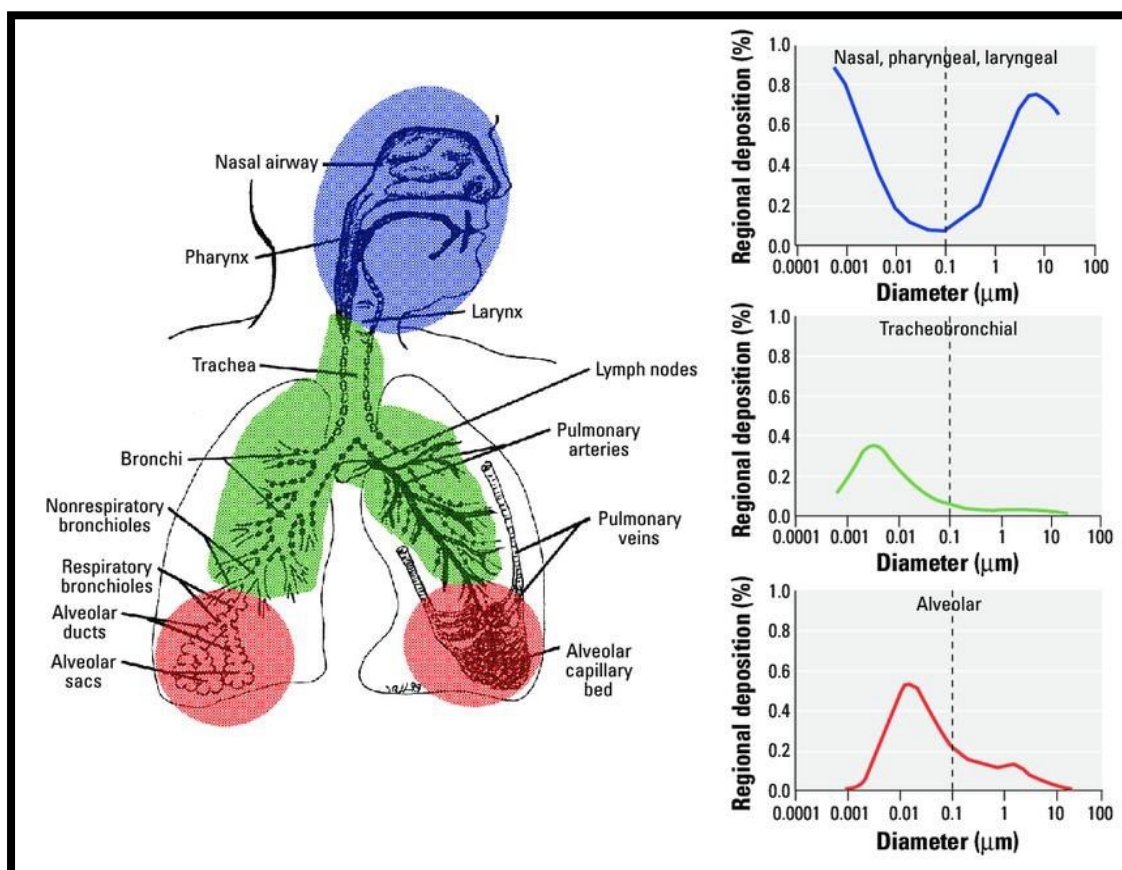


Figure 2.4: Schematic diagram of a Respiratory System (Adapted from the International Commission on Radiological Protection (1994). Drawing courtesy of J. Harkema (45).

The human respiratory system, a complex biological system, primarily supplies the body with oxygen during inhalation and eliminates carbon dioxide during exhalation. The inhaled air enters the respiratory tract through the upper region of the respiratory tract, comprising airways to the nose and mouth, which, together, form the nasopharynx. The overall ‘head’ region is assumed to include both the nasopharynx and the larynx in the present context. The whole region below the larynx is the lung. Air from the nasopharynx enters through the larynx into the trachea, leading to a branching system of conducting airways referred to as bronchi and, eventually, the conducting and terminal bronchioles. Beyond the terminal bronchioles is the alveolar region where gas exchange takes place. The alveolar region consists of the respiratory bronchioles alveolar ducts and alveolar sacs (45).

The respiratory system can be functionally separated into two zones: the conducting zones from nose to bronchiole, which form a path for conducting the inhaled gases, and the respiratory zone (alveolar duct to alveoli), where gas exchange occurs. Anatomically, the respiratory tract

is divided into an upper portion (organ outside thorax - nose, pharynx, and larynx) and the lower respiratory tract (organ within thorax - trachea, bronchi, bronchioles, alveolar duct, and alveoli) (46). The first part of the process of aerosol intake occurs during the entry of particles into the respiratory tract during inhalation. The second part involves the arrival of particles at relevant sites inside the respiratory tract as the result of deposition by a combination of physical mechanisms, including sedimentation, impaction, diffusion, and electrostatic forces. Figure 2.4 shows the physiological anatomy of the respiratory system, including the upper respiratory and lower respiratory sections.

A further subdivision of the thoracic aerosol that penetrates below the larynx occurs between what is deposited in the tracheobronchial region and that which penetrates down to the alveolar region. The fine fraction penetrating down to the alveolar area is known as the respirable fraction. In Fig. 2.4, alongside the alveolar deposition data from experiments with human subjects, a number of the curves adopted over the years as conventions for the respirable fraction are shown (47). Again, it is noted that none of these conventional respirable aerosol curves truly reflect alveolar deposition at very small particle sizes. This does not pose a problem so long as the aerosol in question does not contain a significant proportion of its mass in particles of diameter below about 1 μm . However, caution should be exercised in applying such respirable aerosol conventions to mixed aerosols where important components fall almost entirely in the sub-micrometre particle size range (e.g., diesel fume in dust) (45).

The International Commission on Radiological Protection deposition curve for combined alveoli trachea-bronchial deposition exhibits two distinct peaks (Figure 2.4). The larger deposited fraction peaks at a few micrometres entail the deposition of larger particles due to their inertia. In contrast, the smaller peak centred around 20 nm involves the deposition of nanoparticles. Particle size is, therefore, a crucial parameter to consider when assessing the respiratory health impacts of DPM (41,47,48).

2.2.2 *Health Effects Associated with Exposure to DEP*

Particles are deposited in the human respiratory system size-dependently per their physiochemical composition (41). A study by Rumchev et al. (2020) states that approximately 80–95% of the diesel particle mass is in the fine particle size range ($2.5\mu\text{m}$), with a mean particle aerodynamic diameter of about $0.2\mu\text{m}$ (48). Further, the particles with aerodynamic diameters $>2.5\mu\text{m}$ tend to be retained in the upper portions of the respiratory tract. In contrast, particles

with diameters $<2.5\mu\text{m}$ are deposited into the lower part of the respiratory tract, including the alveolar region (48).

Available research indicates that human health hazards are associated with exposure to DEE/DPM; these include acute symptoms such as irritation of the eyes, nose, and throat, causing neurophysiological and respiratory symptoms, and chronic diseases such as lung cancer (38). Further, DPM's toxic effects negatively impact the lungs, heart, kidney, placenta, brain, and liver. Respirable DPM is now an emerging concern in the mining workplace and is also of concern in both domestic and industrial sites (38,49).

A study conducted by Rumchev et al. 2020 investigated DPM workplace exposure. The key findings highlighted that underground miners were exposed to significantly higher EC concentrations than surface production mine workers over the study period (2006-2012), except in 2006. This was probably due to limited DPM monitoring of underground miners before the introduction of the exposure guidelines by the Australian Institute of Occupational Hygiene in 2007 (48).

Further, the study showed that mining activities had been associated with adverse health conditions, including acute and chronic respiratory diseases, for surface and underground operations. Of the miners interviewed, 29% reported at least one respiratory symptom over the six-year study period, with the highest frequency recorded for cough (15.7%), followed by phlegm (11.7%), wheeze (10.5%), and breathlessness (9.6%). Reports of coughing and breathlessness had the highest prevalence rates at 28.3% and 22.3%, respectively (48).

Another study done in underground trackless mines by Manyike 2014, investigated the prevalence of chronic obstructive airway disease (COPD) in LHD operators. It showed that night shift workers had declined lung functions. It also demonstrated acute respiratory symptoms, as 20 of the 86 workers examined had obstructive lung function patterns (50).

In addition, the study showed that COPD and acute respiratory symptoms were more prevalent among night shift operators. 15 out of 40 night shift workers had developed obstructive lung patterns, 4 of which showed non-reversible obstructed lung patterns. Because of the load and haul cycle, a significantly higher number of night shift workers were coughing at the study or had been coughing for > 3 months compared with day shift workers, who were exposed the most to loading activities (50).

2.2.3 DPM Toxicological Pathway

Toxicological studies with various model/surrogate particle preparations, such as carbon black, suggest that the surface area is the most critical determinant of the effect of ultrafine particles (diameter less than 100 nm). In contrast, chemical composition may be more important for larger particles (32). The mechanisms of PM-induced health effects are believed to involve inflammation and oxidative stress (41,52). Particularly for cancer, bulky deoxyribonucleic acid (DNA) adducts from polycyclic aromatic hydrocarbons (PAH) are also thought to be necessary. Many cohort studies have demonstrated that airborne PM, of which DPM is a significant contributor, is responsible for causing respiratory mortality and morbidity. Despite a substantial body of research addressing this topic, the underlying toxicological mechanisms by which DPM induces adverse health still need to be fully understood. Several recent studies have indicated that inflammation-mediated via oxidative stress is the mechanism by which DPM may exert toxicity (32,41).

A mechanism describing pathways to respiratory illness and disease, synthesising the results presented in this review related to the respiratory health effects of DPM, has been shown in Figure 2.5 reiterates that DPM has three primary physicochemical properties to consider when investigating respiratory health: the DPM surface area, the presence of adsorbed transition metals, and organics. The literature consulted in this review indicates that all these three factors are implicated in the development of oxidative stress. Vital consequences related to the development of oxidative stress are reflected in the figure below:

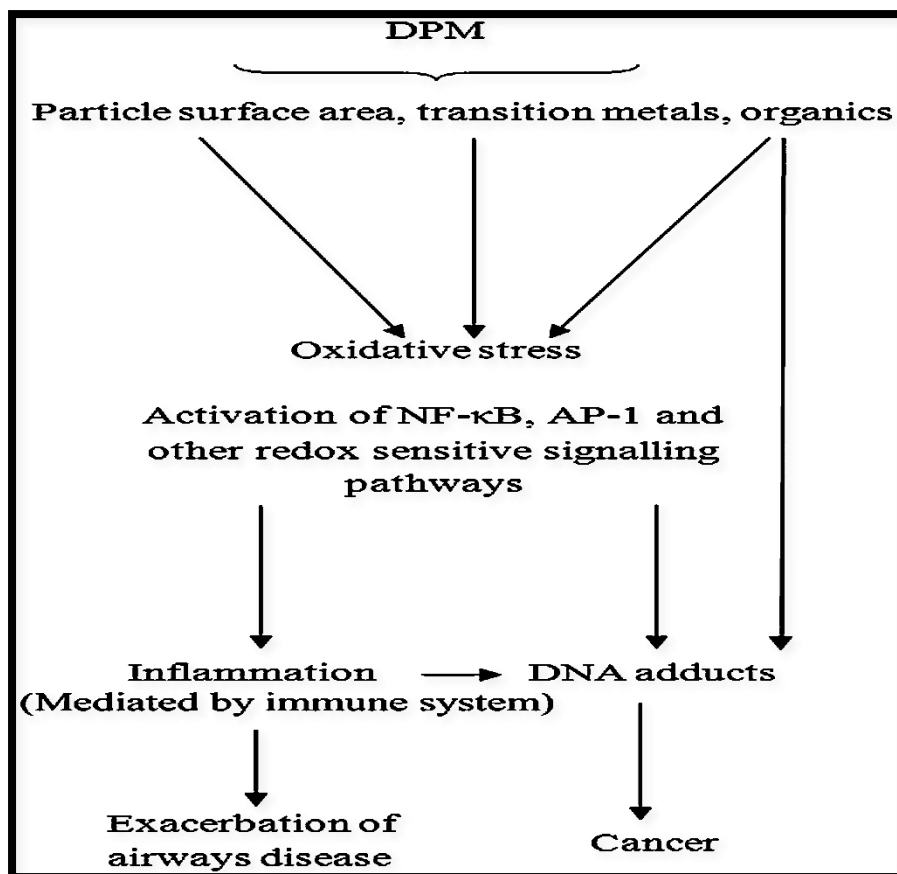


Figure 2.5: Toxicological pathway describing the mechanism of health effects with exposure to DPM (Adapted from Ristovski 2012)(42).

2.3 Legislation

2.3.1 Regulation of Occupational Exposure and threshold limits for DPM/DEE

Results from multiple studies at occupational sites have led to regulatory bodies considering the adoption of stringent threshold limit values or occupational exposure limits from regulated countries (18). In 2012, the International Agency for Research on Cancer (IARC) (4) classified DEE as carcinogenic to humans (class I) by inhalation. The unique nature of diesel particulates is a large surface area that enables further absorption of toxins and mutagenic and carcinogenic compounds, such as polycyclic aromatic hydrocarbons, increasing the likelihood of carcinogenesis (18,41).

Daily operational, DEE is liberated to an underground environment once emitted from the tailpipe, releasing pollution into the air inhaled where employees work. (EPA 2002). The amount and composition of DEE vary tremendously depending on determinants such as fuel type, engine type and age, maintenance schedule, turning, workload, road conditions, and after-treatment diesel exhaust (29,30,54).

2.3.2 Diesel Exhaust Regulations Internationally

Some European countries (Germany and Switzerland), Canada, and the United States have adopted regulations limiting the exposure levels of diesel particulate matter in the workplace. The Mine Safety and Health Administration in the USA (MSHA) has promulgated a rule to limit exposure of metal/non-metal underground miners to Diesel Particulate Matter (DPM) to an eight-hour time-weighted average of 160ug/m³ total carbon (TC) as in Table 2.1. Three European countries (Switzerland, Germany, and Austria), three Australian states (Queensland, Western Australia, and New South Wales), and New Zealand have adopted legally enforceable OELs.

The European Parliament adopted an OEL of 50 µg/m³ of elemental carbon in December 2018 (35). Since then, there have been many changes based on new scientific knowledge. For example, Australia, Switzerland, and Germany have adopted EC as a surrogate for DPM at 0.1mg/m³. Although there is still some controversy regarding the marker for DPM, EC seems to be gaining strength worldwide. Table 2.1 shows the latest exposure guidelines for European countries, which are well-regulated and enforceable within these jurisdictions. Exposure limits are legislated in Australia, Canada, the United Kingdom, and the United States of America.

In recent studies conducted in Australia, underground coal and metalliferous mines have noted that the level of eye and upper respiratory tract irritation is significantly reduced at diesel particulate matter exposure concentrations of 0.2 mg/m³ or less (approximately 0.1 mg/m³ submicron elemental carbon (EC)). The NSW Government adopted and implemented an exposure limit of 0.1mg/m³ EC in February 2021, which came into force after a 12-month transitional period that the legislator deemed achievable within their mines. Considering the carcinogenic nature of diesel particulate matter and other irritant effects, the NSW position believed that introducing an exposure standard is appropriate, and compliance is achievable by applying the hierarchy of controls by all mine operators (55).

Table 2.1: DPM Concentration Limit – Resource regulator(33,55)

Legal Limits			
Regulator/Agency	Date submitted	Exposure Guideline/Limit	Substance Measured
<i>Swiss MAK Exposure limits</i>	2001	0.1 mg/m ³	EC
<i>Australia</i>	2020	0.1 mg/m ³	EC
<i>Canada (Ontario)</i>	2011	0.4 mg/m ³	TC
<i>Mine Safety & Health Administration</i>	2008	0.16 mg/m ³ , 0.123 mg/m ³ EC	TC & EC
<i>Germany, Tunnelling</i>	1996	0.3 mg/m ³	EC
<i>Germany Other applications</i>	1996	0.1 mg/m ³	EC
<i>ACGIH</i>	2001	0.02 mg/m ³	EC

2.3.3 South African Context

South Africa shares the same concern with other countries regarding the DPM challenges in mining operations. The South African legal framework requires the employer to conduct a risk assessment and put measures in place to ensure that a system is in place to prevent employees from overexposure to harmful airborne pollutants (MHSA 1996). Mining companies are, however, obliged to conduct risk assessments in terms of Section 11 of the Mine Health and Safety Act (Act 29 of 1996) on all factors that could adversely affect the health and safety of the workforce and institute appropriate mitigation measures, where no local regulations exist, international best practice should be utilised (56). OEMs are also required to provide full disclosure, in terms of Section 21 of the Mine Health and Safety Act (Act 29 of 1996), of the health and safety impact of the equipment being sold to a mining company and advice on appropriate measures that can be taken to eliminate or reduce the risk. Therefore, without local guidelines and regulations, SAMI can use the available scientific knowledge to control the exposure of DPM to employees and to ensure continuous monitoring of employees while working at the mines.

No specific systems guide sets standards or limits for personal or occupational exposure or tailpipe emissions for DPM (6,37). Further, even though enough knowledge is available from international and local sources, the regulation of DPM still needs to be improved.

The SAMI Group Environmental Engineers submitted a positional paper in 2012(6,7), focusing on the response to the DPM health effects and a phased-in approach recommended exposure limit, post-declaration of DPM as being carcinogenic by both IARC and the World Health Organisation (WHO) as shown in Table 2.2. This paper has also built on the efforts of the Department of Minerals and Resources, together with the Mine Health and Safety Council, regarding the implementation of a DPM target value of 0.300 mg/m³ of elemental carbon (EC) to be reduced over the years to achieve the lowest level of exposure. The group environmental engineers (GEE) recommended a phased-in approach, which was planned from 2013 to reduce the DPM Total Carbon from 350µg/m³ to 200µg/m³ from January 2014 to December 2014, 200µg/m³ from January 2015 to December 2016 where after it would decrease to 160µg/m³. Even though few mines have adopted these recommendations, the recommended limits are not incorporated into the SA Mine Health and Safety Regulations (6).

The GEE in South Africa further recommended multiple control management strategies, which include the following: DPM control level, baseline measure on the inventory list for the fleet, baseline measurements for diesel fleet, baseline assessment on worker exposure, baseline assessment on environmental exposure and clean fuel energy or introduction of electrically powered machines for the new mining projects. To this end, only some mines have implemented the GEE-recommended strategy (6). Many mines find it challenging to meet DPM recommended or target limits during all phases of operational activities. Efforts to establish an Occupational Exposure Limit (OEL) are becoming a necessary reality.

Table 2.2: Diesel Particulate Matter recommended exposure limit phased approach plan (Mine Health & Safety Council 2013) (6).

Proposed DPM Limits	
<i>DPM Exposure control value</i>	Target year
<i>350 µg/m³ (TC)</i>	December 2014
<i>200 µg/m³ (TC)</i>	Up to December 2015
<i>160 µg/m³ (TC)</i>	Up to December 2016
<i>* < 160 µg/m³ (TC)</i>	Beyond 2017

*Note: Subject to review as new knowledge arises

2.3.4 Risk Management Processes

Risk management is one of the most critical tools to identify workplace hazards and controls in the mining industry. South African legislation also requires that the employer identifies and assesses the potential risks employees can face in the workplace. Different companies employ a range of risk frameworks; however, the control strategies are similar. Once risks are identified, controls should be implemented using a systematic process known as the hierarchy of controls. ILO supports risk management and WHO, emphasising a primary preventative approach to protecting workers' health, women and men, in both formal and informal economies and integrating Safety and Health issues with productivity (8,58).

The hierarchy of controls is a method of identifying and ranking risk controls that protect workers from exposure to hazards. The controls are arranged from the most to least effective, including elimination, substitution, engineering controls, administrative controls, and personal protective equipment (8).

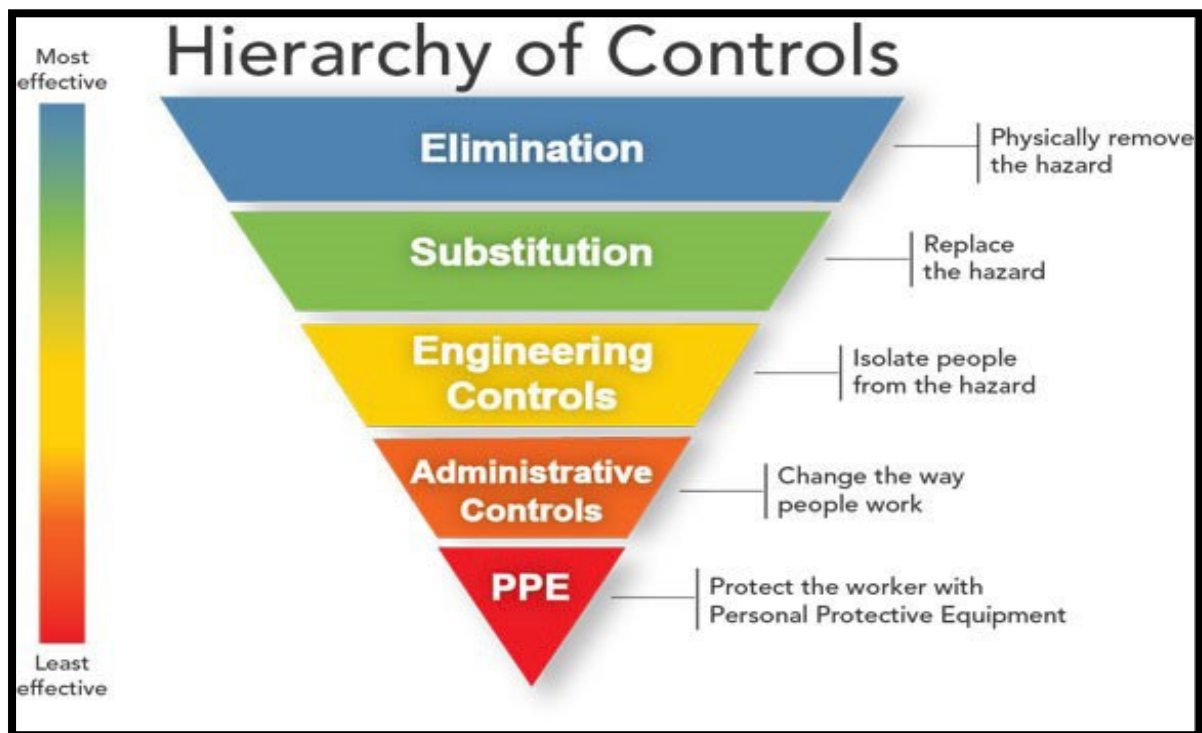


Figure 2.6: hows the Hierarchy of Controls. It is Adapted from the Occupational Cancer Research Centre Report (2017)(8).

Diesel emission is a complex mixture and may require multiple control strategies to minimise employee exposure. In the study that was conducted by Bugarski et al, 2009 they highlighted different monitoring and control strategies ranging from the following: emissions monitoring including undiluted emissions measurements, i.e., both ‘tailpipe output’ and ‘engine out’ (upstream of after-treatment systems), and the installation of after-treatment strategies and

higher tier standard engines emissions. The control strategies can help identify and distinguish between engine maintenance issues and failures of emission control devices and assist in estimating ventilation requirements (53). In addition, an emissions monitoring program is essential to ensure that diesel control strategies are working effectively and sufficient for the amount of diesel exhaust produced (53).

To support the above, a maintenance intervention study conducted by Hines (2019) on emission-based maintenance showed positive results, reducing more than 80% of CO and 47% of DPM. In her study, Hines followed a risk-based approach focused on reducing DEE at source by using diagnostic methods to identify machine faults and improving the blockage in the exhaust pathway and the seals on the filter houses to reduce incomplete combustion. This was done using an emission-based fault-finding software, and the results showed a reduction. The study's success was also embedded in ensuring proper training for the engineering teams to conduct the diagnostic methods as part of the maintenance (11).

The Occupational Cancer Research Centre Report published in 2017 presented different control strategies for DEE following the hierarchy of control principles (8). These ranged from the proactive (most effective) to reactive (less effective) controls and included the following controls: elimination using alternative energy such as electric or battery-powered machines, substitution such as replacing, repowering, or engine rebuilds, and this would typically include retrofitting the engines with engine after-treatment systems; Engineering controls which may include retrofitting the engines with after-treatment technologies, improving general ventilation systems, idling technologies, installation of protective cabs; Administrative controls which may include preventative maintenance, idling policies, operator training and planned schedule for the site such as planning the number of machines required to operate in a working place; and lastly the use of personal protective equipment such as respirators (8,58). These controls can be implemented in a multifaceted approach to reduce or prevent employees from being overly exposed.

2.4 Measuring Techniques for DEP

The current preferred method adopted internationally to sample and analyse EC and TC is using gravimetric personal sampling. This is based on personal monitoring using the NIOSH 5040 analysis methodology. Although many countries are slowly moving towards the use of EC as a surrogate for DPM, the measurement of respirable combustible dust (RCD) methods is still being used in some countries, such as Canada (Table 2.1) (55). Since EC is a product of

combustion composed of inert graphitic carbon, it is a specific marker of diesel exhaust aerosol where other combustion aerosols are absent. On the other hand, the OC portion is subject to interference from other organic aerosols, such as oil mist from different environmental sources, which are not associated with diesel exhaust (57). The Australian Institute of Occupational Hygienists (AIOH) believes that worker exposure to DPM levels should be controlled to below 0.1 mg/m^3 as an 8-hour time-weighted average value, measured as submicron elemental carbon, and this is based on the latest information that in the absence of defined universal dose-response relationship experience has shown that when workplace exposures are controlled below 0.1 mg/m^3 DPM (measured as submicron elemental carbon), the irritant effect decreases markedly. AIOH believes that such a level should result in a reduced lung cancer outcome if such a carcinogenic effect is attributable to DPM exposure (59).

Although particle number concentration (PNC) has not been used as a marker for DPM exposure, it is a growing area of research where correlations between PNC and EC have been evaluated. One aspect that makes this area challenging is the variation of particle diameter with DPM. Other factors to consider include variations in the chemical composition of DPM and the different compounding markers to be considered to monitor DPM.

In a study by Hedmer et al. 2017, a quantitative study to understand the DPM exposure to construction tunnel workers was assessed by different sampling methodologies, including self-administered repeated passive samplings of NO_2 among the tunnel construction workers (main study). Personal exposure, measurements of NO_2 , EC, OC, TC, respirable dust, and particle number concentration (using online nano-tracers) were performed on the workers to characterise their exposure. The study objective was to quantify occupational exposure to diesel exhaust in underground tunnel construction work using a multi-metric approach and to investigate the correlations between NO_2 , respirable EC, respirable organic carbon (OC), respirable total carbon (TC), and respirable dust (RD). Correlations were established between EC and NO_2 and EC and particle number (32). These findings are essential, and exploring the results with additional studies is necessary, especially the linkage between the EC and particle number concentration. Although NO_2 might be a challenge for underground mechanised mines due to possible interferences from the surrounding environment, such as oil mists from other activities, means to explore particle number as a surrogate for DPM may improve the risk management proactive monitoring of DPM using continuous online monitoring of DPM during the shift.

2.5 Determinants of Diesel Exhaust

Physical properties of DPM include the number/size distribution of particles and structure, such as the mass, surface area, and their physical mixing state (48). The physical properties of DPM influence respiratory health in different ways. For example, the particle surface area influences how toxic compounds adsorb or condense upon particles; particle size is a critical parameter that governs where DPM deposits in the human respiratory tract (see Figure 2.4); particle number emissions govern the ability of particles to coagulate and therefore grow to bigger sizes; while the physical mixing state of particles is another factor to take into account when determining respiratory health impact (12). Understanding DPM emission levels is an essential tool to quantify and predict pollution levels underground, ensuring that emissions are controlled at source, enabling effective monitoring, and thereby focusing on reducing exposure by managing emissions at source.

During the ignition process of diesel engines, several factors play a role towards incomplete combustion, which subsequently results in PM, which will be discussed in the next subparagraphs:

2.5.1 *Basic Characteristics of Vehicle Engines*

There are two main types of internal combustion engines: spark-ignition engines (or petrol engines) and compression ignition (CI) engines (or diesel engines). negatively affect. Although diesel engines are more prominent, these two types can contribute negatively to environmental air quality. Research has shown that it is more challenging to control PM with diesel engines due to the heterogeneity of their combustion process (60).

The diesel engine, named after Rudolf Diesel, is an internal combustion engine in which fuel ignition is caused by the elevated temperature of the air in the cylinder due to its mechanical composition (61). Mixture preparation in diesel combustion starts with spray formation after the fuel leaves the injection nozzle; the fuel spray atomises into droplets, vaporises, and mixes with air (62).

It must be noted that diesel engines work by compressing the air, increasing the air temperature inside the cylinder to such a high degree that the atomised diesel fuel that is injected into the combustion chamber ignites spontaneously. After injection, the fuel dispersion is uneven, which is called a heterogeneous air-fuel mixture. Jääskeläinen et al. and Khair et al., 2015, further explain that emissions from burning this heterogenous air/fuel mixture depend on the engine's prevailing conditions during the combustion and expansion process before the exhaust

valve opening (63). The diesel engine relies on the amount of fuel injected during the initial phase, where the air/fuel ratio is controlled (64).

2.5.2 *Fuel Ratio*

The diesel internal combustion engine differs from a gasoline-powered Otto cycle, using highly compressed hot air to ignite the fuel rather than a spark plug (63). In a diesel engine, only air is initially introduced into the combustion chamber, which is compressed with a compression ratio typically between 15:1 and 23:1, causing the temperature of the air to rise. At about the top of the compression stroke, fuel is injected directly into the compressed air in the combustion chamber. Depending upon the engine's design, this may be a (typically toroidal) void in the top of the piston or a pre-chamber (63,65).

The fuel injector breaks down the fuel into tiny droplets to distribute it evenly (65). The heat of the compressed air vaporises the fuel from the surface of the droplets, which ignites the vapour from the compressed air in the combustion chamber. The droplets continue to vaporise and burn, getting smaller, until all the fuel in them has been (63,65).

Combustion occurs at a constant pressure during the initial part of the power stroke. The start of vaporisation causes a delay before ignition, resulting in the characteristic diesel knocking sound as the vapour reaches ignition temperature. This causes an abrupt increase in pressure above the piston. When combustion is complete, the combustion gases expand as the piston descends further. The high pressure in the cylinder then drives the piston downward, supplying power to the crankshaft (64).

It must be noted that as well as the high level of compression allowing combustion to take place without a separate ignition system, a high compression ratio significantly increases the engine's efficiency. Increasing the compression ratio in a spark-ignition engine, where fuel and air are mixed before entry to the cylinder, is limited to prevent pre-ignition, which would cause engine damage. Since only air is compressed in a diesel engine, fuel is not introduced into the cylinder until shortly before the top dead centre (TDC). Therefore, premature detonation is not a problem, and compression ratios are much higher (63).

2.5.3 *Fuel Injection*

Diesel engines rely on air/fuel mixing in the cylinder, so they need a fuel injection system. The fuel is injected directly into a segmented combustion chamber, known as an indirect injection (IDI), an unsegmented combustion chamber, or a direct injection (DI) (66). The definition of

the diesel engine is specific, requiring that the fuel be introduced directly into the combustion or pre-combustion chamber rather than initially into an external manifold. To create fuel pressure, diesel engines usually have an injection pump. Several types of injection pumps and methods exist for producing a fine air-fuel mixture (63).

Injector-to-injector differences may lead to variations in the fuel distribution, the amount of fuel deposited on the walls, cylinder pressure and temperature, and injection duration. In addition, fuel injected during the ignition delay period (premixed portion) will mix with air and produce a wide range of equivalence ratios. At the onset of auto-ignition, mixtures most likely to burn are those closer to the stoichiometric ratio. Combustion will continue unless the local A/F ratio rapidly becomes too fuel-lean due to over-mixing with surrounding air or if the flame is quenched by a thermal boundary layer (63,67).

Hydrocarbons can be generated from fuel injected during ignition delay (Figure 2.7) and fuel injected after ignition delay (Figure 2.8). During ignition delay, evaporation, mixing, and combustion rates must be sufficiently rapid to consume most of the sprayed fuel before significant expansion and cooling off during the expansion stroke; otherwise, excessive unburned hydrocarbons will be found in the exhaust. Problems in the form of excessive unburned hydrocarbons, carbon monoxide, and particulate matter can arise unless extra care is taken in designing the timing and the quantity of this post-injected fuel pulse (63,65).

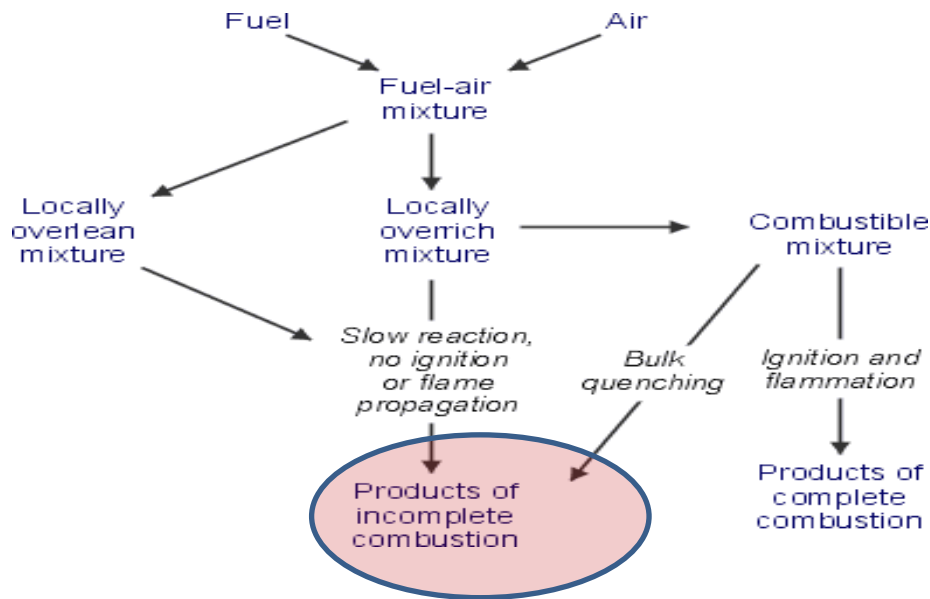


Figure 2.7: Hydrocarbon formation from fuel injected during ignition delay (Adapted from Khair and Jaaskelainen 2015) (63).

When fuel is injected after the start of combustion (illustrated in Figure 2.7), fuel pyrolysis or rapid oxidation occurs by mixing with air, resulting in complete combustion. Conditions that may slow down the rate of pyrolysis and oxidation will lead to localised rich mixtures and delays in completing combustion. If such conditions prevail, the exhaust gas will contain greater concentrations of unburned hydrocarbon (63). Hence, the combustion efficiency (CO/CO₂ ratio) must be measured during tailpipe DEE measurements and addressed accordingly.

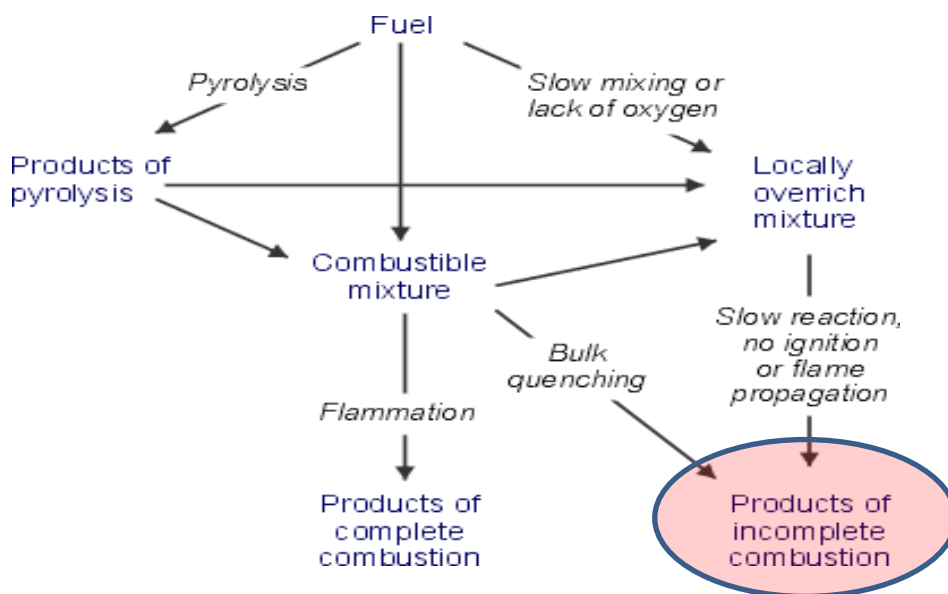


Figure 2.8: Hydrocarbon formation from fuel injected after ignition delay (Adapted from Khair and Jaaskelainen 2015) (63).

Contrary to the direct injection engines, the electronic control high-pressure common rail system has been introduced and presents some advantages, such as high injection pressure and flexible injection parameters (pressure, timing, and fuel quantity). It has become the preferred choice for the advanced diesel engine with low noise, emission, and fuel consumption (64). The combustion results will vary widely when the fuel enters the cylinder with different injection timings and injection rates. Compared with traditional inline pump systems, high-pressure common rail fuel systems have higher injection pressure and smaller nozzle diameters, so spray diameters become smaller, and the interface between air and fuel is expanded significantly. Due to the spray's entrainment effect on its surrounding air caused by the high-speed fuel beam, the mixing is greatly accelerated and more uniformly. Hence, the ignition delay is shortened, and the ignition location transfers to the front of the spray, so the combustion process is different from the traditional direct injection diesel engines (64).

2.5.4 *Formation of DE*

Diesel emissions are formed during combustion, where air and fuel mix in the cylinder chamber. Emissions include particulate matter, hydrocarbons, and NO_x. PM is produced during the diffusion flame process, NO_x emissions can be formed during premixed diffusion burning, and hydrocarbons can be traced to incorrect air/fuel (either under-or over-mixing of air and fuel), lubricating oil, poor mixture formation, as well as cold quench layers on the surface of the combustion chamber (62). factors include ignition delay, mixture preparation, fuel ignition quality, expansion duration, and general engine design features. Complete combustion can be influenced by mixing unburned hydrocarbons with oxidising gases, high combustion chamber temperature, and adequate residence time for the oxidation process (63). Last, the formation of hydrocarbon molecules can also be influenced by the engine design and operating variables, including engine technology (63,65).

2.5.5 *Smoke in Diesel Engines*

Smoke in diesel engines is one of the indicators that the diesel performance is not at its optimum. It is generally caused by an over-rich air/fuel ratio or partially evaporated fuel. Furthermore, smoke may be black or white and appear as suspended solid or liquid particles in the exhaust gasses. Black smoke is more common in diesel engines. It consists of solid particles and is as called hot or black smoke.

In their study, Khair and Jaaskelainen (2021) state that diesel engine smoke will appear blue or grey in cases of excessive lube oil consumption. Poor maintenance of air filters and fuel

injectors and incorrect setting of the fuel injection pump/system contribute to excessive smoke generation. Therefore, it is critically important that the fleet maintenance program is built to combat DPM-related challenges (63).

2.5.6 Engine load

During different stages of engine operation, unburned hydrocarbon emission is generated. The various stages may include the engine operating at idle and light load conditions and high transient mode. Unburned hydrocarbons increase at light load than during high transient load. Factors that may increase the generation of unburned hydrocarbons at idle/light load may include the fuel not reaching the walls of the combustion bowl and burns in the space between the nozzle tip and the combustion bowl perimeter, resulting in spatial combustion. The spray core's fuel concentration is sometimes relatively small (63,65). The effect of load on unburned hydrocarbons is shown graphically in Figure 2. The Effect of load on unburned hydrocarbon emissions (Adapted from Khair and Jääskeläinen 2015)(62).

2.5.7 Turbocharging

Turbocharging provides additional power in diesel-powered engines. It enhances engine oxidation rates by increasing the mass of air inducted into the engine, critical to engine oxidation rates and output/performance. Turbocharged engines provide increased air velocity through the intake port, which is air motion that enhances mixing and mixture preparation. This leads to higher oxidation reaction rates and increasing combustion temperatures, which reduce the concentration of hydrocarbon emissions (see Figure 2.8) (63,65).

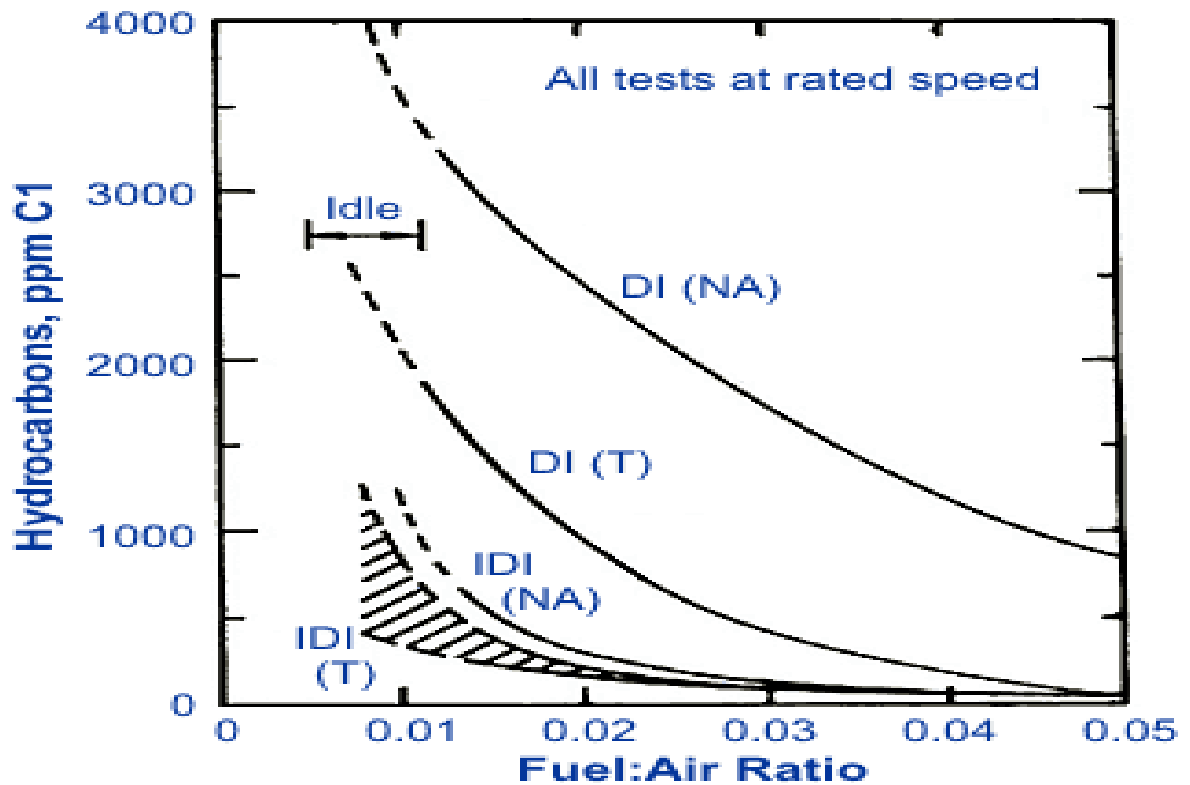


Figure 2.9: Effect of F/A ratio on HC emissions in DI and IDI turbocharged and naturally-aspirated diesel engines (Adapted Khair and Jämskeläinen 2015) (63).

2.5.8 Formation of Carbon Monoxide

Carbon monoxide (CO) can be formed due to incomplete combustion. During the combustion process, generated CO oxidizes to CO₂ through the recombination process. However, conditions that promote high combustion temperature, high oxygen content, and high mixing rates enable the oxidation of CO to CO₂. CO may be left unoxidized if the recombination reactions are incomplete (63,65).

2.5.9 Formation of Nitrogen Oxides

In the exhaust of internal combustion engines, NO_x refers to a class of compounds called nitrogen oxides. In DI diesel engine exhaust, nitric oxide (NO) is usually the most abundant nitrogen oxide, more than 70-90% of total NO_x in engine-out conditions. Nitrogen dioxide (NO₂) typically makes up the balance of NO_x emissions. Some can significantly increase tailpipe levels of NO₂ after-treatment devices that promote oxidation reactions (63,68).

2.6 Tier Standards

Concerns regarding DEE have led to increased regulations and standards to regulate emissions from both light and heavy-duty diesel vehicles. The standards are mainly based on the US and EU emission regulations but differ. For diesel powered engines, these standards are known as

Tier standards. Tier 1-3 Standards are the first federal standards adopted in 1994 for engines over 37 kW (50 horsepower), to be phased from 1996 to 2000 (69).

A statement of principles was signed in 1996 between EPA, California ARB, and engine makers (including Caterpillar, Cummins, Deere, Detroit Diesel, Deutz, Isuzu, Komatsu, Kubota, Mitsubishi, Navistar, New Holland, Wis-Con, and Yanmar) for all non-road diesel engines. These tier standards were set to improve engine technology and reduce exhaust emissions by improving engine design with limited use of exhaust gases after treatment, such as oxidation catalysts (70). These standards are not yet enforced in South Africa, primarily for diesel-powered machines in underground mines.

EPA signed a final rule on 11 May 2004 to introduce the Tier 4 standard. The plan was to use a phase-in approach from 2008 to 2015. The requirement for the Tier 4 standards was to further reduce the emissions of PM and NO_x by a further 90%. This level of emissions reduction can be achieved through control technologies, including advanced exhaust gas after-treatment solutions similar to those required by the 2007-2010 standards for highway engine (71).

Although the sulfur content reduction for Tier 1-3 non-road diesel fuels was not a requirement, the EPA mandated reductions in sulfur content in nonroad diesel fuels from 2007 to enable the sulfur sensitive technological control strategies from 500 ppm in 2007 to 15 ppm ultra-low sulfur diesel from 2010 (70,72). It must be noted that the underground mining equipment for diesel emissions and air quality in mines are regulated by the Mine Safety and Health Administration (MSHA). Further, the overseas government emission standards have yet to be promulgated in South Africa, and adopting improved technologies is company-dependent and not enforceable by the regulatory body department of mineral resources and energy (DMRE).

2.7 Exhaust – Gas after Treatment and Engine Retrofitting Systems/Strategies

An integrated or combination strategy to combat DEE in underground mines is required. The control strategies must follow a standardised approach to risk control hierarchy, including elimination, isolation, substitution, engineering controls, administrative controls, and personal protective equipment (73). In recent years, a focus on replacing diesel machines with electric ones has been considered; however, limitations remain in electric equipment flexibility, build quality, durability, maintenance programs, and other engineering and economic factors (73). In addition, the South African mining industry needs more adequate access to clean engine technologies. Technologies and devices that have been developed to achieve this aim include diesel oxidation catalysts (DOC), diesel oxidation catalytic converters (DOCCs), selective

catalytic reduction (SCR), diesel particulate filters (DPFs), three-way catalysts, thermal reactors, lean NO_x catalysts, lean- NO_x adsorption, plasma-assisted catalytic reduction, flameless thermal oxidation, among others (74).

These limitations indicate that diesel equipment will continue to power an essential part of the underground mechanised mining fleet for some time. Therefore, engineering control strategies that allow the industry to curtail diesel pollutants at their source before they are released into the underground environment should remain central to reducing exposure (73).

McGinn et al. (2002) reported field tests of an underground metal mine where LHD and trucks were tested with DPFs and DOCs. The results showed that three different types of DPFs could significantly reduce EC concentrations compared to the DOC test (75). However, all results exceeded the final DPM exposure limit (3). The study that Ayondhya and Narayanappa conducted in 2018 (76) provided insight into the development of different after-treatment technologies such as diesel particulate filters (DPF), lean NO_x trap (LNT), diesel oxidation catalysts (DOC), selective catalytic reduction (SCR). The layout of the system is defined below: DOC is upstream of CDPF, and its main role is to oxidize HC and CO to produce harmless H₂O and CO₂, and the SCR is downstream of CDPF with a function is to convert NO_x in the exhaust gas into non-polluting NO₂. Finally, the DPF is specially used to deal with PM emissions in the exhaust (68,76). Ayondhya and Narayanappa concluded that a single setup is insufficient to reduce diesel exhaust pollutants completely. However, a combination of devices in a particular order may be required to meet the stringent emission standards; the setup is recommended below:

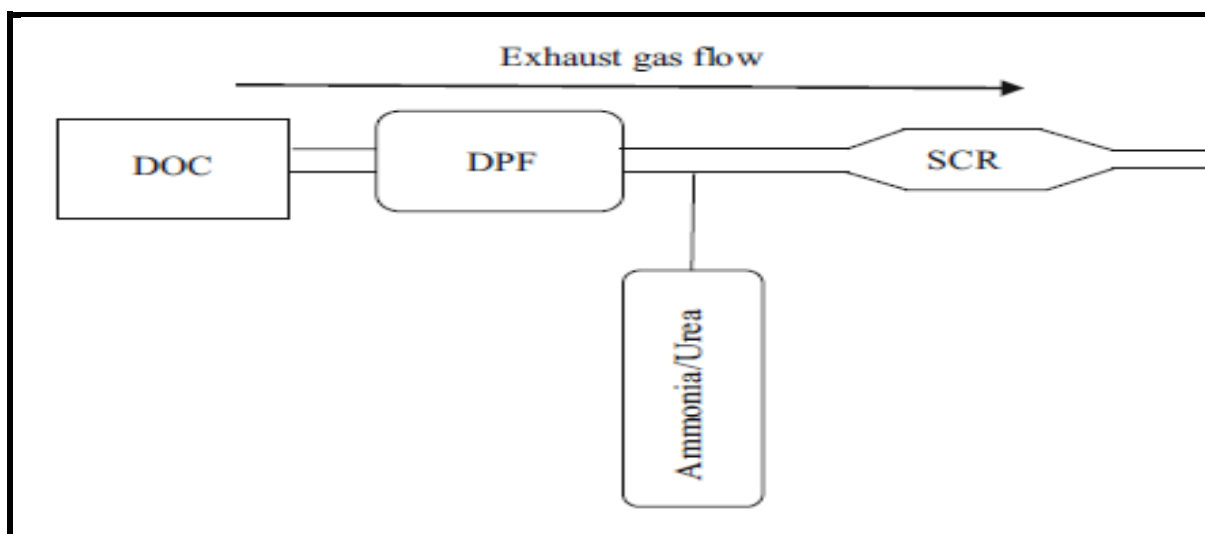


Figure 2.10: Ideal after-treatment set up (adapted from Ayodhya and Narayanappa 2018) (75).

2.7.1 Functional Description of Sintered Metal Filter

The hot exhaust gases from the engine, which contain soot particles, are fed into the housing of the Sintered Metal Filter (SMF). The gaseous components flowing through the microscopic pores of the filter pockets trap soot particles, including fine particulate matter, on the surface and deposit them in the individual filter pockets, as depicted in Figure 2.11 below:

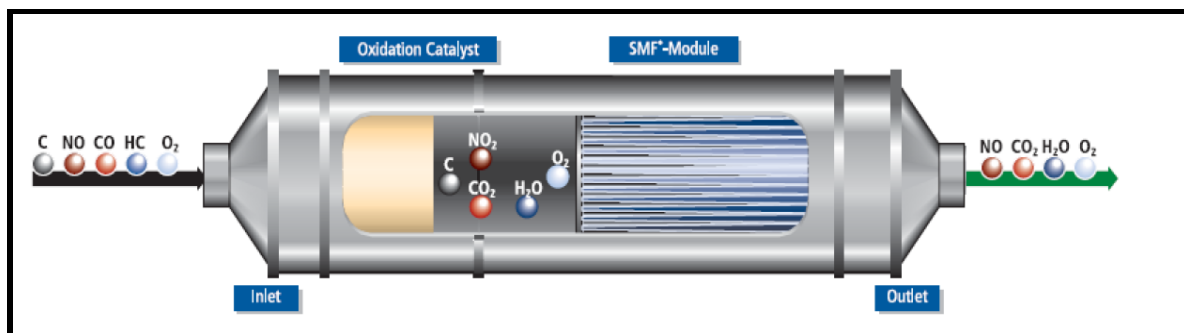


Figure 2.11: Sintered metal diesel particulate filter (Adapted from Kitchen 2021) (76).

The Continuous Regeneration Technology (CRT) effect breaks down the soot collected in the SMF. This system combines a highly efficient upstream diesel oxidation catalyst (DOC) with SMF. The combination is a passively regenerating filter, meaning no external heat sources or additional catalysts (such as liquid fuel-borne catalysts) are required to burn off the soot collected on the filter. For this to work effectively, a reasonably high exhaust temperature is necessary in the application (around 350°C on average) (76). This system set up increased optimisation tuning by continuously and effectively regenerating the deposited soot. The use of exhaust after-treatment devices is sometimes associated with generating secondary emissions. For example, some after-treatment devices increase secondary emissions of highly toxic NO₂ and are of particular concern to the underground mining industry. They have also been observed for DOCs and DPFs coated with platinum group metals (68). However, positive progress has been made in this sphere. In the study by Bugarski et al. 2015, they found a substantially higher reduction of OC and EC mass concentration, and an overall reduction in the total aerosol concentration was achieved by retrofitting the Tier 2 engine with a DPF system (78).

In a study conducted by Bugarski et al. in 2011 reviewing the effectiveness of technology for underground mines under all test conditions, the EPA Tier 4 engine contributed substantially less DE than the US EPA Tier 2 when operated without exhaust after treatment, for the mass concentration of EC and OC, number concentrations of aerosols, concentrations of CO, NO,

and NO₂. It is important to note that the relatively low DPM mass emission was achieved without a DPF system for tier 4 engines and that reductions in NO and NO₂ emissions were partially achieved using cooled EGR and SCR systems (3).

These results further demonstrated that the size distribution measurement indicates that the reductions in aerosol mass concentrations may have been partially achieved through better in-cylinder fuel and air mixing and, hence, reductions in the size of emitted aerosols. The study recommended repowering existing vehicles currently powered by US EPA Tier 2 (and US EPA Tier 3) with US EPA Tier 4 final engines (78).

Although DPF has shown success in reducing the PM underground, there are other shortcomings when it comes to the regeneration of the filters in some cases, depending on the engine type or the technology of the filter. Regeneration is the process of removing PM deposited on the filter. Luo et al. (2023) studied the effectiveness of DFP regeneration (67); they highlighted that During the regeneration process, the temperature of the filter will directly affect the regeneration efficiency by factors such as filter load and exhaust gas concentration. The regeneration process can be carried out during the vehicle operation and will not affect the vehicle's everyday driving during the regeneration process; in this case, the temperature of the filter will directly affect the regeneration efficiency. They further report that in practical applications, soot combustion requires temperatures above 600 °C, but the average exhaust temperature of diesel engines hardly reaches this temperature. Therefore, catalysts or other equipment are used to promote diesel DPF regeneration and reduce the ignition temperature of the soot or increase the exhaust temperature to enable regeneration. Two types of regeneration are active regeneration (a controlled process started by the engine control unit) and passive regeneration (which occurs naturally while the machine is operating). Passive regeneration requires that the exhaust temperature of the diesel engine is sufficient to ignite the particles without additional auxiliary equipment to raise the temperature. However, under normal conditions, the temperature of the exhaust gas has difficulty reaching the temperature required to ignite the soot (67).

2.7.2 *Other Available Control Strategies*

There are currently many control technologies to combat DE emissions in the workplace. The range of technology types, such as biodiesel, synthetic diesel, and water emulsion, can directly reduce the concentration of exhaust gas and PM emissions (53). The use of low sulfur fuel content and fuel additives are examples of some of the available technologies several mines

have adopted. Although the fuel additives can greatly enhance combustion and even reduce the smoke levels, research has shown that they may result in exhaust metallic ash, which may have an additional health impact since they contain metals (38). Therefore, it is essential to ensure that the type of additives used are specifically formulated to lower the exhaust temperatures necessary by burning off the soot collected by the particle filters. Diesel particulate filters are commonly used as part of maintenance in the mines. Diesel oxidation catalysts are also available and critical as part of a reduction strategy; however, the cost of catalytic converters is very high (79).

Maintenance is one of the major controls in the early identification of DEE from diesel-powered underground vehicles (38). The original equipment manufacturers (OEM) have maintenance protocols adopted by the mine maintenance teams to service the equipment. However, these need to be more stringent, as some mines have protocols that appear acceptable for their organisation but are not necessarily in line with OEM requirements. Most mines in South Africa still need to adopt and implement emission-based maintenance programs for all their underground equipment.

It is important to note that emission-based maintenance must be built as part of an engineering control program in all mines using diesel-powered equipment underground for efficient and safe operation of diesel-powered equipment. This is the first step to reducing the worker's exposure to pollutants at the source (11,79). Tailpipe measurements of DPM and gaseous emissions are good tools to assess the state of health status of an engine, and they are also the best way to determine the impact of exhaust cleaning equipment, such as high combustion efficiency.

2.8 Diesel Exhaust Marker

2.8.1 DPM Surrogate

Most studies have identified EC as a better surrogate for measuring DPM. Noll et al. (2015) have studied the metal/non-metal mines to determine if there is a relationship between EC and TC. This study demonstrated a strong relationship between TC & EC in 14 underground mines, even using several control technologies (79). Hedmer et al. (2017) showed a correlation between EC and NO₂ using passive samplers, where diesel exhaust is the only source of NO₂ in the environment (32). Carbon monoxide has also been used as a marker of exposure to DPM in some retrospective studies, showing a (moderate) correlation when compared with EC (81).

However, the letter to the editor distributed by the Oxford University Press in 2011 has disputed the use of CO as a marker for DE exposure in epidemiological studies. They concluded that CO could not be used as a surrogate marker for DE because of the imprecision identified in the methodology (using calorimetric tubes and engine Horsepower) to estimate the CO concentration (37).

2.8.2 *Sensitivity & Suitability for the DPM Markers – interference*

Research has shown that when measuring DPM, DPM mass is prone to interference and that gravimetric sampling methods may not be sufficiently sensitive at low-level DPM in the workplace. The research by Noll and Birch (2008) has shown that when collecting DPM on quartz fibre filters, some anomalies called sampling artifacts may occur, including negative or evaporation artifacts and positive or adsorption artifacts. These artifacts occur through the adsorption of gas phase OC, resulting in a positive or negative bias in the particulate OC and the direct measurement of TC (81).

For the negative artifacts, semi-volatile OC is lost from particles during sampling, resulting in low particulate OC and TC, as the OC, initially present in the air as condensed matter, is lost through evaporation from the filter during sampling. For the positive artifacts, there is OC in the vapor or gas phase, which is present in the air from multiple sources, resulting in artificially higher results of particulate OC and TC, as both the particulate and gaseous OC are quantified (81).

The inorganic component of diesel exhaust, usually measured as tailpipe exhaust gases, is also unstable since it is not covalently bonded and can easily be oxidised in an open environment (81,82). Table 2.3 summarizes the sensitivity of DPM markers.

Table 2.3: Marker for DPM (Noll and Birch 2008) (81).

DPM Marker		
Marker	Interference	Comments
OC	X	Prone to Sampling artifacts
EC	√	Exist in a particulate form only
TC	X	Can change based on sampling artifacts
NO _x , CO, SO ₂ (Environmental Measure)	X	It can easily be oxidised in the open environment
NO _x , CO, SO ₂ (Exhaust after-treatment measurements)	√	It can be used to measure the effectiveness of control strategies It can be used to determine the health of the engine

Note: X – Cannot be the best marker for DPM exposure, prone to interference

√ - Can be a good marker for DPM Sensitivity, Suitability & interferences of the sampling equipment

Sampling equipment can be subject to possible interference. These may include dust, humidity, oil mists, and cigarette smoke (83). The sampling equipment may also not be sensitive enough or suitable in an underground environment. Therefore, the selection process of the equipment to be used must be evaluated to ensure the accuracy of the monitoring system available at the mine. Dilution and sampling methods are vital variables that must be considered to provide accurate and repeatable results (48). The current technology to measure DPM measures the concentration levels of the inhalable or respirable fraction. However, particle sizing instruments exist that have significantly enhanced particle size fraction sensitivities compared to respirable fraction measurements, thus presenting an attractive alternative for PM emission measurement of engines in the future, provided standardised measuring methods are developed.

For this study, the Dekati ELPI+ was used because of its robustness. It also has a dilution device, which can be applied at the ELPI inlet, to allow measurement in an extreme environmental setup, including the exhaust underground. Furthermore, ELPI has a broad operational concentration range, allowing ambient workplace air measurements and the ability to measure directly from a local particle source, such as diesel exhaust. The possibility for chemical analysis of size-classified particles to determine particle source and detailed

characteristics of particles can quickly be done with ELPI. Therefore, it is less sensitive to interferences and is suitable for measuring and analysing data to understand the toxicity degree (83,84).

2.9 Ventilation System & Computational Fluid Dynamics

2.9.1 Ventilation Systems

Ventilation systems are a critical aspect of mine planning. The systems supply the air to the working faces and provide a safe working environment by diluting and removing the airborne pollutants, heat, and gases generated during mining operations. There are two types of ventilating systems: primary and secondary ventilation systems. The primary ventilation system is the central ventilation and cooling infrastructure, including the main surface fans, booster fans, upcast and downcast shafts, vent raises, main airways, bulk air coolers, central refrigeration systems, etc. (86). The objective of the primary strategy is to provide airflow to each section and service zones, in sufficient quantity, at appropriate temperatures, and in quality. Secondary ventilation relates to ventilation control in the actual sections and service zones. Flow-through ventilation is the main ventilation circuit used in mines. Without a primary ventilation system, the secondary systems will never be able to create acceptable conditions. Therefore, both systems must provide a healthy and safe working environment in underground mines (87–89).

Air enters the mine from the surface via a primary ventilation system such as a shaft, a decline, or adits (a horizontal or nearly horizontal passage to an underground mine that can be used for access, drainage, ventilation, and extracting minerals at the lowest convenient level). The air is distributed through the mine via internal ventilation raises, regulators control ramps, and flows with permanently mounted ventilation fans (Figures 2.12-2.15). An auxiliary ventilation system takes air from the flow-through system. It is distributed to the mine workings via temporarily mounted ventilation fans, Venturi tubes, and disposable fabric or steel ducting. Auxiliary fans and duct systems may be forcing systems, where fresh air is pushed into mine headings, or exhausting systems that draw out contamination (secondary ventilation).

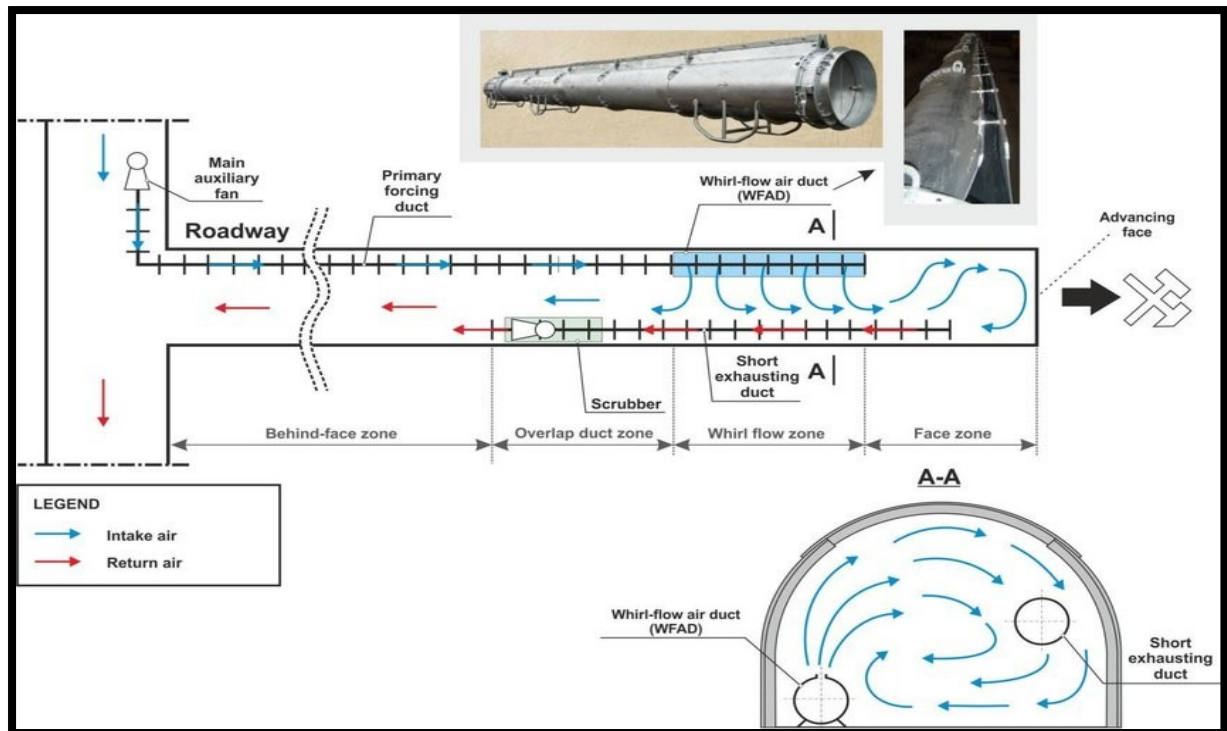


Figure 2.12: Ventilation layout for development end showing intake airway and return airway ventilation flow (Adapted from Obracaj et al. 2021) (88).

2.9.2 Ventilation Layout

The equipment constantly generates gases such as CO, CO₂, or NO_x underground. A method that can control the workplace environment by reducing concentration is crucial. The ventilation layout can be critical in the working faces (90). One of the main functions of the ventilation system is to remove and dilute gases. Unfortunately, this becomes more difficult as the area of the mine expands and the ventilation circuit becomes complex. Development airflow requirements are generally driven by the number of mucking and hauling fleets planned to be used in the section. In the Western Australian (WA) context, applying the Diesel-engine Exhaust Emission (DEE) dilution requirements specified in the Mines Safety and Inspection Regulations, 1995 (MSIR) of 0.05m³/s/kW of installed diesel power requires a minimum airflow of 37m³/s be delivered to face, or working area (26,91). Although mine plans continually evolve, it is essential for far-sighted decision-making to identify overall design constraints and critical design scenarios for the longer term (92–94).

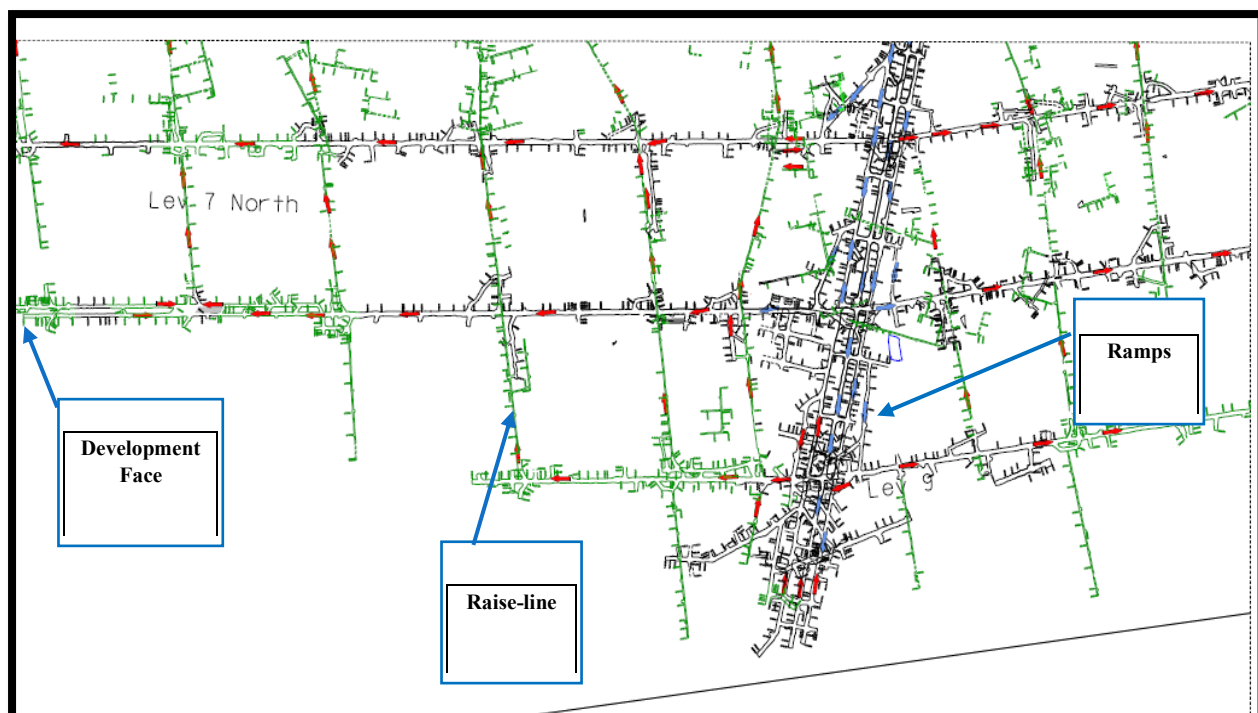


Figure 2.13: The mining layout shows the declines, stopping, and development sections (Adapted from Mine B CAD Mine plan 2022).



Figure 2.14: This schematic diagram shows a closer view of the Ventilation layout for a flat main development end layout (A—adapted from the CAD plan at Mine at B 2022).

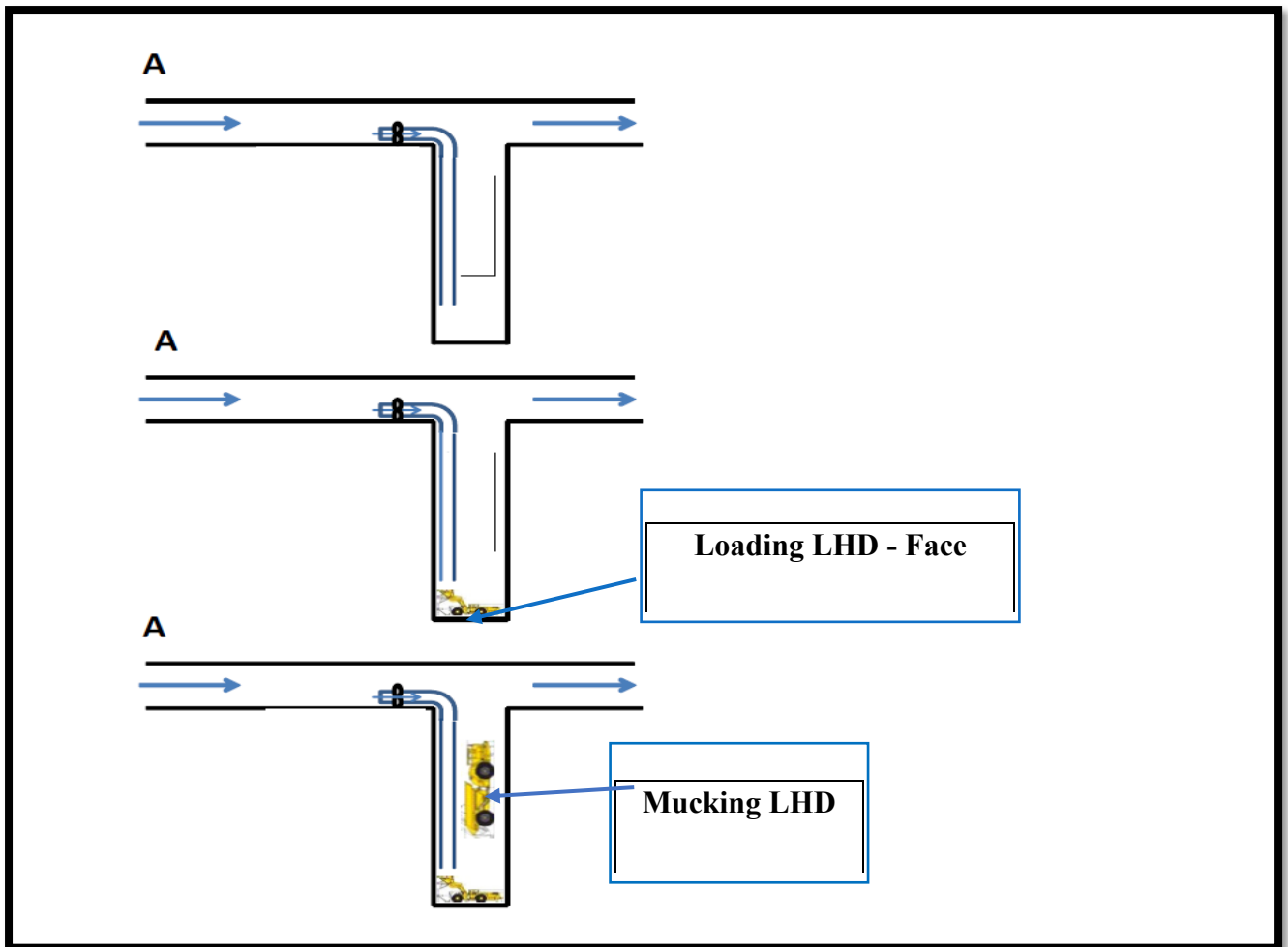


Figure 2.15: Schematic diagram showing a closer view of Ventilation layout for a flat main development end layout with face and mucking LHD's (Adapted from Karsten 2012) (26).

2.9.3 FLUID Flow Dynamics

Fluid dynamics is a branch of fluid mechanics that studies the movement of liquids and gases. Aerodynamics studies the movements of gases and their interactions with moving bodies, whereas the study of liquids is called hydrodynamics. In fundamental fluid dynamics research, three main approaches are considered: 1) theoretical, 2) experimental, and 3) computational modeling and simulations. For theoretical fluid dynamics, the Navier-Stokes equations are used to describe the motion of viscous fluid domains. Fluid dynamics is a research area used extensively in natural science and engineering and is at the center of physics and applied mathematics (95,96). However, despite decades of concerted research, this area has many fundamental unanswered questions due to its complexity in mathematical models. However, progress has been made in this area (95). Mathematical dynamics must generally be validated using experimental measurements to decide on control strategies. The validation of the process requires that the following are assessed: practicability of implementation, competency,

resourcing, and the cost-effectiveness of the preferred methodology. The Governing equations for fluid dynamics are expressed using the Reynolds transport theorem. They are based on the three physics laws of conservation, which include conservation of mass, conservation of momentum, and conservation of energy (97).

Theoretical dynamic simulations are used in the mining industry for ventilation design and planning. In most instances, experimental simulations are built using sensors and software to mimic the natural environmental conditions, including the volume flow, temperature, and gas level sensors. The experimental simulation offers a more robust solution for planning and monitoring; in this instance, an experimental system would benefit employers when monitoring diesel particulate emissions. However, it must be noted that it may be more expensive (due to the cost of devices and materials) than theoretical dynamic simulation but with significant additional benefits to improve the health and safety of workers in the workplace.

Computational fluid dynamics (CFD) has emerged at the forefront of engineering fluid flow analysis due to the increasing need for accurate predictive analysis. However, to perform CFD, one must fundamentally understand the fluid flow from theoretical and experimental perspectives. Further, understanding the environmental pollutant load is also critical before the CFD process can be executed (15,98,99). Further understanding of fluid dynamics is defined in detail below:

Theoretical flow investigation is a simplified and fast method of predicting fluid flow. It is cost-effective and can be applied to standardised cases. The theoretical investigations are supported by mathematical and physics principles (96), and the analysis may form the basis for the computational and experimental methods. The theoretical flow investigation provides knowledge about the flow, which ensures a more qualified point of departure for the computational and experimental methods. This may reduce the cost and time needed to integrate the systems.

Experimental fluid dynamics (EFD) is a physical modelling method for flow investigation. An empirical model is constructed on either a full-scale or model scale, where the flow can be measured at specific points in the model. This allows for precise interpretation of the flow under various conditions. This knowledge can be used in all test conditions requiring special knowledge. The model setup allows for supportive measurements sustaining the numerical investigation from computational fluid dynamics. Furthermore, experimental fluid dynamics

may be applied as the best option in specific cases where existing CFD models are not accurate enough, require incredibly long calculation times, and are costly (59).

Computational fluid dynamics (CFD) is a computer-based simulation method for fluid dynamics investigation. It is applied as a supplement or an alternative to experimental investigations and provides detailed flow prediction. Computational fluid dynamics makes it possible to simulate and describe flows that are complicated, expensive, or impossible to study using experimental techniques. A significant advantage of using CFD is that information about the flow and pressure fields and other related phenomena, such as heat transfer, chemical reactions, or multiphase flow features, are obtained in the fully modelled geometry. This makes CFD an effective tool at the design stage and for optimising and troubleshooting existing installations. Once the CFD model has been set up, geometrical or operational changes can easily be implemented and tested. Computers are used to perform the millions of calculations required to simulate the interaction of fluids and gases with the surfaces used in engineering (15,99,100).

2.9.4 *Ventilation Planning Parameters*

The South African mining industry air volume dilution factor of $0.12 \text{ m}^3/\text{s}$ per kW is stipulated to determine effective ventilation dilution rates over diesel-powered equipment and have a healthy, safe working environment (91). However, many South African mines have adopted a dilution factor of $0.06 \text{ m}^3/\text{s}/\text{kW}$. This factor used during the planning of mine ventilation design to determine the number of dump trucks and load haul dump trucks allowed to load in a development section, based on the airflow design and dilution requirements, to cater for both primary and secondary ventilation systems underground. Mine B's planning and feasibility studies for diesel engine exhaust at a dilution rate of $0.06 \text{ m}^3/\text{s}$ per kW of machinery rate were adopted as the mine standard. The mines adopt this factor to ensure best practices for the safety of the employees (16,91). This project aims to model the main development-end section to determine if additional controlled design parameters are required for the trackless mines. Studies conducted by Zheng et al. 2011 and Zheng et al. 2017 suggest that the CFD can effectively simulate the airflow patterns for the entire mine or single-line headings. The accuracy of the data simulations depends on the accuracy of the input data (96,97).

2.9.5 *Dynamic Simulations*

Ventilation systems form an integral part of underground environmental condition control. The ventilation system is dynamic, as changes in condition in one part of the mine can affect other factors, thus requiring a carefully balanced approach to maintain safe working conditions throughout the mine in real time (108). Ventilation is crucial for diluting ambient gases and particulate matter in underground workings. Further, the literature review has shown that a ventilation strategy successfully manages the risk of exposure to gases and particulate matter, especially in coal mines (89,90).

Mine ventilation network design is traditionally conducted using Hardy-Cross-based dynamic numerical simulators. Computer software packages available and generally used in South Africa are VUMA and VentSim (110). In every case, the mine openings are represented by nodes and branches collectively called a ventilation network. In this network, an airway, drift, or shaft is characterised by a single parameter: the airway resistance can be measured or calculated using Atkinson's equation. The fluid used with the simulator is air or a mixture of air and airborne contaminants. In most cases, this fluid is assumed to be incompressible and of constant density. A fan curve represents the energy source. For a given mine geometry and working face with fixed flow requirements, a simulator is used to determine the airflow/pressure distribution in the network. The results are then evaluated against the flow requirements and other external factors, such as minimum required air velocity, maximum allowable gas concentration, allowable fan pressure, etc. If conditions are not met, the input parameters are modified, and the simulator is executed repeatedly until all the constraints are satisfied (99).

In contrast, Computational Fluid Dynamics (CFD) is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. Computers are used to perform the millions of calculations required to simulate the interaction of fluids and gases with the complex surfaces used in engineering. Zheng and Tien (96,97) successfully used computational fluid dynamics (CFD) to simulate dispersion by ventilation of diesel particulate exhaust from underground mining machinery. In a study conducted in 2011 by Zheng et al. and Li et al. in 2022, the DPM propagation using the CFD method, and when validating the results with experimental and field measurements, the results showed that DPM tends to accumulate near the roof and top area in the tunnel, due to the influence of buoyancy (15,106). Similarly, Yueze et al. (2017) have numerically studied methane and dust dispersion using CFD (19). Xu et al. (2016) have reviewed the CFD

applications in mining engineering research and design, illustrating the success of CFD and highlighting challenging issues (101).

Feroze and Genc (2017) also analysed system variables involving the total amounts in mine development headings. They developed a mathematical formula that can be used to optimise ventilation for any practical scenario using CFD. Once the workplace modelling is done, a critical evaluation of preventative controls can be done, which is key for proper risk management of DEE (98).

It is also important to note that the dilution of underground airborne pollutants largely depends on the particle size distribution of the moved contaminant. Therefore, measuring and controlling the particle size and optimising workplace ventilation are essential (101). In this study, particle size distribution was done using single-dimension computer software.

Previous studies in Computational and Experimental fluid dynamics show evidence that diesel exhaust particles can be linked to a real-time digital monitoring process. Ventilation network software systems can predict the spatial and temporal evolution of DPM concentration and the effect of the ventilation strategy. Most CFD pollutant systems were extensively studied at the coal mines (board and pillar mining method), with limited studies on conventional mining. Further, limited studies exist regarding the use of real-time monitoring data for diesel emission particle concentration. In this study, two underground sections in the conventional mining half level were modelled using a single-dimension numerical modelling/simulation for the pollutant dispersion patterns, namely, the development section includes the intake airway, development face, and the return airway for the section (Figure 2.12). TFD is often used to set up ventilation networks and monitor heat loads and air volume requirements in conventional mines. The TFD can be integrated into experimental fluid dynamics to mimic real-world simulation. These two methods can be used to implement the results output from CFD. The advantage of using the TFD and EFD is that most are already established at the mines and can be easily linked to existing mining digital systems. The TFD can be equipped with sensors for easy monitoring, triggering action response, and decision escalation. This can be immediately taken to a control room set up, as it is easy to update and cost effective.

In the study by Zheng et al. 2011, they studied the DPM and gaseous dissipation using an experimental approach (workplace DPM measurements) to validate the CFD. It was found that CFD simulations can forecast the location of DPM concentration with a practical accuracy of less than 0.15m (96). Another study by Zheng et al. 2017 investigated the effects of tunnel

inclination on the DPM dispersion pattern. It was found that DPM accumulated quickly in the upward dead end due to the combined effect of the roadway inclination and buoyancy; that is, the DPM was hard to remove by the current ventilation. They recommended that CFD be used to study DPM distribution in commonly used working faces and guide DPM reduction strategy. However, they stressed the need to validate models by taking many sampling points to confirm DPM concentration to enable linkage of the CFD and the actual experimental measurements (97).

Diesel engine exhaust spreads to the environment when released from the tailpipe. Previous studies have shown the possibility of using single-dimension (1D), 2-dimension (2D), and 3-dimension (3D) CFD to build models that can assist in strategically managing the exposure pathway. Single dimensions are mainly Hardy-Cross numerical mathematical models used for the simulation of airflow and pollutant dispersion on a larger scale; however, they are not effective in solving complex three-dimensional fluid dynamics as the 2D and 3D because of the assumption that the ventilation flow is laminar as opposed to the 2D and 3D where turbulent flow is considered, such is used mainly in tunnels where bends or complex slopes are uncounted. Further, the single dimension only shows the particle size distribution in a single direction in two or three directions for the 2D and 3D CFD. In 2015, Yu and his colleagues studied the behaviour of DPM in the development-end headings and the effectiveness of auxiliary ventilation systems on DPM dilution. The study aimed to build reliable CFD models to characterise DPM distribution patterns for effective ventilation planning and miner training (107). The study demonstrated that airflow features in the development face highly affect the DPM dispersion. Further, DPM may accumulate in the recirculation areas or complex bends on the structures, resulting in DPM overexposure. Therefore, it is necessary to understand the behaviour (94).

Another 2D CFD by Chang in 2019 was shown to simulate the DPM distribution for a loading activity in an underground development face. The dynamic mesh method was applied to study the motion of the loader. The airflow features and DPM concentration distributions were presented under vehicle motion, and auxiliary ventilation was combined. The simulation results indicated that the current ventilation system failed to maintain the DPM concentration below the limit. The high DPM concentration zones mainly occurred downstream of the loader due to exhaust flow and airflow direction. With the loader working in the development face, the DPM diffused slowly to the caddy. When the loader moved downstream, following the airflow, the high DPM concentration areas upstream were diluted quickly by the airflow, except for the

cuddy, due to the poor ventilation. Their study recommended that experimental studies and 3D CFD further assessments must be done to validate the model; they further suggested that miners working in high-concentration areas should be given additional protective equipment to avoid DPM overexposure (105).

DEE exposure in underground workings is inevitable, especially in confined spaces, and measures to avert the health effects must be considered, especially during the early mine planning stage (93). It is worth noting that redesigning a system and its operation can be very costly and challenging; therefore, critical planning is required at the initial phase of establishing the mine to ensure that all the infrastructure and resources are considered timeously. Most DPM/DEE dispersion studies focused on measuring the workplace tailpipe gases and EC only; very few studies have focused on measuring the particle size and number concentration, which is essential when planning to implement the control strategies.

It is also evident that a multifaceted approach will be required to decide on the best optimised strategies to prevent or reduce exposure at source and implement effective risk-based prevention and monitoring strategies to manage DEE. Even though CFD is a significant tool for studying the dispersion of DEE, this method is not widely used for day-to-day planning at the Platinum underground mines compared to the ventilation network modelling. Ventilation dynamic network simulations have efficiently designed and predicted mine ventilation flows, heat load, and fire prediction simulation. A consideration to further assess this methodology for DEE predictions and monitoring could benefit the Platinum mines as the tool has already been established for mine ventilation and monitoring at most mines. The tool is cost effective, easy to access, and can be used by Ventilation Engineers and Occupational hygienists. It accurately predicts ventilation parameters and can be supplemented easily by CFD and experimental fluid dynamics models.

2.9.6 Digital Mining Data Management Systems

Digitalisation in mining refers to using computerised or digital devices or systems and digitised data to reduce costs, improve business productivity, and transform mining practices (106). For example, fleet and process data/digital management systems are good examples in the mining industry. One such example of a system is the Supervisory Control and Data Acquisition (SCADA) (107). The critical attribute of a SCADA system is its ability to perform a supervisory operation over a variety of other proprietary devices. It can easily be interfaced with other systems, such as ventilation computer software and fire monitoring systems, to

report information in accurate times architecture effectively comprises computers, networked data communications, and graphical user interfaces for high level supervision of machines, processes, and conditions (108). Another key feature of the SCADA system is the real-time control logic or controller calculations, which are performed by networked modules connected to the field sensors and actuators as the system monitors whether certain alarm conditions are satisfied, an alarm event has occurred; once an alarm event has been detected, one or more actions are taken (such as the activation of one or more alarm indicators, and perhaps the generation of email or text messages so that management or remote SCADA operators are informed).

In many cases, a SCADA operator may have to acknowledge the alarm event to deactivate some alarm indicators, whereas other indicators remain active until the alarm conditions are cleared. This enables the teams to respond swiftly and escalate critical or material issues to supervisors and management, allowing for effective management. In the Occupational Hygiene and Ventilation space, monitoring systems such as those tracking blasting fumes, and gas ventilation air flow are used effectively to measure effective ventilation and blasting clearance. Recently, mines have been improving on using fibre optics underground to integrate data systems into centralised (control room) systems (107).

Another advantage of digital mining data systems is Real-Time condition monitoring for equipment and conditions. In a study conducted by Alla et al. in 2020 (108), strategic maintenance real-time condition monitoring (RTCM) was evaluated as the ability to perform real-time condition monitoring and alert maintenance and operations of abnormal conditions (106).

Strategic maintenance is crucial in ensuring haul trucks' high availability and utilization. As equipment began to grow more complex towards the end of the 20th century, there was a need for a proactive maintenance strategy, which led to the development of condition-based maintenance. RTCM is the ability to perform real-time condition monitoring and alert maintenance and operations of abnormal conditions. The alarms can be automated and used as an indication of a problem. If suitable corrective action is initiated in time, it could significantly save equipment downtime and repair costs. This study compares maintenance performance indicators before and after implementation (109).

CHAPTER 3 – STUDY METHODOLOGY

This chapter describes the methodology used in the study. The study area and population are described in the first paragraph, i.e., the characterisation of trackless mobile machinery at the mine, including their make, rated power, tier engine make, and age. Next, the methods used for sample collection are detailed, including the type of sampling equipment and operation parameters. The paragraph explains the sampling requirements and setup for the tailpipe diesel emissions and defines the operation mode at which the machines were sampled. Baseline tailpipe samples were measured, and improvement interventions were applied viz; Maintenance, and maintenance, plus retrofitting the machines with diesel particulate filters. The Original Equipment Manufacturer (OEM) maintenance protocol was reviewed against the mine planned maintenance orders (PMO) systems, and the maintenance profiles were completed for all the machines. The measuring method is extensively explained in this chapter. All the aspects of quality control and documentation of protocols and standards and related mathematical equations for ventilation dynamic simulations are presented.

3. STUDY METHODOLOGY

3.1 General study description

The study approach was a quantitative quasi-experimental designed study with an intervention component. The study methods are divided into three sections, i.e., measuring emissions at source on trackless mobile machinery (TMM) tailpipe, measuring the underground environmental emissions, which includes diesel particulate matter (DPM) personal exposure using EC as a surrogate measure for DPM, and the evaluation of airborne pollution dispersion within the underground environment once it is emitted from the source. The tailpipe measurements, taken at the underground workshops at mine A and at the surface workshop at mine B, were as follows:

1) Measure the total particle emissions of diesel engine exhaust at the tailpipe of TMM. Measurements were taken in two phases, viz; baseline measurements before interventions for mine B. Mine A did not undergo a true baseline; however, the measurements were taken before the filter, and the measurements have been deemed a baseline. Exhaust gasses were measured directly from the tailpipe of the trackless mobile machinery. The results were used to evaluate the effectiveness of maintenance and maintenance plus retrofitting the machines with diesel particulate filters.

2) Personal sampling of diesel particulate matter (DPM) underground, analysing total carbon (TC) and elemental carbon (EC). EC was chosen as a surrogate measure of DPM, and

3) Simulations regarding diesel exhaust once emitted into the work environment. A ventilation simulation program was used to evaluate the flow patterns of the DPM at the underground workplace. This part of the study aimed to build a model to characterise DPM distribution patterns and simulate the dilution of concentrations by effective ventilation planning and other interventions to improve underground environmental conditions.

Two Platinum mines were selected for the study, although the type of mining method and type of trackless mobile machinery employed at the two mines differed. Mine A was comprised of lower power (kilowatts (kW) -rated) machinery, it also included the primary loading fleet and the drilling fleet, whereas Mine B included the primary loading fleet only.

The intervention part of the study aimed to lower the engine emission and comprised two regimes: 1) implementation of strict maintenance protocols as defined by the Original Equipment Manufacturer (OEM) and 2) additional retrofitting with diesel particulate filters (DPFs). Overall, the intervention focused on evaluating the direct impact of maintenance and/or maintenance, plus installing retrofitted diesel particulate filters (DPF) on the machines. Baseline measurements, i.e., pre-intervention, were conducted for particle number concentration and exhaust gasses at the tailpipe of the machines.

The second part of the evaluation of the impact of the interventions was related to workers' exposure to diesel emissions during the loading activities underground.

Lastly, ventilation flows and temperatures were verified from the monthly inspection records at the underground development headings/end and main decline sections. Ventilation officers record the inspections on routine underground planned inspection documents. This information was used to verify design versus underground conditions and the tailpipe emission data to develop a DPM exposure prediction model/simulation in the underground shafts workplace using a computational fluid dynamics (CFD) tool. The assumption here is that the operation of diesel-powered equipment is the only source of CO and/or EC.

3.1.1 Study population and sampling strategy

The study was performed in two underground platinum mines in the Limpopo province. The two mines employ different mining methods, which are conventional and bord/pillar mining methods. However, regardless of the differences in the mining methods, both methods use

diesel-powered mobile machinery for loading and hauling ore from blasted faces to conveyor belts, which then convey the ore to the surface stockpile for processing. Diesel-powered machines are the primary source of diesel emissions during load and haul processes.

The study's initial phase was conducted in mine A and included 10 trackless mobile machines (TMMs) comprising six LHDs, two roof bolters, and two drill rigs. These machines' primary functions are loading and hauling the ore, installing support by drilling the roof bolts on the hanging wall and drilling the face.

For mine B, 41 TMMs were selected from the primary fleet. The 41 machines were planned to be installed with diesel particulate filters (out of the total 73 TMMs at the whole mine). Mine B measurements took place at the surface workshop, as the mine did not have an underground workshop. The 41 machines included 23 LHDs and 18 Dump trucks.

3.1.2 TMM Engine Design Composition

The TMMs' engine series was mainly Volvo and Detroit, the tier type was TIER II engines, and the engine rated power ranged from 224 kilowatts (kW) to 405 Kw. The engine operating hours ranged from 280 hours to 16 527 hours. Based on the engine operating hours and engine-rated power, TMMs were divided into three (3) study categories: A, B, and C, as presented in Table 3.1.

Table 3 1: An overview table of the TMM population by category

<i>Machine Category</i>	<i>Machine power (Kilowatts)</i>	<i>Machine Age (running hours)</i>
<i>Cat A: ≤ 4000 Engine hours</i>	224 – 404 kW	280 - 3868 hours
<i>Cat B: $>4000 \leq 10000$ engine hours</i>	224 – 405 kW	4071 – 7895 hours
<i>Cat C: ≥ 10000 engine hours,</i>	175 – 392 kW	10200 – 16060 hours

3.1.3 Study Population – Category A: Engine hours ≤ 4000

- A total of 14 machines were selected for category A,
- Engine type was tier II for all 14 machines
- Engine power or Kilowatts (Kw) included
 - o 224Kw – 2 machines
 - o 256Kw – 2 machines

- 352Kw – 1 machine
- 392Kw – 4 machines
- 405Kw – 5 machines

Intervention Strategy – Category A

- All the machines underwent baseline measurements where tailpipe exhaust gasses, particle number, and size concentration were recorded using an exhaust gas measuring equipment and a size-selective particle monitor, respectively.
- All machines underwent 250 operation hours-weekly scheduled maintenance, and post-maintenance measurements were taken
 - Seven machines underwent maintenance only (as per 250h-maintenance plan), and
 - Seven machines underwent a 250h- maintenance plan and were also fitted with Wall-flow Actively regenerating sintered metal diesel particulate filters (DPFs)
- The measurements were carried out in a stationery mode at the surface workshop. The engines were evaluated for low idle and snap acceleration (high transient RPM)

3.1.4 Study Population – Category B: $>4000 \leq 10000$ engine running hours.

- A total of 14 machines were selected for Category B
- Engine type was tier II for all 14 machines
- Engine power or Kilowatts (Kw) included
 - 224Kw – 5 machines
 - 256Kw - 2 machines
 - 392Kw – 6 machines
 - 405Kw - X1 machines

Intervention Strategy – Category B

- All the machines underwent baseline measurements where tailpipe exhaust gasses, particle number, and size concentration were recorded using an exhaust gas measuring equipment and a size-selective particle monitor, respectively.
- All machines underwent 250h and a 500h (after three weeks) scheduled maintenance, post measurements were taken after the machines

underwent the 500 scheduled maintenance (approximately after 4 weeks post-baseline)

- Seven machines underwent maintenance only for 250h and 500h- maintenance plans) and
- Seven machines underwent 250h and 500h maintenance plans and were also fitted with Wall-flow Actively regenerating sintered metal diesel particulate filters (DPFs)
- The measurements were carried out in a stationery mode at the surface workshop. The engines were evaluated for low idle and snap acceleration (high transient RPM)

3.1.5 Study Population – Category C: ≥ 10000 engine running hours.

- A total of 13 machines were selected for Category C
- Engine type was tier II for all 13 machines
- Engine power or Kilowatts (Kw) included
 - 220Kw – 3 machines
 - 256Kw – 3 machines
 - 354Kw – 1 machine
 - 392Kw – 6 machines

Intervention Strategy – Category C

- A total of 13 machines were selected
- All the machines underwent baseline measurements where tailpipe exhaust gasses, particle number, and size concentration were recorded using exhaust gas measuring equipment and a size-selective particle monitor.
- All machines underwent 250, 500, and 1000 hours of scheduled maintenance, post measurements were taken after the machines underwent the third scheduled maintenance of 1000 hours (approximately after 7 weeks post-baseline)
 - Six machines underwent maintenance only for 250h, 500h, and 1000h maintenance plans) and
 - Seven machines underwent 250h, 500h, and 1000h scheduled maintenance plans and were also fitted with Wall-flow Actively regenerating sintered metal diesel particulate filters (DPFs)

- The measurements were carried out in a stationery mode at the surface workshop. The engines were evaluated for low idle and snap acceleration (high transient RPM)
 - Cat C: $\geq$ machines tested after the third maintenance at 10000 hours
 - All the machines underwent the scheduled maintenance schedule for 250 hours (week 1), 500 hours (week 3), and 1000 hours (week 7)
 - The maintenance intervention strategy was further divided into two parts of intervention, namely a full maintenance protocol and a full maintenance protocol plus an installation of a diesel particulate filter (DPF); however, for sampling and analysis purposes, the three maintenance categories (A, B, and C) were sampled after the TMM underwent maintenance protocol at either 250 (category A), 500 (category B) and 1000 (category C) maintenance schemes.
 - Baseline measurements were taken at the beginning of the study, and the engine hours were recorded accordingly. Post measurement followed a planned maintenance and/or maintenance and an installation for DPF.

3.2 Interventions regimes

Mine A's equipment was on hourly-based scheduled maintenance, meaning that all TMM were planned for maintenance at 250, 500, and 1000 hours as the Original Equipment Manufacturer (OEM) recommended. The normal life-cycle of machine maintenance is such that a machine will undergo 250 hours of maintenance on week 1, on week 3 of operating it, then undergo maintenance that covers 500 hours, and the 1000 hours of maintenance, which is then done in week 7 to complete the full maintenance cycle, at which the machine goes through the repeat cycle until it reaches a stage where it goes for rebuild or scrapped depending on final assessment at 16000 hours which is approximately four (4 to 5) years.

Before the study, Mine B's maintenance strategy was based on usage-based maintenance. TMMs were undergoing weekly spot checks at the service maintenance station before proceeding underground, and only major maintenance was performed when the TMM was on break down. The intervention maintenance was generally to adopt the OEM maintenance plan, which recommends maintenance at 250h, 500h, and 1000h of equipment usage as Mine A; however, for Mine B, the intervention further included daily torquing of hydraulic systems

because, during the breakdown review, the workshop breakdown stops were mainly due to hydraulic pipe system failures.

The study population at Mine A and Mine B were not fitted with any particulate filtration systems before the study. No modification or removal of mechanical components or devices was made except for the DPF. One (1) Diesel Particulate Filter was fitted for machines with a kilowatt power rating of 200kW, and two (2) DPFs were fitted for machines with a kilowatt power rating of ≥ 300 kW kilowatts.

The following aspects were included in the maintenance protocol:

- At mine A, the maintenance interval of 250 operating hours, the engine was serviced, and the following checks were done:

Table 3.2: Summary of engine maintenance checks per intervals

<i>Maintenance schedule</i>	<i>Maintenance Requirements</i>
<i>250 hours</i>	• Engine oil replaced • Oil filters replaced • Diesel fuel filters replaced • Engine air filters replaced
<i>500 hours</i>	• Engine oil replaced • Oil filters replaced • Diesel fuel filters replaced • Engine air filters replaced • V-belts replaced.
<i>1000 hours</i>	• Engine oil replaced • Oil filters replaced • Diesel fuel filters replaced • Engine air filters replaced • V-belts replaced. • The fuel injectors are replaced • The valve clearance is set • DPF filters are cleaned

The same protocol was adopted for Mine B. However, it included daily torquing of hydraulic pipes. Mine A's equipment used 10 ppm diesel, and mine B's used 50 ppm diesel sulphur content.

3.3 Sampling strategy and methods

The sampling was carried out over 3 months in Mine A and 6 months in Mine B. The true baseline measurements in Mine B could be done due to the timing of the installation of the new diesel particulate filters (DPF). However, all measurements were taken before DPF (raw engine exhaust) and after the DPF to mimic the intervention. Due to the nature and design of Mine A and the fact that the TMM maintenance workshop was underground, the tailpipe measurements of the selected 10 TMMs were taken at the workshop underground before and after routine maintenance. To ensure the quality and consistency of the results, the TMM engine was warmed up for 10 minutes before taking the sample. Samples were taken for each TMM while revving on an idling more and in high Revv mode.

A similar approach was followed in mine B, where the measurements were taken at baseline (before the machine underwent any maintenance). Mine B also excluded the drill rigs and bolters (secondary fleet) because the secondary fleet is mostly stationed underground, and the maintenance schedule is needed to allow the constant movement of the machines to come to the surface. Pre (before) and Post (after) will be used interchangeably within the report.

3.3.1 *Measuring method*

The TMMs' DPM emissions were characterized by the cumulative (5 min) real-time particle concentration over the 14 size bins of the low-pressure particle impactor (Dekati ELPI®+) with no repetition of each measurement and further analysis of the particles to determine their chemical composition. The instrument was assembled at the underground and surface workshops for Mine A and Mine B, respectively, where measurements took place. It was switched on 30 minutes before measurement to stabilize the electrometers.

Only single (i.e., no duplicate or triplicate) emission measurements were taken with the Dekati ELPI. This is because it is a complex machine that requires delicate connections and setting up before use; with the time constraints during production to measure the emissions, time management was needed to enable the machines to stay within the production cycle and to prevent delays. A justification was derived from the analysis of repeated (three) Exhaust gas measurements taken on two machines. Statistical analysis revealed no significant differences within the measurement sets. The p-values of 0.97 and 0.19 demonstrate this for the idling and high revv machines. (See Table 3.3).

Table 3.3: Triplicates statistical paired t-test results for tailpipe exhaust gasses

Variable	Mean	Standard deviation	95%CI	P-value
Idle - CO, NO, NO _x , NO ₂	248	112.5	129-366	0.97
High Revv - CO, NO, NO _x , NO ₂	531	74	452-609	0.19

**p-value significant at 0.05, IQR – interquartile range*

The systems were checked and calibrated before the Dekati ELPI and the Testo 350 measurements were taken. The Dekati ELPI+ has a functional report if the machine is out of calibration, has increased system temperatures, has a dirty corona needle, or has a drop in system pressure during the measuring process. Those sample results were deleted, and new samples were taken.

The Testo 350 also flashes if there are system errors; the samples were discarded in such cases, and new measurements were taken accordingly.

3.3.2 Diesel Particulate Filters – Installation and Layout

The functioning of DPF is critical and sized according to the manufacturer's specifications. The filters are sized according to the engine rated power, exhaust gas flow rate, and back pressure limits and specified by the engine manufacturer. For the purpose of this study, all diesel equipment with a rated power of ≤ 250 kW were installed with one DPF; this was specifically for the LHDs as presented in Figure 3.1, and the machines with engine rated power of >250 kW were fitted with two DPFs, these specifically were the dump trucks as presented in Figure 3.2.

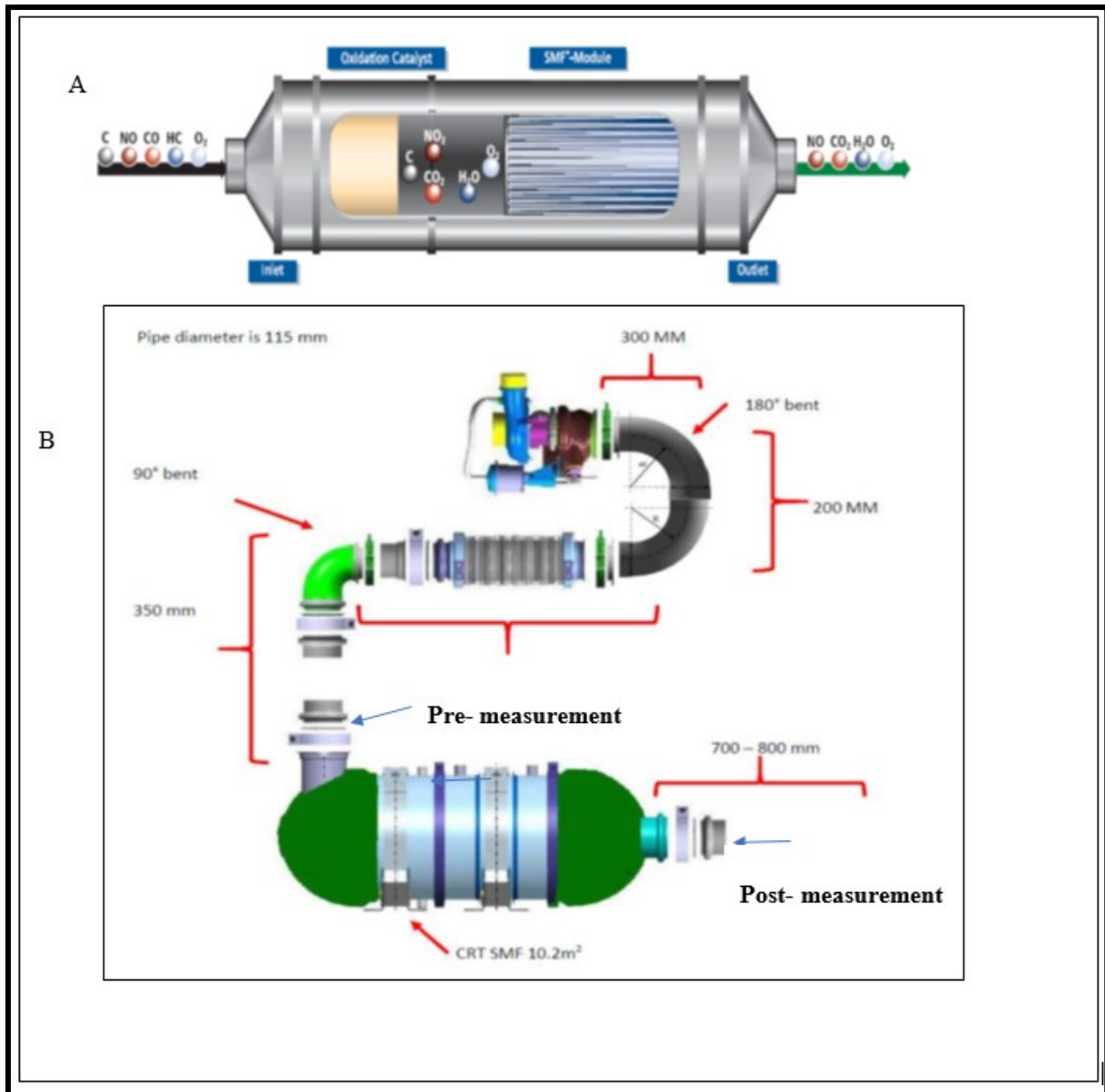


Figure 3.1: (A) showing the type and make of the filter, (B) showing the layout and piping for the LHD installation with rated power of $200kW \leq 300kW$ (Adapted by Kitchen 2021) (76).

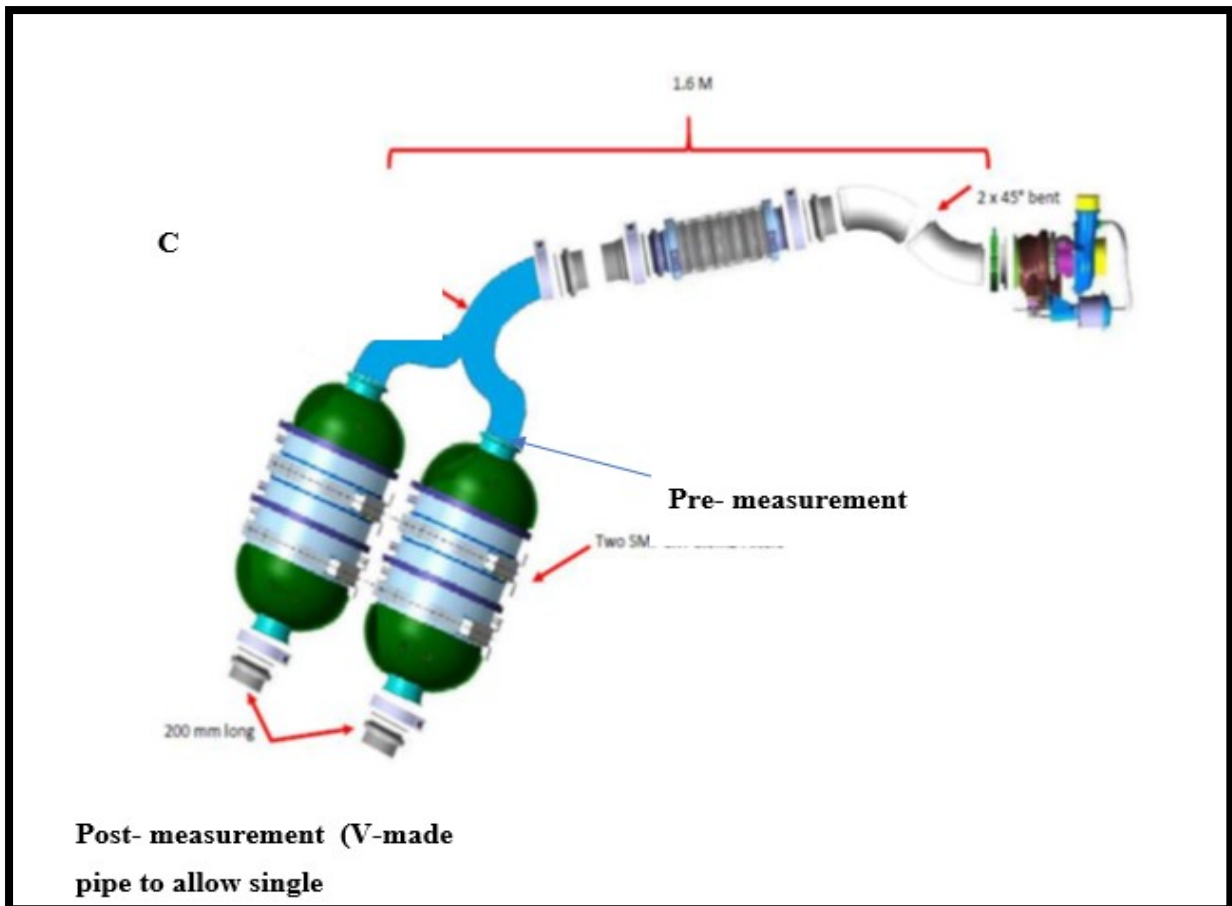


Figure 3.2: The layout gives an indication and piping for the LHD and dump truck installations with a rated power of $\geq 300\text{kW}$ (Adapted by Kitchen 2021) (76).

3.4 Tailpipe measurements

Two types of measuring equipment were used to address objective 1: the ELPI+ (Dekati, Finland) for particle size concentration and distribution measurements and the Testo 350 gas measuring instrument (Testo Germany, 2021) for measuring tailpipe exhaust gases.

Based on the maintenance strategy currently used at the mine, the selected primary trackless mobile machinery was subjected to pre-intervention/baseline measurements as it reached the service workshop.

3.4.1 Tailpipe Particle and size concentration measuring Instrument - Dekati

A Dekati real-time Electrical Low-Pressure Impactor, the ELPI®+ (Finland 2018), was used to measure the size-selective particle concentration and the size distribution of the particulate emissions. This instrument is well-characterized for real-time particle size distribution and concentration measurements with 14 size bins of the particle size range from 6 nm - 10 μm . It is equipped with a cyclone to control possible interference by larger particles. A density of 1

mg/ μ l was assumed as a default for the measured aerosol. However, it must be noted that previous studies have shown that the density of DEE can vary depending on the aerodynamic size, diameter, size of the machine, and activity (high load versus light load). The literature review by Rissler et al. (2013) mentioned the effective density measurements of the primary particles constituting the soot core of ~ 2 g/cm³ and the effective density of the agglomerated soot particles is lower and may substantially decrease with size to less than a factor of ten of the material density (109).

ELPI®+ measures size-resolved particle number concentration, enabling particle size distribution in real-time at a 10 Hz sampling rate. The ELPI®+ operating principle can be divided into three stages: 1) particle charging, 2) inertial size classification of the particles in a cascade impactor, and 3) electrical detection of particle charge with sensitive electrometers. This enables real-time particle size distribution and total concentration measurements with one measurement method and one instrument throughout the complete size range. The impactor can be heated up to the sample temperature to avoid condensation and sample transformation; this is made possible by thermocouple controllers connected to the machine. The instrument is suitable for measuring tailpipe emissions and considering the high particle temperatures when leaving the exhaust system.

Particles are classified based on their inertia, with larger particles collected in the upper impactor stages and smaller particles collected in the lower stages. First, the particles pass through a unipolar corona charger, charging up to a known positive charge level. Depending on their aerodynamic size, the particles are then size-classified in a cascade impactor into 14 size classes/bins.

All the impactor stages are electrically insulated from each other and connected to an electrometer. As the charged particles collect in the different impactor stages, the electrometers detect the charge they are carrying. This measured current signal is directly related to the number of particles, thus enabling the ELPI®+ to measure particle number size distribution and concentration in real-time.

The Dekati ELPI+ has integrated flow control and pressure adjustment. It can be operated independently, stand-alone, or controlled via laptop using ELPI®+VI software, automatically converting the data into a logarithmic format without complex formulas. This enables the ELPI+ to produce the normalised particle number and size concentration per bin size (dN/dlogDp).

Each ELPI®+ unit is individually calibrated before delivery; the calibration includes a detailed determination of the exact sample flow rate and D50% values, and the certificate is attached to Appendix 3. Further, the instrument is calibrated before and/or during the measuring process, and the following steps were performed:

1. Air-zeroing/Flushing of the instrument after each measurement before commencing with the following vehicle/machinery was conducted.
2. A constant clear graph was measured to ensure that air-zeroing was successful.
3. If the instrument was dirty, a thorough cleaning was done, including the opening of cascade cyclones and cleaning the corona charger before new samples could be taken.
4. The impactor low pressure was adjusted and set at 40mbar.
5. Compressed air was connected to the air conditioning system's unit, and double diluters were also connected. The compressed air pressure was set at three mbar to achieve appropriate dilution. TMM was warmed up for a sufficient period (10 minutes) before taking measurements. The full sample was taken for at least 5 minutes (idling and revving); the reason for that was to allow enough sample through the ELPI and to prevent overheating of the equipment due to sample overload, which presented itself by flashing on the screen of the ELPI+.

Each test mode was supposed to be conducted for a minimum of 10 minutes (adopted from the Mine Health and Safety Council – Methodologies for measuring DEE and DPM (57)). All measurements were also supposed to be collected at the exhaust discharge point of the tailpipe. However, this could not be achieved because the instrument flashes “high concentrations” on the screen when taking pre-filter/raw exhaust DPM emissions. Therefore, the measurements were limited to 5 minutes each for both modes to avoid clogging up the device.

3.4.2 *Tailpipe Gas measuring Instrument*

A Testo-350 professional portable measurement system of industrial emissions (TESTO, Germany 2021) was used to measure tailpipe exhaust gasses, including CO, NO_x, NO, and NO₂. The instrument has a tailpipe sampling probe, making it easy to sample. The control unit is the removable operation and display unit of the Testo 350. The measurement results are presented via the colour graphic display. The unit also has an internal memory, which is used for data management.

The measurement technology is situated in the analyser box. The robust housing has integrated impact protection. Contamination of the instrument is almost eliminated since inherently closed

chambers protect the instrument's interior from dirt from the surroundings. As an alternative to the control unit, the operation can also be carried out in direct connection to a PC or notebook or via an Android smartphone or tablet with the free App. After programming, the analyser box carries out measurements and stores measurement data independently.

The air sample is pulled from the tailpipe using the probe's tip into a built-in second probe through a hose assembly. It is then moved to the combustion analyser, where exhaust gasses are filtered, water is removed, and the sample passes over the gas sensors before it gets to the analysing part. The sampling path is performed to ensure that the hoses are leak-free.

Zeroing and system checks were conducted to ensure no residues in the gas sensors by allowing oxygen to flow through while the instrument was running. Before sampling and between measurements, a 30-second warming-up phase was allowed. Each TMM was measured during idling and high revving (on a transient cycle), and both modes were evaluated at baseline and after the intervention.

3.4.3 *Carbon monoxide personal monitoring*

Personal workplace carbon monoxide (CO) monitoring was done using the wearable gas detection instrument GDI Sentinel Gas detection system. The GDI Sentinel Instrument is a multi-gas detection instrument that measures oxygen (O₂), methane (CH₄), and CO continuously during the shift in a workplace. It is worn by the supervisors in that section to check if a workplace is safe before work starts and during the shift. The GDI continuously measures workplace air and utilises wireless data for communication and downloading. The firmware has a storage capacity of up to 16,000 gas events.

The GDI is inspected and calibrated, while the response time and visual alarm parameters are checked automatically. The Sentinel sensors auto zero, and the instrument flashes red at 5 seconds intervals until the instrument is tested. The instrument responds to the CH₄ and the CO test gas alarms within 20 seconds and 45 seconds, respectively, up to 80% of the applied gas concentration. The response time is checked on the second timer, where the final reading is recorded after 60 seconds. The instrument is pre-programmed with predefined alarm levels for each of the gasses. If a gas concentration exceeds a predefined alarm level, the instrument will alarm and indicates the type of gas and vapour that caused the alarm.

The GDI has geochemical sensors installed at the instrument's rear side with inlet ports. Air is drawn into the instrument through these sensors, which can read up to 5% CH₄ and 999 ppm CO. If the instrument is exposed to higher values, it will latch into the over-range. The sensor

value will change from white to the corresponding associated gas colour to indicate which sensor's pre-programmed alarm level was exceeded. The alarm will clear as soon as the level is below the pre-programmed alarm level. An alarm image will indicate the risk associated with this alarm, and an audible and visual alarm will also be activated.

The instruments were issued to the supervisors and section-competent persons at the start of the shift and collected back at the end of the shift. The instrument measures in real-time and calculates at 8 hours' time-weighted average (TWA). At the end of the shift, this needs to be downloaded and exported into Excel sheets to assess if there was any over-exposure.

3.4.4 Personal particle exposure measurements

For personal measurements underground, 34 employees were randomly selected based on the description of the activities related to their job title occupation from selected homogeneous exposure groups for sampling (HEGs) as per Table 3.4.

Table 3.4: Population underground personal sampling for DPM

<i>Sampled Occupation</i>	<i>Job title/ Job Description</i>	<i>Day Shift</i>	<i>Night Shift</i>	<i>Total</i>
<i>TM3 Dump truck Operators</i>	Haul ore and waste	4	6	10
<i>LHD Operators</i>	Haul ore and waste	4	10	14
<i>Drill Rig Operator</i>	Drilling development heading	2	1	3
<i>Roof Bolter Operator</i>	Drilling of hanging wall	0	2	2
<i>TM3 Dozer</i>	Dozing ore into LHD	0	1	1
<i>TM3 Miner</i>	Crew Supervisor	1	2	3
<i>Shift-boss</i>	Mining supervisor	1	0	1
<i>Total number of samples</i>		12	22	34

Higher risk employees for diesel particulate matter included diesel equipment operators, and supervisors in an environment where diesel vehicles are routinely sampled. The 2019 sampling data was used as a baseline (pre-intervention) for DPM (specifically elemental carbon (EC), and total carbon (TC) prior to the intervention on the trackless mobile machines. Post-intervention sampling (when all TMMs were fitted with DPF) was conducted in April 2022 for the same job titles but not necessarily the same employees previously sampled in 2019.

Gillian-air pumps were used for personal sampling, and two methods were used to analyse or assess the DPM personal exposure. The NIOSH 5040 method was used to sample the respirable fraction of EC and TC on the same filter to represent exposure to diesel particulates. An SKC DPM 37mm diameter cassette and a GS-1 single-inlet cyclones were used for sampling and were held together with a filter cassette/cyclone holder accessory for this configuration as a sampling medium.

The GilAir plus sampling pumps were calibrated and set at a flow rate of 1.7 L/min, and the cyclone was attached to the employee's breathing zone. The pumps were run throughout an entire shift of 8 hours, and the analysis was based on the time-weighted average (TWA) of 8 hours. At the end of sampling, post sampling flow rate was 5% deviation from pre-calibration) using a DryCal volumetric flow meter. Sampling filters were transported to the laboratory for analysis.

The 2019 baseline exposure data monitoring used a sampling methodology similar to April 2022. The results were analysed at the accredited laboratory CHEMTEC for all the samples. Further, similar occupations were sampled. However, it must be noted that although samples were taken at the development heading area, the actual working place had changed between the baseline period (2019) and the current sampling.

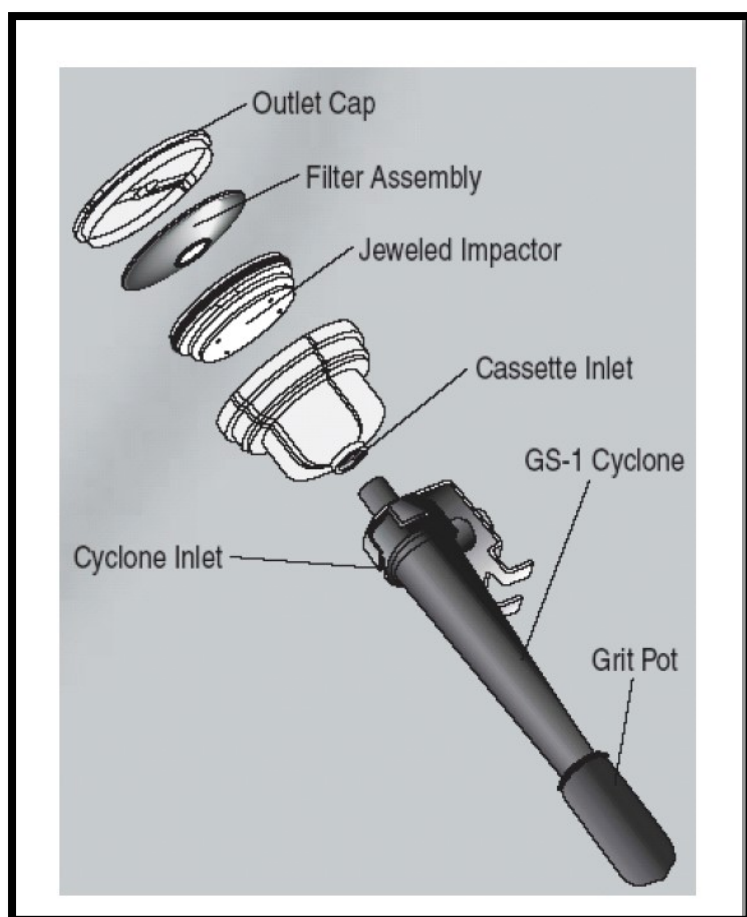


Figure 3.3: Image of the GS-1 single-inlet cyclone: Adapted from SKC Particulate Sampling (111).

3.5 Data Analysis

The data generated and logged by the direct reading instruments were downloaded into an Excel spreadsheet for analysis. Once the laboratory results were received, the personal sampling data was recorded on a spreadsheet.

Data pre-processing for the ELPI+ data was done as follows.

- Verification was done to check if all samples ran for a full 5 minutes in both the idling and high-revving modes,
- Spikes were checked on the graphical presentation to ensure there were no negative recorded spikes, which are indicative that the sample did not stabilise through the ELPI+,
- Outliers were removed from the sampled data.

For further analysis, the data was divided into two different sections;

First, The ELPI+ data for particle concentration consists of 14-size bins. For analysis, the data of various size bins were combined into three size fractions, which are defined as follows:

- “ultrafine” : ≥ 0.0019 size bin $< 0.3123 \mu\text{m}$
- “fine”: ≥ 0.312 size bin $< 2.002 \mu\text{m}$
- “respirable”: ≥ 2.002 size bin $< 7.259 \mu\text{m}$

Second, the analysis of particle size-fractions was further categorized per machine hours as defined for category A (250 to 4000 engine running hours), B ($> 4000 \leq 10000$ engine running hours), and C (≥ 10000 hours)

The ‘total’ or ‘overall’ particle number concentration was also assessed. The impactor generated this concentration based on particle numbers, normalised for bin width ($dN/d\log D_p$, where dN = particle concentration and D_p = particle diameter), and processed by the device software to generate particle size distributions.

The mass concentration was calculated from the particle number concentration (also using built-in software), assuming the default effective density for aerosols of $1 \text{ mg}/\mu\text{l}$.

The effectiveness of the DPF system in reducing tailpipe emissions was calculated as:

$$\text{Efficacy} = \frac{\text{Pre DPF system emission} - \text{Post DPF system emission}}{\text{Pre DPF system emission}} \times 100 \quad (a)(116)$$

The following statistical tests were carried out using Stata version 17.1 and Excel MS pack:

The data was tested for normality and was found to be not normally distributed. Therefore, non-parametric tests were deployed for statistical inference, with the median and interquartile ranges (IQR) provided as summary indices for the data. Wilcoxon signed-rank test to compare medians for total particle number and size fraction concentration, intervention strategies, exhaust gasses concentration, workplace CO concentrations, and personal monitoring concentrations for the before and after intervention. For unpaired data (personal sampling and CO sampling), the Mann Whitney U test was used to compare the medians. The confidence level for these analyses was set at $p < 5\%$.

Spearman correlation (p) was used to evaluate the association between total particle concentration by power (Kw of the machine) and machine age (in hours).

The total particle concentration (post-intervention) was selected for simple regression analysis as a dependent variable. In the analyses, the following variables were selected as independent

variables: the age of the machine (in hours), the power rating (Kw), and the maintenance scheme protocol. The 250h maintenance group was used as a reference group for multivariable regression. The regression equations were defined as follows:

A simple regression of the following:

$$Y = \alpha + \beta_1(\text{machine Kw})$$

$$Y = Y = \alpha + \beta_2(\text{machine Age})$$

$$Y = \alpha + \beta_3 (500 \text{ hr. maintenance})$$

$$Y = \alpha + \beta_4(1000 \text{ hr. maintenance}) \quad \text{_____} (b)$$

To analyse the overall effect of interventions on workers' exposure, pre- and post-intervention personal sampling results of elemental and total carbon were evaluated through the Mann Whitney tests. The confidence level for these analyses was set at $p < 5\%$.

3.6 Ventilation and Dispersion Modelling

3.6.1 Simulation Planning

This section describes the step-by-step process followed to simulate workplace airflow rates and the dispersion of pollutants (diesel particulate matter and gasses) to give the spatial distribution of the DPM in the development section. The three-step process is defined as follows:

- I. Step 1 - Defining the input parameters, such as the source pollutant, airway diameters (including duct sizes), air quantities, and fans within the specific ventilation section.
- II. Step 2 - Determine the pollutant emission rate by evaluating the machines' engine size and performance, the number of machines within the specified working areas, and each machine's operating times during the load and haul cycle.
- III. Step 3 - Dispersion of the pollutant, which combined the airflow simulation at a ventilation base case (normal planned ventilation requirements for the section), the emission rate of the pollutant, the dimensions of the development heading, and the dynamic timing of the pollutant dispersion, these were done to determine the spatial distribution of the pollutant in the development headings.

3.6.1.1 Ventilation Dynamic Simulation Planning

Ventilation dynamic simulation starts with the planning phase; the planning process includes evaluating the critical ventilation infrastructures such as airway sizes, number of airways required, size of the shafts, fan sizes for the primary and secondary ventilation including location, production tonnage profiles, tramming (load and haul) requirements, location of return airways, thermodynamics requirements, etc. The pre-feasibility study uses all the inputs to design conducive conditions through building scenario ventilation models. Computational fluid dynamic models and software ventilation network packages are used for pre- and definitive feasibility studies. This study used an integrated mine and tunnel ventilation software package to design the ventilation circuits and assess the emission flow dynamics within a ventilation district. Ventilation districts define different working areas with their own intake and return airways. Typically air is segmented and distributed between ventilation districts to minimise the spread of pollution or increasing heat load from one section to the other. The software capabilities include modelling of airflow, pressure, heat, gases, power, radon, fire, and many other types of ventilation information; for this study, the ventilation, gases, and diesel particulate matter modules (DPM VentSim version 5.4) were deployed. The module can predict the diesel exhaust particle concentration in the different parts of the mine, such as the development headings and all areas where load and haul are taking place. The workplace concentration of diesel engine emissions is a function of the rate and concentration of exhaust emissions and the amount of diluting airflow around the equipment. By introducing an engine size and emission concentration in VentSim™, the program uses simulated airflows to calculate the resulting atmospheric concentration, taking into account the area volume where the machines are operating (36,114).

In the present case, the input emission concentration was from the tailpipe of the TMM, where the assessed mass concentration of the tailpipe emissions and gasses were considered the 90th percentiles. The 90th percentile particle concentration (mg/m^3) and exhaust gasses (parts per million) were used from the Dekati ELPI+ and Testo350 output as input data to the dynamic simulation model. The ELPI+ gives output results in particle number ($1/\text{cm}^3$) and mass concentration (mg/m^3); mass concentration was used in this instant. Further, 50% of the engine output was assumed to be Elemental carbon (EC), the recommended surrogate for diesel particulate matter in this study.

To reach the 90th percentile, similar machines were grouped based on the intervention type, viz., the LHDs. The 90th percentile was calculated using the Excel spreadsheet formula, and

the same was done for the LHDs. The results were then used as input data for the source diesel engine exhaust pollution concentration. The results were then used as input data to calculate emissions for the computational dynamic modelling.

3.6.1.2 Building of Ventilation Models

VentSim DESIGN™ uses a visual approach to creating models. The models' fundamental structure (shape) is built from a mining computer-aided design (CAD) program focusing on a specific section of the mine. The CAD program is specifically used to build the 3D models, allowing VentSim to automatically use parameters such as size, length, and depth for simulation.

An open system/model was built with three main airways (the trackless decline, material decline, and chairlift decline) and two airways serving as exhaust return airways.

The mining network for the development section at Mine B was selected; this included two lateral developments and the main capital development (the deepening section).

Ventilation appliances and control information used in the model were recorded during the underground section visit by ventilation officers and coded into the model. The environmental conditions were captured on a standard inspection template for a specific workplace and included the following:

- Through ventilation (before the fan intake), quantities and temperatures
- Intake of air quantities and temperatures
- Fan sizes
- Delivery of air quantity at the fan outlet
- Face quantities (based on the airway dimensions) and temperatures.
- Air leakages – between the intake and delivery of development heading levels
- 75Kw fans with 1015mm diameter were used for the twin flat/lateral haulages.
- 90Kw fans with 1015mm diameter columns ventilated the main declines.
- Ventilation seals/stoppings were installed between the haulage laterals for air control and to prevent short-circuiting of air within the district

Table 3.5: Summary of ventilation infrastructure requirements

Current Ventilation Infrastructure Current		
<i>Airway Name</i>	Airway sizes (Width x height)	Air Quantities (m³/s)
<i>Main Haulage declines</i>	5.5mx4.2m	50m ³ /s
<i>Belt Decline</i>	6mx4m	20m ³ /s
<i>Material</i>	5.5mx5m	30m ³ /s
<i>Development heading – Main decline</i>	5.5mx4.7m	30m ³ /s
<i>Development heading - lateral</i>	6mx4.7m (the maximum length of development heading is 200m)	25m ³ /s
<i>Muck bay</i>	5mx4.2m	N/A

3.6.1.3 Development of ventilation ducting for a development heading

The auxiliary ventilation duct building function in VentSim DESIGN™ allows for modelling complex auxiliary duct arrangements in a mining model. Auxiliary ducts in mines are essential to ensure that quality fresh air reaches areas of the mine without flow through ventilation, which in most cases will be blind headings.

The section of the mine simulated in this study is called a development heading/development and is mainly ventilated by auxiliary fans to effectively remove airborne pollutants outside the mine. Pathways were built into ducts to allow airflow to be drawn and delivered to the underlying airway.

The modelling of auxiliary fans and ducts is one of the critical aspects to ensure adequate ventilation is delivered to the key area, that the correct size duct and the fan are used for a given length of duct, and that the impact of heat, humidity, and fumes generated in auxiliary ventilated areas is correctly modelled on the remainder of the mine network.

The ventilation duct airway carries air to the blind heading face. The blind heading airways carry airflow back to a model junction and join any other airflow beyond the blind heading. Once the ducts are constructed, fans are added to one section of the duct to simulate flows. A total of 8 fans were built in this study, including the 1) fan intake airway and 2) and 6 section fans.

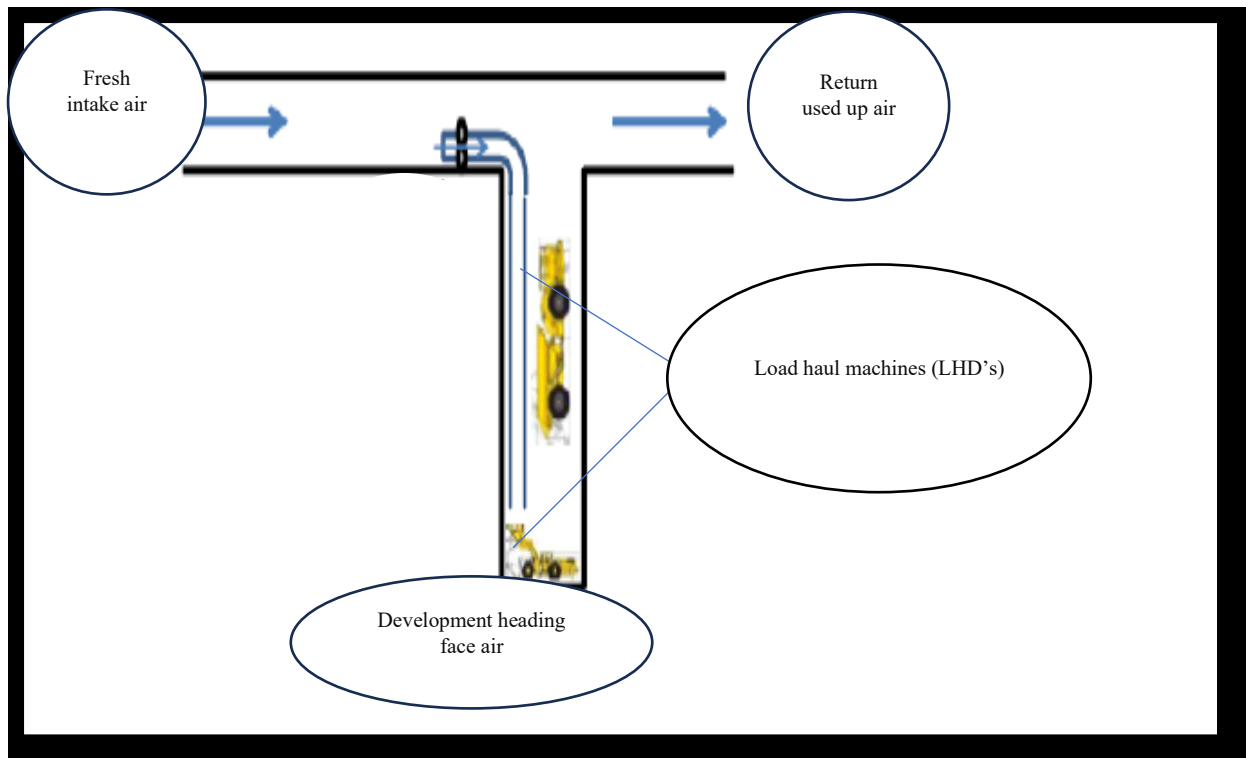


Figure 3.4: Image of a development heading with auxiliary fan and the loading machines (Adapted from Karsten et.al (2012) (26).

Footnote: The maximum length of a development heading is 200m

3.6.1.4 Ventilation Dispersion Modelling

Ventilation dispersion modelling was developed based on the built ventilation simulation models. VentSim version 5.4 was used to simulate the ventilation flow, and the new module VentSim DESIGN™ Advanced was used to predict the dispersion of diesel particulate emissions in the underground development headings. When modelling the dispersion of pollutants in a working place, a point source emission strength must be determined by considering varying dispersion factors and parameters. This section describes the critical parameters that were considered.

3.6.1.5 Pollutant Emission Strength

Engine performance and flow rates were considered and used with the input pollutant source data to determine the emission strength. Table 3.6 below shows the engine flow rates for LHDs and Dump trucks based on their displacement capacity and speed.

Table 3.6: Summary of engine performance and air flow rates of the machines included in the emission scenario.

Engines	Displacement Capacity (L)	Speed (RPM)	Flowrate (l/s)	Flow rate m3/s
LHD	10,8	2100	11340	11,34
Dump truck	12,8	2100	13440	13,44
Dump truck (Idle)	12,8	800	5120	5,12

The LHDs have 10.8-litre or 10800 CC engines, and the Dump trucks have 12800-litre engines (Appendixes 5-10).

- The machines' engines run at a speed of 2100 revolutions per minute (RPM), which creates a flow of 11300 l/s or 11.34 m3/s for LHDs and 13440l/s or 13.44 m3/s for Dump trucks. Based on the engine's airspeed, an emission strength for DPM was calculated.
- The dump truck was assumed to run at 800 RPM when idling because it does not continuously run. LHD was assumed to be running at full speed the whole time.

Based on the engine flow rates and the point source pollutant input concentrations, the emission strength for diesel particulate matter and tailpipe gases was calculated using the following equation:

$$\text{Emission strength/rate (mg/s)} = \frac{\text{particle concentration (mg/m}^3\text{) / gasses (ppm)} \times (\text{Engine airflow rate (l/s)} \times 1000)}{\text{(c)}}$$

The emission rate results were used as an input parameter to calculate the diesel particle concentration at the workplace, considering the number of machines in the simulated load and haul scenario, the length of the development end from the face to the end, and the development end itself.

Equation (d) was used to calculate the concentration manually; however, the VentSim Algorithm was used to calculate (formula embedded in the system) the diesel particle concentrations, using the design quantities, and the minimum allowed leakages on the ventilation columns was 15%. Damaged ventilation columns can cause leakages, resulting in air loss along the ventilation column route, less air delivered to the development heading face, and less dilution of pollutants. The formula used to calculate concentration within the section is as follows:

$$Q_v [m^3/s] = \frac{Q_E [m^3/s] \times (C_E [ppm \text{ or } \mu g/m^3] - C_T [ppm \text{ or } \mu g/m^3])}{C_T [ppm \text{ or } \mu g/m^3] - C_B [ppm \text{ or } \mu g/m^3]} \quad (d)$$

(Morla et al. 2019) (115)

Where;

Q_E – Exhaust flow rate ($\mu g/m^3$)

C_E – Concentration of gas or DE concentration (ppm or $\mu g/m^3$)

C_T – target concentration of the corresponding gas or DE concentration and

C_B – concentration of the gas or DE concentration in the diluted air

3.6.1.6 Dynamic Simulation

A dynamic simulation approach was followed to model the dispersion of diesel particulate emissions in the workplace based on the total number of machines, total exposure time based on the number of hours it takes for machines to load, development heading dimensions, workplace concentration, and the available air quantities. This approach was most preferred based on the nature of load and haul processes, which does not follow a steady state release of emissions but the time-dependent dynamic of the overall time of pollutant dispersion. The TMM load and haul scenario follows a specific time sequence, allowing ore to be moved from the face into the muck bay by LHDs and from the muck bay to the conveyor belts by a Dump truck, as presented in Table 3.7 and Figure 3.5. The dynamic system means that the emission strength and pollution dispersion in the underground environment will vary based on the number of machines operating at a given specific time, the type or rated power of the TMM, and the ventilation performance within that particular workplace.

Table 3.7: Dynamic simulation time input for the machinery during loading and hauling activity at the development section of the mine

Location	Type of heading	Machine type and dynamic	Delay time(s)	Total time(s)
North	Dev	*LHD (full capacity)	0	14400
North	Muck	**LHD (full capacity)	3600	10800
North	Muck	***Dump truck (Idle)	5400	10800
South	Dev	*LHD (full capacity)	0	14400
South	Muck	**LHD (full capacity)	3600	21600
South	Muck	***Dump truck (Idle)	5400	10800
Decline	Decline	*Dump truck (full capacity)	0	21600

*LHD loading for 4 hours

**LHD starts loading and loads for 3 hours (delay by 60 minutes)

***Dump truck starts loading 1.5 hours and load for 6 hours (delay by 90 minutes)

The loading sequence was as follows:

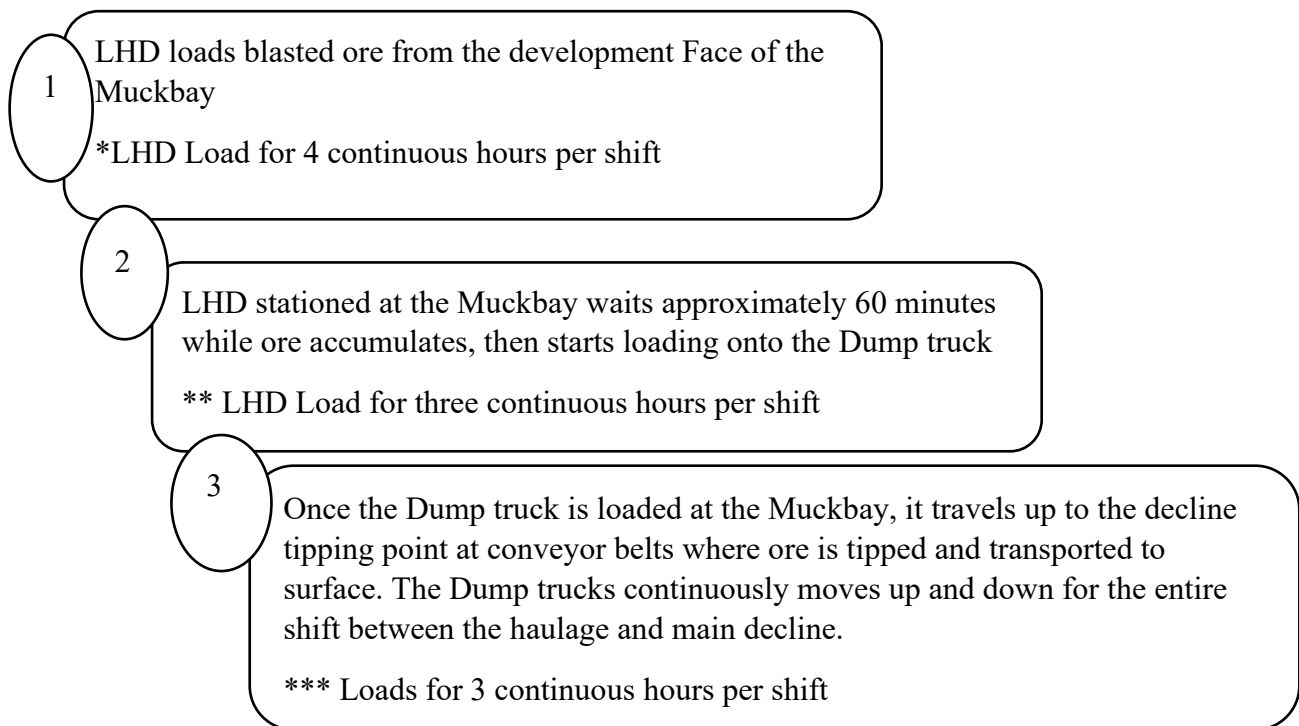


Figure 3.5: Step by step presentation of loading sequence and timing for LHD's and Dump trucks

A step-by-step method was followed to design and simulate the emission-based dispersion model:

- A specific ventilation district at the mine was selected for the purpose.
- Airway graphic data was imported from the mine planning CAD system DXF/Datamine file into VentSim, and the data was converted into airways.
- Airways were constructed using the import function, ensuring that all airways join correctly to each other from intake, working faces, and to the return.
- The airways were connected to the surface, and the correct size and shape for all airways were set as per the Datamine graphical data.
- Ventilation controls/regulators in the model and specific airway characteristics such as friction factors and shock losses were built into the system.
- Fans with column sizes of 1015 diameter and 90Kw fans and 1012 diameters with 75Kw fans were added for lateral development haulages and capital developments respectively, in the different airways to provide pressure and to drive the airflow through the model; the fan sizes were included as per current mine ventilation design. VentSim utilises a fan curve to establish accurate working flow and pressure in a ventilation model.
- The ventilation model construction design was checked to ensure everything was constructed correctly; for example, the airflow data and arrows show the simulation result.
- Air volumes were constructed in a fixed airflow of 100m³/s on the intake and return to allow increasing air and fan volumes in the model. This total volume was the air quantity available for the entire ventilation district.
- Cleaning of the blasted face in the development heading made use of two (2) LHDs and one (1) Dump truck
 - 1x LHD was utilised to clean the ore from the face to the muck bay
 - 1x LHD was utilised to load the ore from the muck bay into the dump truck
 - 1x dump truck hauling the ore from the muck bay to the decline tipping conveyor belt tipping point

3.6.1.7 Workplace Scenarios

a) The dynamic pollutant dispersion simulation models were developed based on the following scenarios:

Scenario 1- Actual/Implemented Interventions strategies scenarios

- ✓ Maintenance of the machines only
- ✓ Maintenance and retrofitting of the machines with DPF

Scenario 2- Recommended technological strategies scenarios

- ✓ Replacement of the two diesel-powered LHDs with electrified-powered machines
- ✓ Replacement of diesel-powered dump truck with an electrified powered machine

Scenario 3- The following dilution ventilation scenarios were considered:

Intervention whereby ventilation was altered from the base case was done to test the effects of ventilation on the DPM dispersion; the ventilation alterations were as follows:

- ✓ 10% ventilation increase
- ✓ 20% ventilation increase and
- ✓ 30% ventilation increase

The dispersion modelling was done for the machines which underwent maintenance only and maintenance plus retrofitted with DPF.

b) Additional input data considered for developing the scenario

1. The load and haul activities (Figure 3.5).
2. Total number of machines in a working place and duration (Table 3.7)
3. The main decline Dump trucks ran continuously for 6 hours, Face LHD ran for 4 hours, and Muck Bay LHD ran for 3 hours. The dump truck idling state was also considered.
4. Emission strength per machine was combined to give the final summary input of the emission strength for the total number of machines at the workplace.
5. Base-case ventilation was established - Contaminant at baseline with no intervention
6. Emission scenarios were developed, in which the evolution of emission concentrations over time was modelled within the ventilation district.

7. For this scenario, an estimated running time of four hours (which is loaded in seconds in the model) was built into the model for the loading from the development heading face to the muck bay.
8. After a lag time of 60 to 90 minutes (the time it takes to move enough ore from the face to the muck bay), a second LHD starts loading the ore into the Dump truck after 90 minutes.

3.6.1.8 Assumptions

1. The source was assumed to include all the particle size fractions.
2. Particle emission strength was cumulative, as reused air was built into the system.
3. In the LHD and Dump truck dynamic modes, idling and full acceleration were assumed, and the contaminant was adjusted accordingly (based on Table 3.7). Dump trucks haul the ore to the main decline belt or the surface for processing.
4. Possible additional idling machines in the section were not considered.

EC was assumed to be 50% of the total engine-out emission and estimated from the tailpipe source data's 90th percentile. This data point was used as the input source/tailpipe concentration.

3.7 Cost component formulation

Cost is critical when conducting mine ventilation planning, especially where different ventilation or control strategies are followed. In some cases, capital costs may be required to implement solutions, whereas operational costs may also be required for the continuous ventilation operation at the mine. Some of the most critical physical factors to be considered with ventilation planning are the following:

- Life of mine airways
- The mean volume of airflow
- Mean density
- The ratio of height to width for non-circular airways
- Airway friction factors (Atkinson's friction factors)
- Total running power for the overall ventilation infrastructure (such as ventilation fans)

The cost functions were considered based on the above physical parameters. An example of an airway cost can be calculated using the following formula:

$$\text{Cost} = 20A + 7.39\text{USD}/\text{m}^2 \quad (e)$$

Where A = the area of the airway in m²

Other critical ventilation running cost functions include electrical costs. Electrical power costs typically comprise components such as the basic rental charge for the facility, consumption cost per kWhr, and peak power demand charge per kW. In practice, these components are combined into an approximate total cost for this application. The representative cost in RSA at present (April 2024) is about 0.629 USD per kWhr (R 1.20 per kWhr), although this can vary between mining companies depending on specific negotiations for power supply. The power cost will be 64.53 USD (R 1230) per annum. The mining company will pay this equivalent value for each year of the mining cycle.

Table 3.8: Summary table showing the input air quantity, pressure and system resistance for surface fans supplying the air to the shaft, scenario options are applied at 10%, 20%, and 30%

Parameters	Base	10%	20%	30%
<i>Volume (m3/s)</i>	435	478,5	522	565,5
<i>Pressure (Pa)</i>	3136	3794,56	4515,84	5299,84
<i>R = System resistance (Ns²/m8)</i>	0,016573 (Atkinson's friction factor)			

Formulae were used to determine the Airpower and absorbed power (the power required to overcome the system pressure). Basic ventilation calculations were used to derive inputs to determine the estimated costs to run the ventilation systems, which are presented below:

$$P = \frac{K \text{ CL } Q^2 x}{A^3} \frac{w}{1.2} \quad (f)$$

Where p = pressure loss due to friction (Pa)

K = Friction factor (Ns²/m²)

C = Circumference (m)

L = Length (m)

Q = air quantity (m/s)

V = air velocity

A = Area (m²)

W = air density (kgm³)

Resistance

$$R = \frac{KCL}{A^3} \times \frac{w}{12} \text{ (g)}$$

Where R = resistance (Ns²/m²)

K = friction (Ns²/m²)

C = circumference (h+w)² = hlge/πD = pipes (m)

L = Length (m)

A = area (hxw) hlge/x(D²/4) = pipes (m²)

W = air density (kgm²)

In this simulation, the absorbed power for the main fans was used. This is because the section ventilation fans can only be increased when the main surface air power increases.

In summary, the following steps were followed to determine the running cost for control strategies.

Air Power (Wa)

$$Wa = \frac{PxQ}{1000} \text{ (h)}$$

Where Wa = air power (kW)

P = pressure (Pa)

Q = air quantity (m³/s)

R = Resistance (Ns²/m³)

- The total air volume, pressure, and resistance for the shaft and 10 half levels were determined
- The total air power required to run the fans was determined
- Absorbed power for the fans was determined
- An electrical running cost of 0.629 USD/kW (R1.20/kW) was determined
- The cost of installing DPF was determined

The following formula to determine power cost was used:

Total electrical fan power for the main fans and auxiliary fans (10 half levels) was calculated using this formula:

$$\text{Air Power (kW)} = P \cdot Q / 1000 \quad (I)$$

where

W_a = Air Power [kW]

P = pressure [Pa]

Q = air quantity [m^3/s]

R = Resistance [Ns^2/m^3]

$$\text{Absorbed Power} = (\text{Air Power} \cdot \text{Load factor}) / \text{Efficiency} \quad (j)$$

a standard efficiency of 30% is used

$$\text{Cost of electricity} = \text{kW} \times 24 \text{ hours} \times 365 \times \text{price per kWh} \quad (k)$$

The cost results are presented in the results section, considering the output results of the network dynamic simulation for the maintenance regime and for maintenance plus DPF retrofitting, as well as the ventilation dilution control strategies.

3.8 Project Approval

The Ethics Committee approved this project for Health Research at Wits University, project number **M190308** (Appendix 1).

CHAPTER 4 - RESULTS

This chapter presents the field survey of diesel engine exhaust (DEE) results taken at the point source tailpipe of diesel-powered trackless mobile machinery and detailed dispersion results for the DEE once it is emitted into the environment in the underground working place. Population and characteristics data for machines are presented first, followed by the results of the different interventions to reduce DEE. The impact of the interventions is assessed using personal exposure monitoring for employees working underground at the development head. Further computational fluid dynamics simulations/modelling are done to evaluate the pollutant dispersion once liberated into the environment and to evaluate the impact of controls on reducing the pollutant in the underground environment. Results are presented in sequence based on the maintenance regimes and modelling scenarios. Finally, the cost for different controls was assessed and reported accordingly.

4. RESULTS

4.1 Presentation of the study population

Tables 4.1, 4.2, and 4.3 present the trackless mobile machinery (TMM) study population. Baseline tailpipe measurements were taken on all TMM at the beginning of the study, followed by measurements after the machines underwent intervention, which includes 1) maintenance intervention and 2) maintenance plus installation of a diesel particulate filter. The measurements were based on the engine hours. Maintenance was scheduled at 250, 500, and 1000 hours as follows:

- i) After 250 hourly scheduled maintenance for TMM engine age of ≤ 4000 hours
- ii) After 500 hourly scheduled maintenance for TMM engine age of $>4000 \leq 10000$ hours
- iii) After-1000 hourly scheduled maintenance for TMM engine age of ≥ 10000 hours

The characteristics of the machines included make, design, power and the engine running hours. All machines were found to be operating at ≤ 4000 engine hours before maintenance, as shown in Table 4.1. Engine hours were recorded at baseline (pre-measurements) and again after the first maintenance at 250 hours (the total number of machines serviced, $N = (14)$).

Table 4.1: Characteristics of Trackless Mobile Machinery (TMM) for machines with ≤ 4000 engine hours (N=14)

Machine Type	Engine Series	Machine Rated Kilowatt (Kw)	Engine Tier Type	Engine Age (running hours before)	Engine Age (running hours after)
<i>DT 46**</i>	Detroit	392	II	3294	3544
<i>LHD 72**</i>	Volvo	405	II	280	506
<i>LHD 70**</i>	Volvo	405	II	280	530
<i>DT50**</i>	Detroit	352	II	2892	3142
<i>LHD 49**</i>	Volvo	224	II	3868	4118
<i>LHD 39**</i>	Volvo	246	II	3833	4083
<i>DT71**</i>	Volvo	405	II	100	506
<i>DT 39</i>	Detroit	392	II	3452	3702
<i>LHD 50</i>	Detroit	224	II	2552	2802
<i>DT 63</i>	Volvo	392	II	1670	1920
<i>DT 68</i>	Volvo	405	II	3478	3728
<i>DT 67</i>	Volvo	405	II	2366	2616
<i>DT13</i>	Detroit	392	II	3294	3544
<i>LHD 64</i>	Volvo	256	II	3735	3985

**Machine retrofitted with Diesel Particulate Filter (DPF)

Table 4.2: Characteristics of Trackless Mobile Machinery (TMM) for machines with $\leq 4000 < 10000$ engine hours (N = 14)

Machine Type	Engine Series	Machine Rated Kilowatt (Kw)	Engine Tier Type	Engine Age (running hours before)	Engine Age (running hours after)
<i>LHD 62**</i>	Volvo	256	II	7973	7973
<i>LHD 64**</i>	Detroit	393	II	5294	5294
<i>DT 58**</i>	Detroit	392	II	6454	6454
<i>LHD 41**</i>	Detroit	224	II	4071	4071
<i>LHD RAM 56**</i>	Detroit	224	II	5600	5600
<i>LHD 44**</i>	Detroit	256	II	4540	5600
<i>LHD 51**</i>	Volvo	224	II	6700	7750
<i>Dump truck 34</i>	Detroit	405	II	4100	5120
<i>Dump truck 20</i>	Detroit	392	II	5200	6300
<i>LHD 48</i>	Detroit	224	II	6680	6680
<i>DT56</i>	Detroit	392	II	4611	4611
<i>DT 61</i>	Detroit	392	II	7895	7895
<i>DT 12</i>	Detroit	392	II	4679	4679

**Machine retrofitted with Diesel Particulate Filter (DPF)

Table 4.3: Characteristics of Trackless Mobile Machinery (TMM) for machines with >10000 engine hours (N = 13)

Machine Type	Engine Series	Machine Rated Kilowatt (Kw)	Engine Tier Type	Engine Age (running hours before)	Engine Age (running hours after)
<i>DT 62**</i>	Detroit	392	II	10891	12934
<i>LHD 60**</i>	Detroit	392	II	16060	11534
<i>DT 59**</i>	Detroit	392	II	11934	11270
<i>DT 22**</i>	Detroit	392	II	10891	11211
<i>LHD 44**</i>	Volvo	256	II	11977	12775
<i>LHD 33**</i>	Detroit	175	II	10290	13450
<i>LHD 25**</i>	Volvo	256	II	11769	12775
<i>DT 60</i>	Detroit	392	II	10517	11520
<i>DT 65</i>	Detroit	354	II	13271	14271
<i>LHD 71</i>	Detroit	220	II	11468	12977
<i>LHD 55</i>	Volvo	220	II	16527	11300
<i>LHD 46</i>	Detroit	220	II	10200	11891
<i>RHAM 54</i>	Volvo	392	II	12400	12468

**Machine retrofitted with Diesel Particulate Filter (DPF)

Comparison of particle number concentration per size fraction

Tables 4.4, 4.5, and 4.6 represent the diesel exhaust particle number concentration by size fractions and the total particle concentration for all the size bins from 0.0019 to 7.259 μm (3.630 midpoint). The size fractions are divided into three sections, which were defined as the ‘ultrafine/submicron fraction’ ($\geq 0.0019 < 0.3123 \mu\text{m}$; the ‘fine fraction’ $\geq 0.312 < 2.002 \mu\text{m}$; and the ‘respirable fraction’ $\geq 2.002 < 7.259 \mu\text{m}$). Most of the differences before and after interventions were in the lower particle size fractions (ultrafine and fine particles) and showed to be statistically significant.

Table 4.4: Comparison of the particle number concentration size fraction before (baseline) and after 250hrs intervention (i.e., maintenance only and maintenance plus DPF) (N = 14)

Particle number concentration (1/cm ³)			
Size fractions sub-groups (diameter $\mu\text{m}/\text{cm}^3$)	Before	After	P-value*
<i>Ultrafine/submicron size fraction ($\geq 0.0019 < 0.3123 \mu\text{m}$)</i>	625 023 (884 491-412 420)	260 459 (501 808-53 449)	0.0051
<i>Fine size fraction ($\geq 0.312 < 2.002 \mu\text{m}$)</i>	625 023 (412 420-884 491)	260 459 (501 808-53 449)	0.0284
<i>Respirable size fraction ($\geq 2.002 < 7.259 \mu\text{m}$)</i>	0.25 (0-2.8)	0 (0-0.5)	0.0999
<i>Overall (size bins $\geq 0.0019 < 7.259 \mu\text{m}$)</i>	136 231 (184 086-61 908)	31 279 (88 865-7 072)	0.0051

*p-value significant at 0.05, IQR – interquartile range

The particle number concentration after the 250-hour maintenance protocol demonstrated a significant reduction compared to the baseline measurements. The median particle number concentration significantly decreased for the ultrafine/submicron size diameter, fine particle size diameter, and the overall bin reduction (p-values = 0.0019; 0.21; 0.0012, respectively). The reductions in respirable particle size fractions were insignificant (p-value= 0.84).

Table 4.5: Comparison of the particle number concentrations per size fraction before (baseline) and after 500hrs interventions (maintenance only and maintenance plus DPF). Total number of machines N = (14)

Particle number concentration (1/cm ³)			
Size fractions sub-groups (diameter $\mu\text{m}/\text{cm}^3$)	Before	After	P-value*
<i>Ultrafine/submicron fraction</i> ($\geq 0.0019 < 0.3123 \mu\text{m}$)	625 023 (884 491-412 420)	260 459 (501 808-534 49)	0.0051
<i>Fine fraction</i> ($\geq 0.312 < 2.002 \mu\text{m}$)	625 023 (412 420-884 491)	260 459 (501 808-534 49)	0.0284
<i>Respirable fraction</i> ($\geq 2.002 < 7.259 \mu\text{m}$)	0.25 (0-2.8)	0 (0-0.5)	0.0999
Overall (size bins $\geq 0.0019 < 7.259 \mu\text{m}$)	136 231 (184 086-619 08)	31 279 (88 865-7 072)	0.0051

*p-value significant at 0.05, IQR – interquartile range

The particle number concentration after the 500-maintenance protocol was conducted showed a significant overall reduction compared to the baseline measurements. The median particle number concentration significantly decreased for the ultrafine/submicron for fine particle size fraction, which was statistically significant (p-value = 0.0051 and 0.02 respectively). The median particle concentration for respirable particle fraction decreased but was not statistically significant.

Table 4.6: Comparison of the particle number concentration per size fraction before (baseline) and after 1000hrs intervention (maintenance only and maintenance plus DPF). Total number of machines N = (13)

<i>Particle number concentration (1/cm³)</i>			
Size fractions sub-groups (diameter $\mu\text{m}/\text{cm}^3$)	Before	After	P-value*
<i>Ultrafine/submicron fraction $\geq 0.0019 < 0.3123 \mu\text{m}$</i>	5 465 764 (743 809 9-4 146 572)	2 286 857 (442 728-146 218)	0.0051
<i>Fine size fraction $\geq 0.312 < 2.002 \mu\text{m}$</i>	64 207 (84 349-24 502)	15 652 (39 940-3 515)	0.0022
<i>Respirable fraction ($\geq 2.002 < 7.259 \mu\text{m}$)</i>	72 (248-0.997)	0 (0.8-0)	0.0544
Overall (size bins $\geq 0.0019 < 7.259 \mu\text{m}$)	923 663 (1 214 267-699 930-)	624 260 (786 898-579 91)	0.004

*p-value significant at 0.05, IQR – interquartile range

After the 1000 maintenance protocol, particle number concentration demonstrated an overall significant reduction compared to the baseline measurements. The median particle number concentration decreased for ultrafine/submicron, fine particle size diameter, respirable particles and with the overall size bins. (p-value=0.0051; 0.002; 0.05 and 0.004).

Total Particle Number Concentration results of the Machines after the two interventions, Maintenance, and Maintenance plus installation of Diesel Particle Filters (DPF), are reported below:

Tables 4.7 and 4.8 present the total particle number concentration before and after the two interventions. Machines that underwent maintenance and machines that underwent maintenance plus retrofitting with diesel particulate filters, categorised by engine hours as Category A (250hrs maintenance), B (500 maintenance), and C (1000 maintenance), showed a significant reduction in particle number concentration.

Table 4.7: Comparison of total particle number concentration results of before and after-maintenance only intervention Total number of machines N = (21)

Particle number concentration (1/cm ³)			
Maintenance Categories	Before	After	P-value*
<i>Cat A – Engine Age of ≤ 4000 hours n= (7)</i>	187 821(289 747-68 741-)	29 215 (76 983-820 0.6.	0.0077
<i>Cat B - Engine Age $>4000 \leq 8000$ n=(7)</i>	251 808 (2 611 089-169 129)	178 584 (229 213-128 906)	0.0679
<i>Cat C - ≥ 10000 n= (7)</i>	2 075 708 (2 828 719-2 033 208)	991 112 (1 926 819-175 146)	0.0601

*p-value significant at 0.05, IQR- interquartile range

Particle number concentration has reduced significantly after the maintenance protocol for 250 hours, and a marginal significance was achieved for 500 and 1000 hours. The median particle number concentration significantly decreased for category A, which was statistically significant (p-value = 0.0077). Although the particle number concentration decreased for categories B and C, the reduction was not significant (p-value>0.05).

Table 4.8: Comparison of total particle number concentration results of before and after-maintenance plus DPF installation intervention. Total number of machines N = (20)

Particle number concentration (1/cm ³)			
Maintenance Categories	Before	After	P-value*
<i>Cat A Engine Age of ≤ 4000 hours n=7</i>	27 734 (59 838-12 118)	6 129 (17 604-2 014)	0.0249
<i>Cat B Engine Age $>4000 \leq 8000$ hours n=7</i>	273 437 (26 773-8 767)	25 712 (385 014-180 355)	0.0431
<i>Cat C ≥ 10000 hours n=6</i>	2 405 227 (3 419 958-1 301 178)	922 070 (1 909 353-57 803)	0.0277

*p-value significant at 0.05, IQR – interquartile range

The median particle number concentration for machines that underwent maintenance and were retrofitted with DPF showed significant decrease for categories A, B, and C (p-values= 0.024, 0.0431 and 0.0277 respectively).

4.1.1 Assessing the Efficacy for before and after interventions

Tables 4.9, 4.10, and 4.11 present the calculated efficacy results based on the concentration before and after the particle number concentration. The results were also captured graphically in Figures 4.1 and 4.2.

Table 4.9: Efficacy for total particle number concentration for before and after-measurements machines that were tested after the first maintenance at 250 hours. Total number of machines N = (14)

Machine ID Number	PNC Before (1/cm ³)	PNC After (1/cm ³)	Efficacy (%)
DT 46**	262 949	114 809	96
LHD 72**	2 547 998	126 453	95
LHD 70**	1 977 543	224 70	99
DT50**	837 734	282 09	97
LHD 49**	13 517 034	88 757	99
LHD 39**	13 214 966	55 258	100
DT71**	169 649	16 020	91
DT 39	2 609 073	1 943 879	25
LHD 50	4 441 572	3 056 479	31
DT 63	4 294 743	3 276 533	24
DT 68	2 126 553	1 665 506	22
DT 67	2 024 972	1 468 486	27
DT13	197 291 931	136 341 233	31
LHD 64	16 714 959	104 539 310	37

**Machine retrofitted with Diesel Particulate Filter (DPF).

Table 4.10: Efficacy for total particle number concentration for before and after-measurements machines tested after the first maintenance at 500 hours. Total number of machines N = (14)

Machine ID Number	PNC Before (1/cm ³)	PNC After (1/cm ³)	Intervention Effectiveness (%)
<i>LHD 62**</i>	9 042 872	122 744	99
<i>LHD 64**</i>	3 361 498	359 965	89
<i>DT 58**</i>	5 390 190	170 824	97
<i>LHD 41**</i>	68 668 925	336 1498	95
<i>LHD RAM 56**</i>	2 524 973	111 670	96
<i>LHD 44**</i>	3 577 929	301 865	92
<i>LHD 51**</i>	30 119 502	1 341 809	96
<i>LHD 48</i>	2 609 073	1 943 879,	26
<i>Dump truck 56</i>	4 441 572	3 056 479	31
<i>DT 61</i>	4 294 743	3 276 533	24
<i>DT 12</i>	2 126 553	1 665 506	22
<i>LHD Rham 57</i>	2 024 972	1 468 486	28
<i>Dump truck 34</i>	197 291 931	136 341 233	31
<i>Dump truck 20</i>	167 149 593	104 539 311	37

**Machine retrofitted with Diesel Particulate Filter (DPF).

Table 4.11: Efficacy for total particle number concentration for before and post-measurements machines tested after the first maintenance at 1000 hours. Total number of machines N = (13)

Machine ID Number	PNC Before (1/cm³)	PNC After (1/cm³)	Intervention Effectiveness (%)
<i>DT 62**</i>	84 285 282	6 526 647	92
<i>LHD 60 **</i>	15 432 500	1 108 627	93
<i>DT 59**</i>	48 744 149	3 009 237	94
<i>DT 22**</i>	21 786 137	2 077 449	91
<i>LHD 44**</i>	290 599 906	23 924 519	92
<i>LHD 33**</i>	18 216 494	1 289 050	93
<i>LHD 25**</i>	1 802 256	250 241	86
<i>DT 60</i>	32 557 928	24 937 920	23
<i>DT 65</i>	33 673 179	26 730 843	21
<i>LHD 71</i>	28 464 904	19 666 972	31
<i>LHD 55</i>	47 879 411	33 951 232	29
<i>LHD 46</i>	41 851 935	33 547 435	20
<i>RHAM 54</i>	39 602 070	31 026 430	22

**Machine retrofitted with Diesel Particulate Filter (DPF).

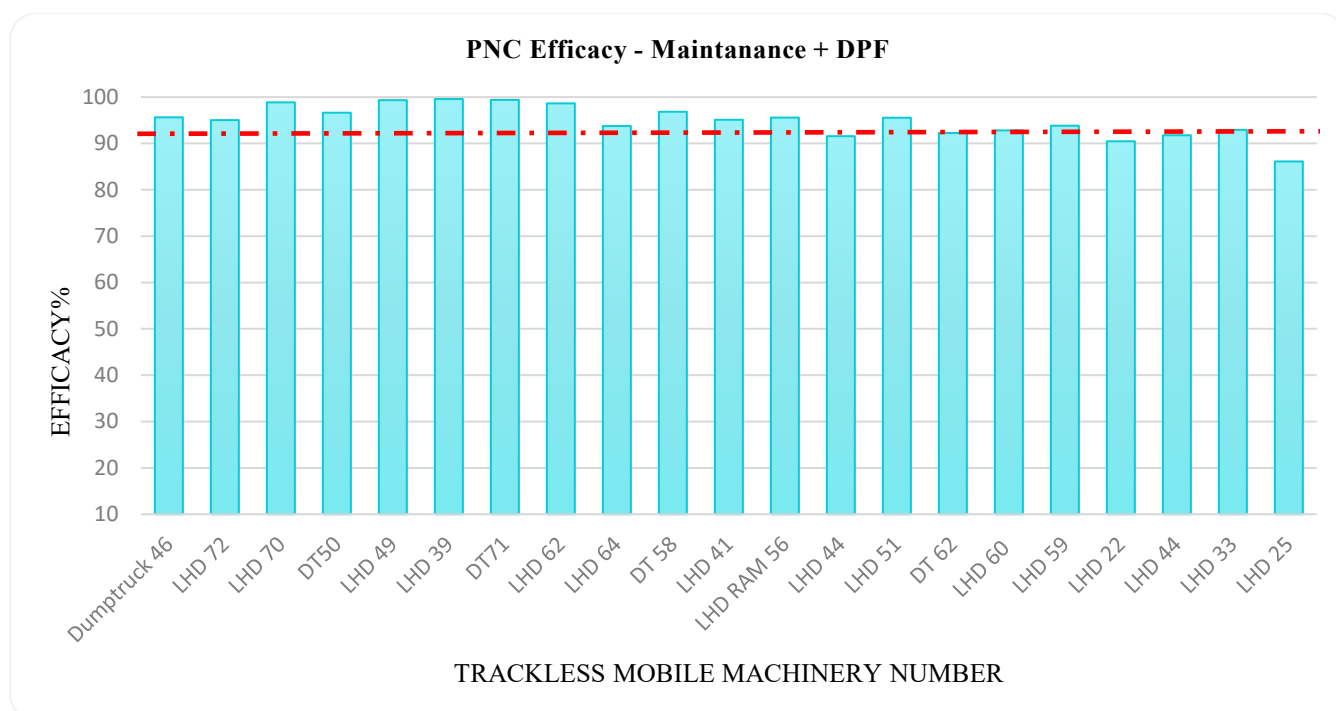


Figure 4.1: Efficacies post the intervention for machines that underwent maintenance and were installed with DPF; efficacy is presented in percentage reduction. The dashed line shows the group average.

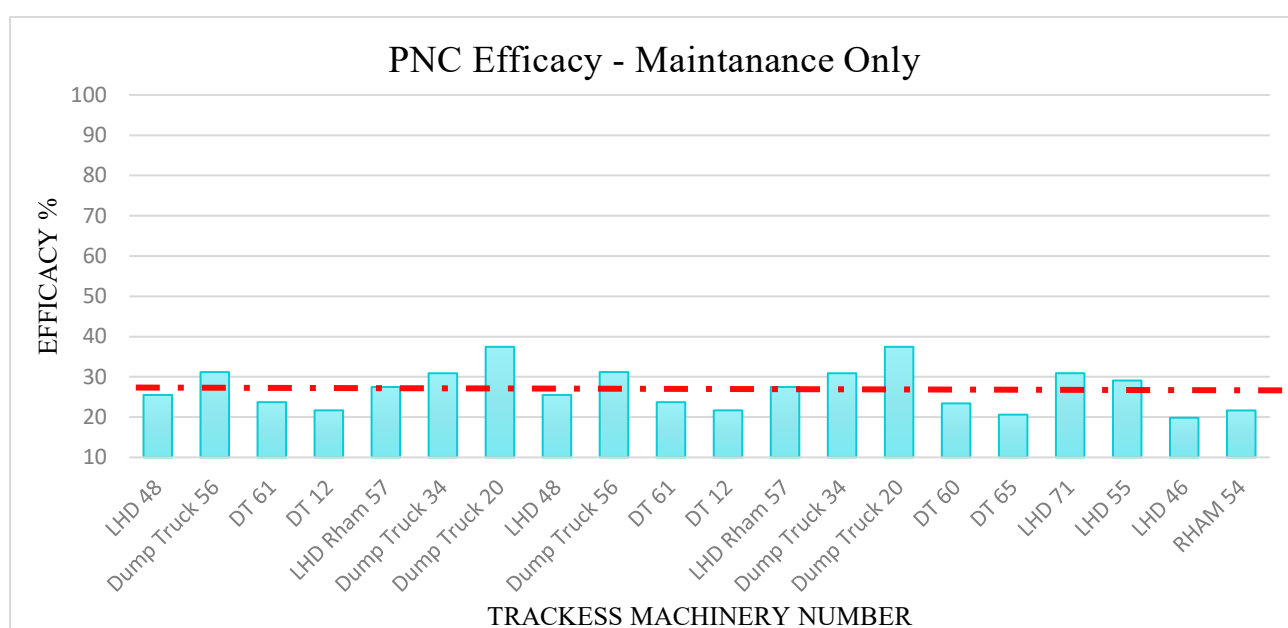


Figure 4.2: Efficacies after the intervention for machines that underwent maintenance only; efficacy is presented in percentage reduction. The dashed line shows the group average.

According to the calculated efficacies (Tables 4.9-4.11), machines that underwent maintenance and retrofitted with a DPF system achieved an average filtration reduction efficacy (AM) of 95% (SD 3.29%) based on total particle number concentration with a range of 90 – 100%

(Figure 4.1). For machines that underwent maintenance only, the reduction efficacy was only 34.31% (SD 13.9%), ranging from 20-40% (Figure 4.2). Machines with lesser engine age showed an increased reduction.

Table 4.12 presents the statistical test results of the efficacy comparison for both intervention regimes, i.e., maintenance and maintenance plus DPF.

4.1.2 Association between the efficacy of interventions and TMM characteristics

Table 4.22: Comparing the efficacy for TMM with maintenance only and maintenance plus DPF intervention. Total number N = (41)

Intervention efficacy by %				
Group	Parameter	Maintenance + DPF	Maintenance	P-value*
Combined Interventions n=(41)	Median (IQR)	96.2 (91.8 -96.8)	30.9 (23.7-38.3)	0.0001

*p-value significant at 0.05, IQR – interquartile range.

An improvement was achieved for both the intervention regimes with TMMs fitted, with DPF achieving the highest efficacy. An overall efficacy for machines that underwent maintenance plus DPF was achieved at a median of 96.2% (91.8 % - 96.83%), which was statistically significantly different for machines that underwent maintenance only, where the median efficacy was 30.9% (23.7%-38.3%) reduction was achieved.

Tables 4.12 and 4.13 present the association between before and after-intervention particle number concentration, with some characteristics of the TMMs, i.e., the engine age and power. The correlation between the total particle number concentration difference before and after showed a positive correlation with the engine age and a negative correlation with engine power (kW) Table 4.13 and Figure 4.3).

Table 4.13: Spearman correlation assessing the relationship between the total particle number concentration by Kilowatts and engine age (time)

Total particle number concentration difference between Before - and After-intervention		
Variable	Spearman correlation coefficient	P-value*
Engine age	0.6633	<0.0001
Kilowatts	-0.3332	0.0581

*p-value significant at 0.05

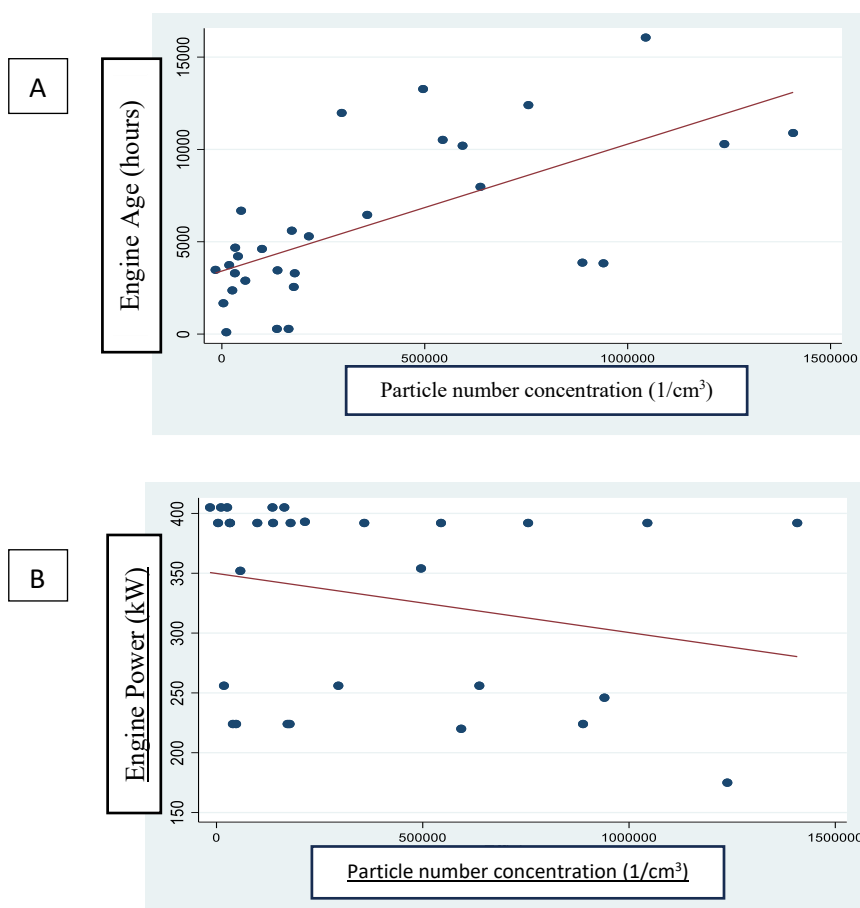


Figure 4.3: Scatter plots representing the relationship between the total particle number concentration (difference before and after intervention) by age and machine power (kW) performance.

Footnote: Panel A - represents the relationship between particle number concentration by age (hours), panel B - represents the correlation between total particle number concentration by machine-rated power (Kw) measured in total running hours.

Table 4.14: Comparing the efficacy for TMM with maintenance only and maintenance plus DPF intervention. Total number N = (41)

Intervention efficacy by %				
Group	Parameter	Maintenance + DPF	Maintenance	P-value*
Intervention Effectiveness	Median (IQR)	96.2 (91.8 -96.8)	30.9 (23.7-38.3)	0.0001

*p-value significant at 0.05, IQR – interquartile range

An improvement was achieved for both the intervention regimes, with TMMs fitted with DPF achieving the highest efficacy. An overall efficacy for machines that underwent maintenance plus DPF was achieved at a median of 96.2% (91.8% - 96.8%), and this was statistically significantly different from the median efficacy for the machines that underwent maintenance only, i.e., a median of 30.9% (23.7%-38.3%) reduction.

4.1.3 Particle Size Distribution

Figures 4.4, 4.5, and 4.6 present the particle size distribution (PSD) results before and after the interventions; the PSD is presented by engine hours. Most particle modes were concentrated around the 0.1 μm region in both instances. Further, based on particle number concentration, significant reductions were observed with both the ultrafine and fine particle size fractions; reduction per size bin also showed similar reduction patterns in all the TMMs, with the highest reductions in the maintenance + DPF intervention.

Most particles emitted before intervention were both in the ultrafine size (PM₁), known as nucleation mode (aerodynamic size diameter of between $\geq 0.01 < 0.1 \mu\text{m}$), and fine size (PM_{2.5}), known as accumulation mode (aerodynamic size of $\geq 0.1 < 1 \mu\text{m}$). The GM of the particle size distribution for machines that underwent maintenance was 0.19 μm (GSD 3.07) before and 0.098 μm (GSD 2.4) after intervention. For machines that underwent maintenance and retrofitted with DPF, the GM was 0.139 μm before (GSD1.48), and GM was 0.056 μm (GSD1.45) after the intervention. However, a multi-modal particle distribution was observed for the higher engine hour group, category C (1000 hours), and particle diameter aerodynamic size of $\geq 1 \mu\text{m}$. After the intervention, all results showed particle distribution mainly in ultrafine and fine size ranges and very few in the respirable size range.

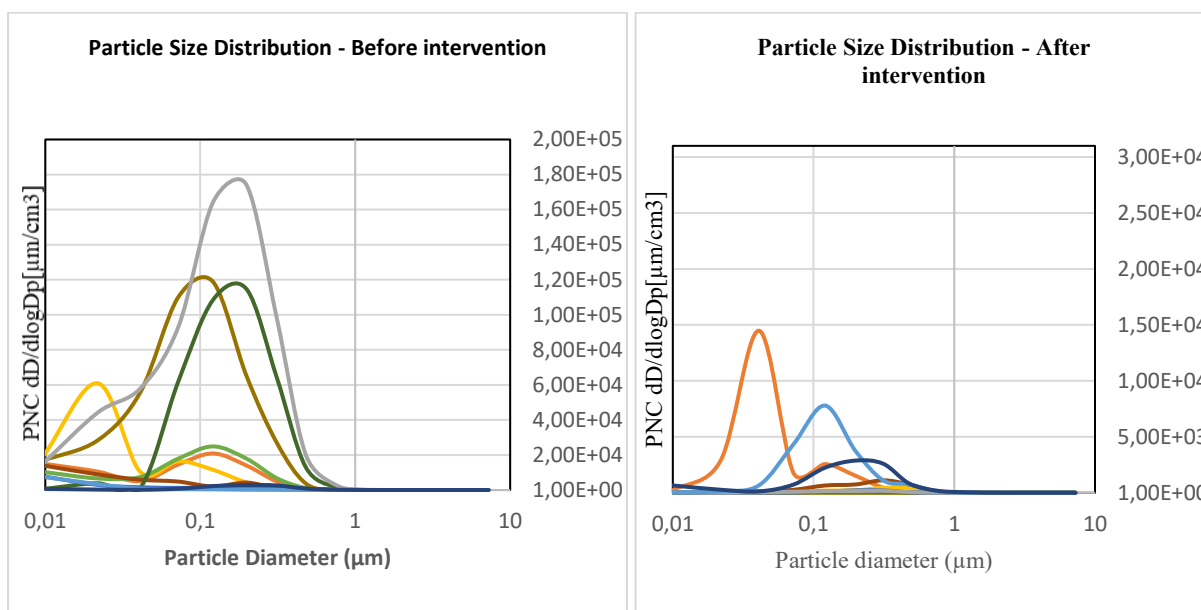


Figure 4.4: Particle size distributions of the 14 TMMs under study before and after intervention at 250 hourly maintenance and maintenance plus DPF.

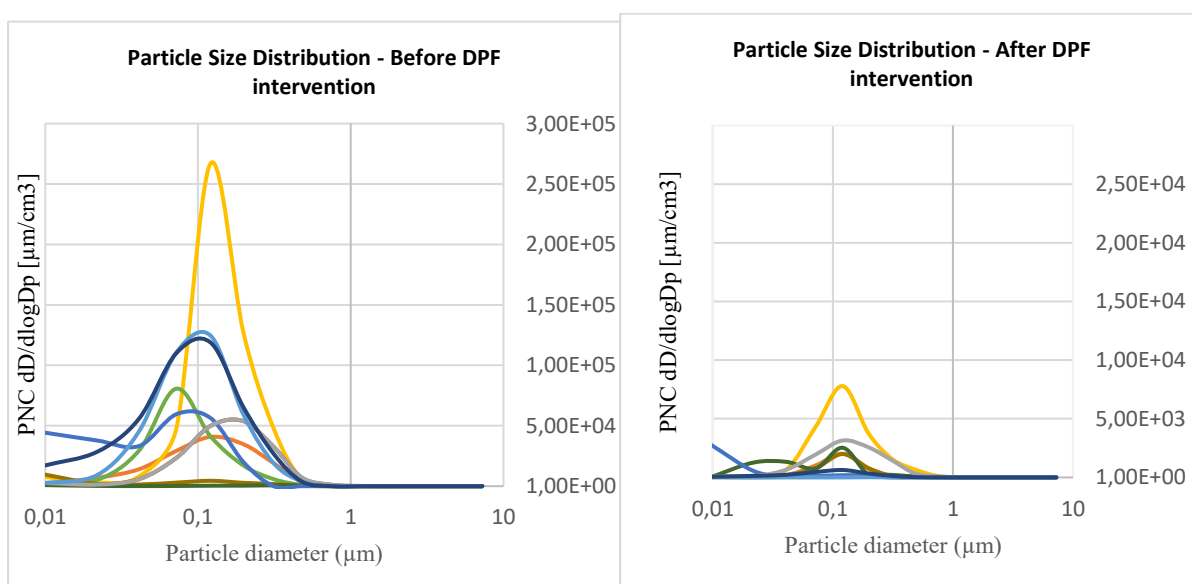


Figure 4.5: Particle size distributions of the 14 TMMs under study before and after intervention at 500 hourly maintenance and maintenance plus DPF.

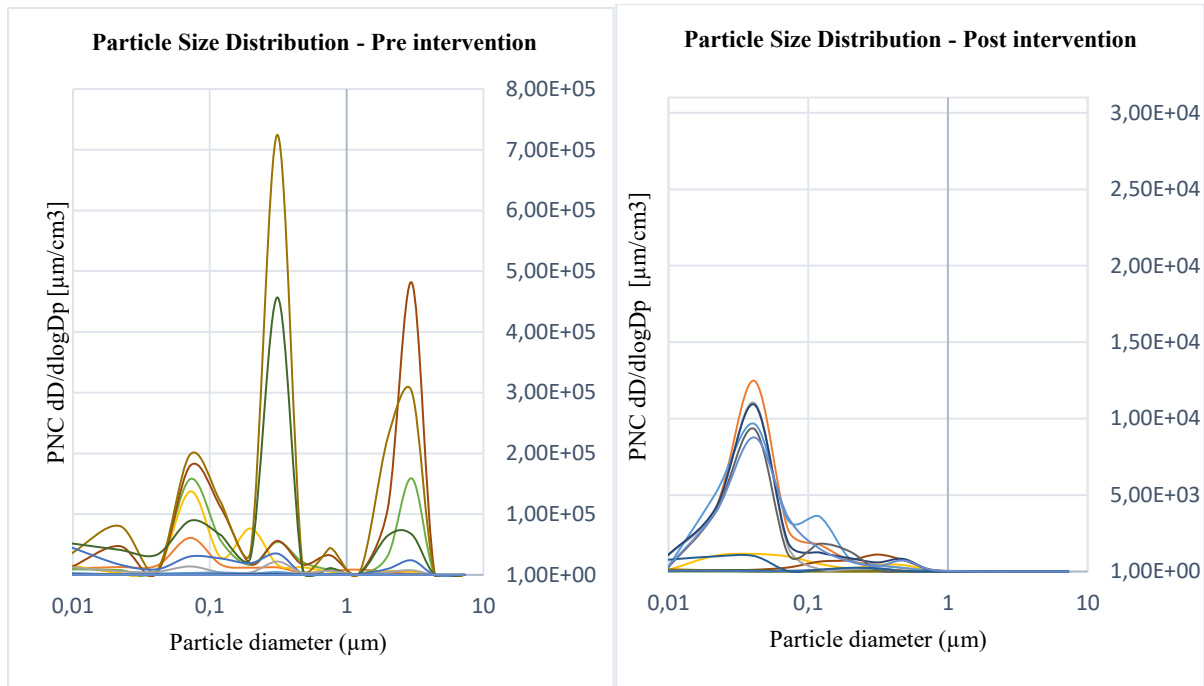


Figure 4.6: Particle size distributions of the 13 TMMs under study before and after intervention at 1000 hourly maintenance and maintenance plus DPF.

4.1.4 Regression Analysis

Regression statistics were used to predict the factors that influence the total number of particle concentrations in the tailpipe from the machines. Particle number concentration was a dependent variable, and the independent factors were the machines' age, the machines' rated power, and the type of maintenance done. The 250 hours of maintenance was used as a reference value for the maintenance assessment. Single regression was considered for this study due to the smaller sample size. The results are presented below.

The results for simple linear regression to predict the correlation between total particle number concentration as a proxy for diesel engine exhaust, engine age, engine power, and maintenance, plus retrofitting the machines with DPF, are shown in Table 4.15. A positive correlation between engine age and maintenance was observed. The model statistically significantly predicted particle number concentration as a function of engine age, which decreased when maintenance and retrofitting of the machines with DPF were done. However, machine power did not affect the total particle emissions (p-value = 0.73).

Table 4.15: Regression Analysis for total particle number concentration after the intervention, with particle number concentration as the dependent variable and the TMM Age, power in kilowatt (kW), and type of maintenance as independent variables

Simple linear regression				
<i>Variable</i>	Coefficient	95%CI	P-value	R²
<i>Age in hours</i>	116.12	8.79 - 223.45	0.035	0.1358
<i>KW power</i>	967.896	-4828.6 – 6 764.4	0.737	0.0029
250 Maintenance	4811010			
<i>500 Maintenance</i>	1048470	-30 476.04 -21 274 15	0.05	0.3704
<i>1000 maintenance</i>	1118915	19 416.61 – 22 184 14	0.001	0.7595

Simple regression Equation:

$$Y = \alpha + \beta_1(\text{machine Kw})$$

$$Y = Y = \alpha + \beta_2(\text{machine Age})$$

$$Y = \alpha + \beta_3 (250 \text{ maintenance})$$

$$Y = \alpha + \beta_4(\text{machine Kw})$$

Maintenance was categorical at 250h, 500h, and 1000h maintenance scheme

4.2 Results Particle Mass Concentration and Efficacy

Tables 4.16, 4.17, and 4.18 present the results for tailpipe mass concentration. The mass concentration was calculated automatically by the Dekati ELPI+ on a density of 1g/cm³. The results are presented for both interventions. Tables 4.17 and 4.18 specifically show the calculated efficacies for particle mass concentrations. Maintenance and DPF intervention significantly reduced total particle mass concentration, with the maintenance only intervention showing moderate reduction (insignificant at p-value = 0.06). The results are also graphically

presented in Figure 4.7 (Maintenance plus DPF intervention) and Figure 4.8 (Maintenance Only).

Table 4.16: Comparing total particle mass concentration before and after the intervention. The interventions are assessed individually, and all groups combined. Total number N = (41)

Intervention Category	Median (IQR) Total PMC Before (mg/m ³)	Median (IQR) Total PMC After (mg/m ³)	P-value*
<i>Maintenance only n = (20)</i>	0.39 (0.91-0.14)	0.174 (0.41-0.06)	0.060
<i>Maintenance + DPF n = (21)</i>	0.3905 (0.91-0.23)	0.017 (0.419-0.06)	0.0010
Overall (Cat A, B and C) Mass Concentration n = (41)	0.42 (0.88-0.23)	0.06 (0.34-0.032)	<0.0001

*p-value significant at 0.05, IQR – interquartile range

According to the efficacies calculated for tailpipe particle mass concentration (mg/m³) in (Tables 4.17 and 4.18), the machines retrofitted with the DPF system achieved an average reduction efficacy (AM) of 90% ($\pm 10\%$), with a range from 58.9 – 100% (Figure 4.7). For machines that underwent maintenance only, the reduction efficacy (AM) was 31% ($\pm 7\%$), with a range from 11-40% (Figure 4.8). Machines with a lesser engine age showed a more significant reduction.

Table 4.17: Efficacy for tailpipe particle mass concentration for before and after measurements for the machines that underwent maintenance and retrofitted with DPF. Total number of machines N = (21)

Machine ID Number	PMC Before (mg/m ³)	PMC After (mg/m ³)	Intervention Efficacy (%)
<i>DT 46**</i>	0.16	0.03	82.8
<i>LHD 72**</i>	0.14	0.02	83.8
<i>LHD 70**</i>	0.41	0.04	90.9
<i>DT50**</i>	0.33	0.04	89.1
<i>LHD 49**</i>	0.40	0.06	85.1
<i>LHD 39**</i>	0.02	0.00	86.2
<i>DT71**</i>	0.44	0.02	96.4

<i>LHD 62**</i>	0.18	0.03	82.1
<i>LHD 64**</i>	0.97	0.05	95.3
<i>DT 58**</i>	1.20	0.04	96.8
<i>LHD 41**</i>	1.33	0.00	99.7
<i>LHD RAM 56**</i>	0.24	0.10	58.9
<i>LHD 44**</i>	0.99	0.00	99.6
<i>LHD 51**</i>	0.62	0.05	92.4
<i>DT 62**</i>	0.99	0.00	99.6
<i>LHD 60 **</i>	0.62	0.05	92.4
<i>DT 59**</i>	0.51	0.04	91.9
<i>DT 22**</i>	0.92	0.01	98.7
<i>DT 44**</i>	0.45	0.05	88.8
<i>LHD 33**</i>	0.41	0.03	92.1
<i>LHD 25**</i>	0.81	0.14	82.8

**All Machines retrofitted with Diesel Particulate Filter (DPF).

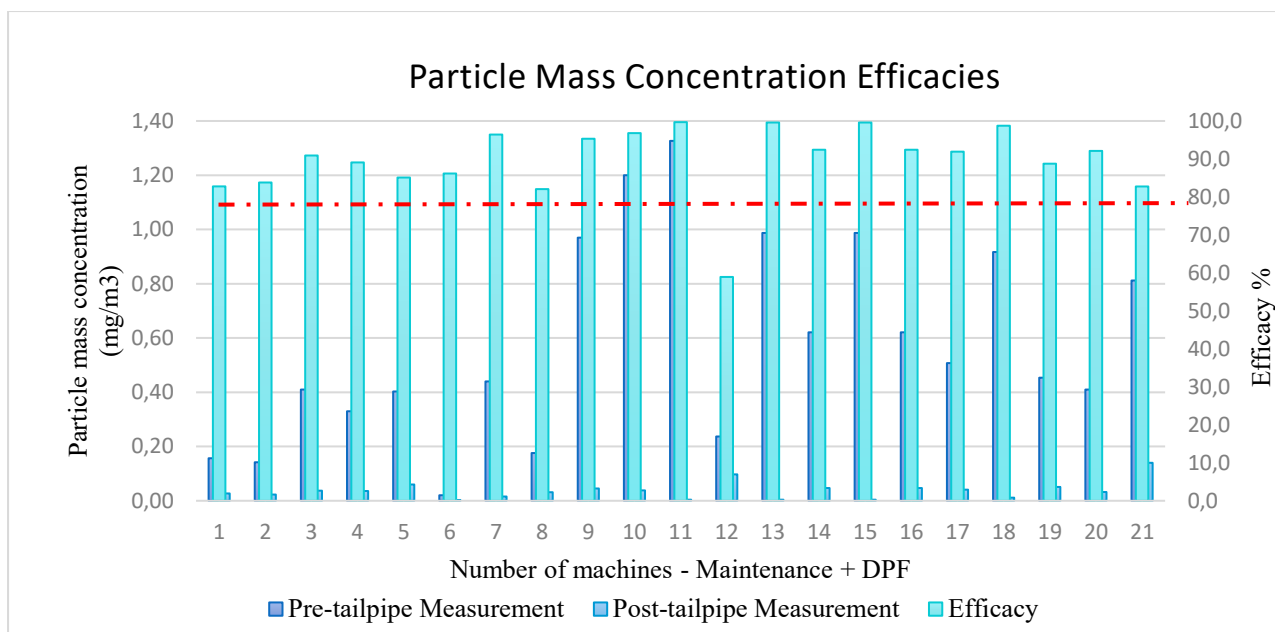


Figure 4.7: Graphical presentation of particle mass concentration efficacies (%) based on before-and after-intervention for machines that underwent maintenance only. The dashed line shows the group average.

Table 4.18: Efficacy of tailpipe particle mass concentration before and after measurements for the machines that underwent maintenance intervention N = (20)

Machine ID Number	PMC (mg/m³)	Before	PMC After (mg/m³)	Intervention Efficacy (%)
DT 39	0.78		0.52	33.1
LHD 50	0.32		0.24	26.6
DT 63	1.34		0.82	38.7
DT 68	1.49		0.91	38.6
DT 67	0.88		0.54	38.6
DT13	0.29		0.18	36.8
LHD 64	0.14		0.10	26.7
LHD 48	0.89		0.55	38.6
Dump truck 56	0.60		0.44	39.7
DT 61	0.05		0.03	25.0
DT 12	0.23		0.19	17.9
LHD Rham 57	0.06		0.04	41.2

<i>Dump truck 34</i>	026	0.20	23.5
<i>Dump truck 20</i>	016	0.10	41.7
<i>DT 60</i>	0.51	0.32	37.6
<i>DT 65</i>	1.33	0.91	31.4
<i>LHD 71</i>	0.38	0.28	25.9
<i>LHD 55</i>	0.88	0.67	23.7
<i>LHD 46</i>	0.41	0.36	11.6
<i>RHAM 54</i>	0.21	0.16	25.5

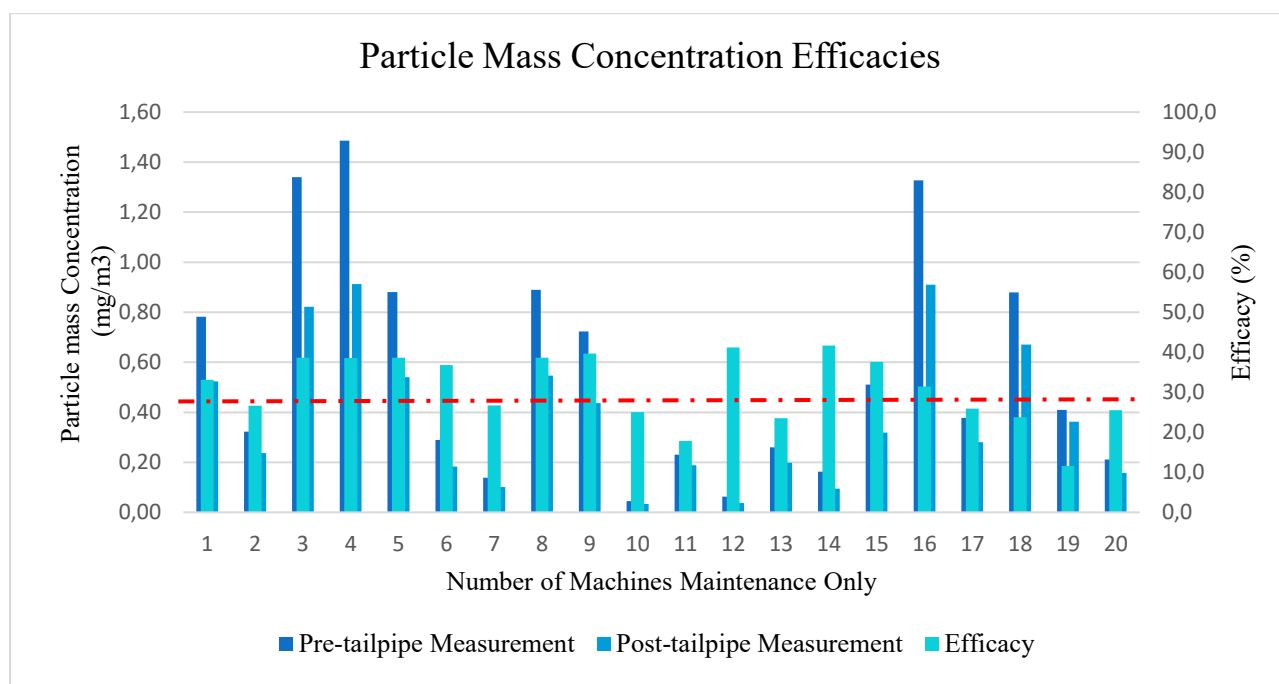


Figure 4.8: Representation of particle mass concentration efficacies after the intervention for machines that underwent only; the dashed line shows the group average: Exhaust gasses measurement on tailpipe before and after-intervention.

Tables 4.19 and 4.20 present the results of tailpipe gas measurements taken at baseline (before) and after maintenance intervention, and Tables 4.21 and 4.22 for machines that underwent maintenance and retrofitted with DPFs. The measurements were taken at two operating modes, i.e., idling and high revving mode, and the following gasses were tested: CO, NO, NO₂, and NO_x. When comparing results before and after measurements, there was a significant reduction in the total gases detected for the TMMs fitted with DPF and those that underwent maintenance only. The results are presented below.

Table 4.19: Compares before- and after-tailpipe measurements for Exhaust gases comprising CO, NO, NO₂, and NO_x during the idle mode for maintenance-only intervention N= (20)

Engine Mode	Gas	Pre-gas concentration (ppm) Median (IQR)	Post-gas concentration (ppm) Median (IQR)	P-value*
<i>Idling</i> <i>N=20</i>	CO	122(51-153.5)	77.5(10-139.5)	0.0001
	NO	284(177-457.5)	210(72-224.5)	0.0001
	NO _x	290(219-500.5)	196.5(74.5-230.5)	0.0001
	NO ₂	39.5(13-51.5)	15(3-18.5)	0.0001

*p-value significant at 0.05, IQR – interquartile range

Table 4.20: Compares before- and after-tailpipe measurements for Exhaust gases comprising CO, NO, NO₂, and NO_x during the idle mode for maintenance-only intervention N = (20)

Engine Mode	Gas	Pre-gas concentration (ppm) Median (IQR)	Post-gas concentration (ppm) Median (IQR)	P-value*
<i>High Rev</i> <i>N=20</i>	CO	383(254.5-412.5)	230(12.5-301)	0.0002
	NO	505.5(385-595)	305.5(78-397)	0.0001
	NO _x	580(409-699.5)	420(84-460.5)	0.0001
	NO ₂	25(20-30.5)	16.5(14-19)	0.0001

Table 4.21: Comparing before and after-tailpipe measurements for Exhaust gasses comprising CO, NO, NO₂, and NO_x during the idle mode for maintenance plus DPF intervention N = (21)

Engine Mode	Gas	Pre-gas concentration (ppm) Median (IQR)	Post-gas concentration (ppm) Median (IQR)	P-value*
<i>Idling</i> <i>N=21</i>	CO	120(72-181)	11(6-15)	<0.0001
	NO	330(211-399)	77(55-97)	<0.0001
	NO _x	391(305-432)	78(61-97)	<0.0001
	NO ₂	43(20-60)	5(1-5)	<0.0001

*p-value significant at 0.05, IQR – interquartile range

Table 4.22: Compares before- and after-tailpipe measurements for Exhaust gases comprising CO, NO, NO₂, and NO_x during the idle mode for maintenance plus DPF intervention N = (21)

Engine Mode	Gas	Pre-gas concentration (ppm) Median (IQR)	Post-gas concentration (ppm) Median (IQR)	P-value*
<i>High Rev</i> <i>N=21</i>	CO	327.5(205-440)	10(3-31)	<0.0001
	NO	577.5(488-673)	68(41-234)	<0.0001
	NO _x	622.5(519-732)	60(33-222)	<0.0001
	NO ₂	28.5(19-38)	2(1-4)	<0.0001

The exhaust gasses measurements (Tables 4.18 and 4.19) show a significant decrease for both the idling and high transient modes before and after maintenance interventions for median CO, NO, NO₂, and NO_x, at p-value = 0.0001. Significant reduction in Exhaust gasses was also achieved for machines that underwent maintenance and retrofitted with DPF (p-value<0.001). The results are presented in Tables 4.20 and 4.21.

4.3 Personal Exposure Results

4.3.1 *Description before and after intervention for personal sampling for diesel particulate matter using sampling pumps and NIOSH 5040 Analysis*

Tables 4.23, 4.24, and 4.25 represent the population sample for underground personal sampling and the results of personal measurements for underground elemental and total carbon concentrations. Based on the description of their activities related to their job title/ occupation, 34 employees were randomly selected from selected homogeneous exposure groups (HEGs) for sampling (Table 4.23).

The sampling of higher-risk employees for diesel particulate matter included diesel equipment operators and supervisors in an environment where diesel vehicles are used routinely. The 2019 personal sampling data for Elemental carbon (EC) and total carbon (TC) was used as a baseline, the period before the trackless mobile machinery interventions. The intervention sampling (after all TMMs were fitted with DPF) was conducted in April 2022 for the same job titles but not necessarily the same employees previously sampled in 2019.

This section evaluates whether after-treatment technologies (DPFs) have an effect (directly or indirectly) on the levels of personal elemental carbon (EC) samples taken within the same mine where the intervention occurred. There was a significant reduction of both EC and TC concentrations compared to the baseline measurements for both shifts (day and night).

Table 4.23: Population underground personal sampling for DPM N = (34).

<i>DPM Personal Sampling</i>				
<i>Sampled Job title/ Occupation</i>	Job Description	Day Shift	Night Shift	Total
<i>TM3 Dump truck Operators</i>	Haul ore and waste	4	6	10
<i>LHD Operators</i>	Haul ore and waste	4	10	14
<i>Drill Rig Operator</i>	Drilling development heading	2	1	3
<i>Roof Bolter Operator</i>	Drilling of hanging wall	0	2	2
<i>TM3 Dozer</i>	Dozing ore into LHD	0	1	1
<i>TM3 Miner</i>	Crew Supervisor	1	2	3
<i>Shift-boss</i>	Mining supervisor	1	0	1
<i>Total number of samples</i>		12	22	34

Table 4.24: Compares total carbon (TC) concentrations for pre- and post-intervention; the pre-intervention data consist of retrospective 2019 data, and the post-intervention data are after the installation of DPFs in all TMM (N = (34))

Personal Sampling Results – Total Carbon				
Mass concentration TWA.8h	Shift	TC TWA ($\mu\text{g}/\text{m}^3$) Before	TC ($\mu\text{g}/\text{m}^3$) After	P-value*
<i>Total Carbon (TC)</i> <i>N = (34)</i>	Morning	245.20 (363.42-214.49)	72.27(83.14- 32.58)	<0.0117
	Night	295.73 (536.23-199.42)	84.09 (107.69-56.51)	<0.0001
	Overall samples	271 (423-208.3)	79.2(102-53)	<0.0001

*p-value significant at 0.05, IQR – interquartile range

Table 4.25: Comparison of elemental carbon (EC) concentrations before and after the intervention; baseline data consists of retrospective 2019 data and the after-intervention data taken after the installation of DPFs in all TMM at the mine N = (34)

Personal Sampling Results – Elemental Carbon				
Mass concentration (TWA.8h)	Shift	EC mass concentration ($\mu\text{g}/\text{m}^3$) Before	EC mass concentration ($\mu\text{g}/\text{m}^3$) After	P-value*
<i>Elemental Carbon (EC)</i> <i>N = (34)</i>	Morning	147.7 (232.1-97.3)	3.6 (5.1-2.0)	<0.0001
	Night	203.1 (344.2-100.4)	5.2 (7.3-3.1)	<0.0001
	Overall samples	178.4 (323.6-100.4)	5.1 (7.3-2.9)	<0.0001

*p-value significant at 0.05, IQR – interquartile range

Tables 4.24 and 4.25 show the results of elemental carbon (EC) and total carbon (TC) for the morning shift and night shift employees taken before and after interventions (maintenance and retrofitting the machines with DPFs). Results were significantly lower post-intervention compared to the baseline (maintenance and retrofitting of the machines with DPFs).

4.3.2 Workplace CO monitoring by wearable gas detection device

Table 4.26 presents the shift average concentrations of the gas detection instrument worn by the supervisor at the same mine during the working shifts where the TMM intervention(s) occurred. The 2019 pre-data for CO supervisory personal exposure, which aligns with the 2019 DPM personal sampling measurements, was used; data was pulled from the system for the exact calendar dates.

The monitoring results taken at baseline (before intervention) and after intervention were significantly reduced. During the shift, it is assumed that the only source of CO is the operation of diesel-powered machinery underground.

Table 4.26: Compares the CO personal concentrations (TWA8h) collected by the supervisor's wearable gas measuring detector before and after N = (34)

Personal Sampling Results – Elemental Carbon			
Shift Category	Personal CO concentration (ppm) Before	intervention CO concentration (ppm) After	P-value*
Morning N = (17)	5.36 (9.04-3.74)	3.02 (3.89-2.61)	0.0140
Night N = (17)	6.04 (7.84-4.64)	2.75 (4.06-1.83)	0.0001
Combined shifts N = 34	5.66 (7.84-4.33)	2.88 (4.06-2)	<0.0001

*p-value significant at 0.05, IQR – interquartile range

The median CO concentration after the intervention, as monitored with the wearable gas detection instrument, was significantly lower than before the intervention data. The morning shift was 5.36 ppm to 3.02 ppm; for the night shift, 6.04 ppm to 2.75 ppm; and for the combined shifts, 5.66 ppm to 2.88 ppm. All differences are statistically significant.

4.4 Ventilation Simulation and Diesel exhaust dispersion modelling

4.4.1 Ventilation Simulation – Developing the ventilation backbone

4.5.1.1 Construction Layouts for Ventilation Simulation

This section focuses on the ventilation simulation and dispersion of diesel emissions in an underground environment. A specific portion of the mine, a selected section or ventilation

district, was identified and selected for the modelling exercise. The ventilation air quantities allocated in the different sections are divided into the intake and return airflow, airflow at the development headings, and airflows indicating contaminated air towards the return and exhausted to the surface by primary ventilation fans. Figure 4.9 shows the selected ventilation district.

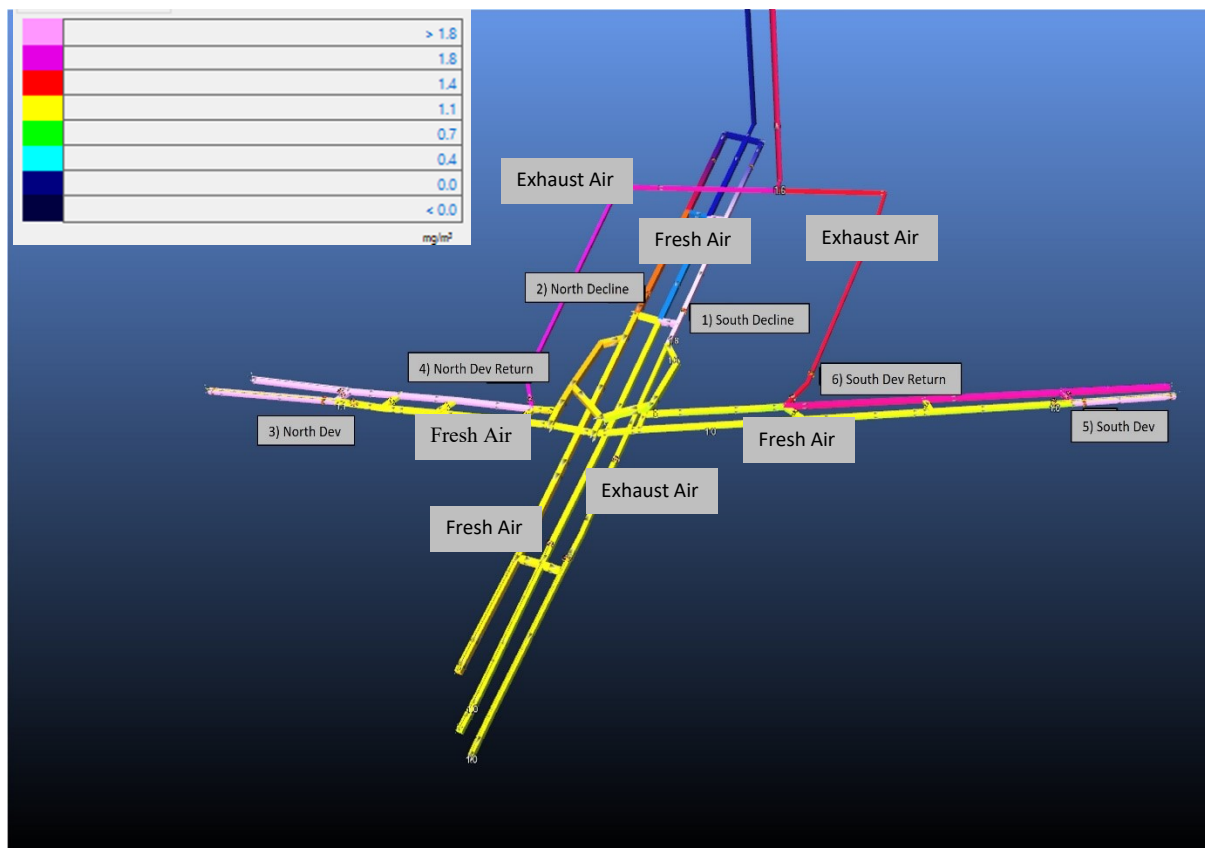


Figure 4.9: The portion of the mine used for ventilation dynamic simulation with intake, workplace, and return airways. Note: The grey shaded box represents the location within the section where ventilation simulation for contaminants was considered.

Locations 1 and 2 represent the intake airways, which is split between the South and the North intake section airways. Additional air volumes flowing within the material decline is also available as an intake volume. Location 3 is the North development airway/heading, which is ventilated to return airway through a return twin haulage and subsequently surface through the North decline return airway. The primary declines are also ventilated right to the haulage faces ventilates; this air returns into Location 5 and ventilates the South Development end (re-use), where it returns to surface ventilation fans through the South Development return airway. The volume mass flow rate disperses with the pollutant from the intake working place until it reaches the return airway, which is exhausted by the main fans to the surface.

The layout of the development headings is such that the North and main decline development headings use the air first; a portion of that air is then reused at the South development heading. This means that employees working in the South section will be more exposed to higher levels of DPM than the other two sections where the air is used first; a cumulative dose for the South development heading increases the risk of exposure.

The air volumes in Table 4.27 formed the basis for constructing the ventilation simulation model. The base-case volumes were used as a reference point for increasing the ventilation flow in the section.

Table 4.27: Ventilation air volumes (m³/s) for a simulated section of the mine for the intake, development face, and return airways. Air volumes representing base-case quantities and the altered ventilation volume increments of 10%, 20%, and 30%

Section Ventilation Modelling				
Location	Altered Ventilation Air volumes			
	Base Air Volumes (m ³ /s)	10%	20%	30%
<i>1 – Intake North Decline</i>	24.2	26.6	29.0	31.5
<i>2 - Intake South Decline</i>	45.9	50.5	55.1	59.7
<i>3 – North Face development</i>	25.0	27.5	30.0	32.5
<i>4 – North development return</i>	50.0	55.0	60.0	65.0
<i>5 – South Face development</i>	25.0	27.5	30.0	32.5
<i>6 – South Development return</i>	50.0	55.0	60.0	65.0

*An additional 30m³/s was passed through the conveyor belt intake airways, which is not shown in this table.

The total planned air volume for the section was 100m³/s for the simulated area. The volumes were spread between three-barrel declines; the two intake declines airways and a belt decline. The volumes were split across the South and North sections by 50m³/s volumetric flow rates. The lateral developments were ventilated with a 1015-diameter ventilation column and 75Kw fans, with a fan duty capacity of 25m³/s of air. The main decline development barrel had a 90Kw fan, with 1020 diameter ventilation columns to deliver between 25-30m³/s of air. The secondary ventilation depended on the primary ventilation system, which supplied air from the surface to the working places, where the auxiliary fans conveyed air to the working faces.

Table 4.28 details the current primary ventilation system for the shaft used for the study, including the air volumes (m³/s), overall system pressure (Pa), and system resistance pressure (Ns²/m⁸).

Table 4.28: Summary table showing the primary ventilation (surface fans) input air quantity, pressure, and system resistance for surface fans supplying the air to the shaft. Results are also presented for the altered ventilation increase at 10%, 20%, and 30%.

Parameters	Altered Ventilation Airflow			
	Base Volume	10%	20%	30%
<i>Volume (m³/s)</i>	435	478.5	522	565.5
<i>Pressure (Pa)</i>	3136	3794.56	4515.84	5299.84
<i>R = System resistance (Ns²/m⁸)</i>	0.016573			

4.5.1.2 Results of the Emission Strength Input Data for the Dispersion Simulation

Tables 4.29 – 4.32 represent the summary results of point source particle mass concentration (mg/m³) at the 90th percentile. The input data was taken from the raw tailpipe output data and used to determine the diesel exhaust engine out emissions, which was then used to calculate the emission strength dispersed in the underground working place. The input data for LHDs and dump trucks are summarised separately in Tables 4.29 - 4.32. A consolidated summary for 90th percentile mass concentration was used to calibrate the dispersion modelling and presented in Table 4.33. Fifty percent (50%) of the diesel exhaust engine out emission was assumed to contain EC. A similar process was used to model the gasses, and the summary of the 90th percentile is shown in Table 4.34.

Table 4.29: Results of the 90th percentile for point source tailpipe particle mass concentration for Dump trucks that underwent maintenance and were retrofitted with DPF N = (7)

Mass Concentration (mg/m ³) - Maintenance + DPF		
Trackless Mobile Machinery (Tier II)	Filter Measurement Before	Filter Measurement After
<i>DT46</i>	0.16	0.04
<i>DT50</i>	0.33	0.04
<i>DT 63</i>	0.20	0.02
<i>DT71</i>	0.44	0.02
<i>DT 58</i>	1.20	0.04
<i>DT 59</i>	0.99	0.00
<i>DT 60</i>	0.51	0.04
<i>90th percentile</i>	<i>0.69</i>	<i>0.04</i>

Table 4.30: Results of the 90th percentile for point source tailpipe particle mass concentration for the LHDs that underwent maintenance and were retrofitted with DPF N = (11)

Mass Concentration (mg/m ³) - Maintenance + DPF		
Trackless Mobile Machinery (Tier II)	Before-Filter Measurement	After-Filter Measurement
LHD 72	0.14	0.02
LHD 70	0.41	0.03
LHD 49	0.40	0.30
LHD 62	0.18	0.03
LHD 64	0.97	0.05
LHD Rham 57	0.33	0.00
LHD RAM 56	0.24	0.10
LHD 55	0.62	0.05
LHD 46	0.92	0.01
LHD 25	0.45	0.05
Rham 54	0.41	0.03
<i>90th percentile</i>	<i>0.92</i>	<i>0.10</i>

Table 4.31: Results of 90th percentile for point source tailpipe particle mass concentration for Dump trucks that underwent maintenance Only N = (11)

Mass Concentration (mg/m³) - Maintenance Only		
Before-Filter Measurement	Before Maintenance	After Maintenance
<i>DT 39</i>	0.78	0.52
<i>DT63</i>	1.34	0.82
<i>DT 68</i>	1.49	0.91
<i>DT 67</i>	0.88	0.47
<i>DT13</i>	0.29	0.13
<i>DT 56</i>	0.72	0.44
<i>DT 61</i>	0.05	0.01
<i>DT 12</i>	0.23	0.09
<i>DT 60</i>	0.51	0.32
<i>DT 65</i>	1.33	0.42
<i>DT 62</i>	0.41	0.36
90th percentile	1.34	0.82

Table 4.32: Results of the 90th percentile for point source tailpipe particle mass concentration for the LHDs that underwent maintenance. Only N = (7)

Mass Concentration (mg/m³) - Maintenance Only		
Before-Filter Measurement	Before Maintenance	After Maintenance
<i>LHD 50</i>	0.32	0.24
<i>LHD 64</i>	0.14	0.10
<i>LHD 48</i>	0.89	0.07
<i>LHD 44</i>	0.38	0.23
<i>LHD 33</i>	0.88	0.46
<i>LHD 41</i>	0.30	0.06
<i>LHD 71</i>	0.21	0.04
90th percentile	0.88	0.045

Table 4.33: Results of engine out particle mass concentration emissions input into the ventilation model for maintenance only and machines that underwent Maintenance + DPF

Results of Engine out PMC (90 th Percentile)				
Intervention regime of TMMs in the work scenario	PMC Before mg/m3	PMC After mg/m3	50% of PMC Before (EC)	50% of PMC After (EC)
<i>Maintenance + DPF</i>				
<i>LHD</i>	0.88	0.045	0.49	0.022
<i>Dump truck</i>	0.90	0.004	0.45	0.002
<i>Maintenance Only</i>				
<i>LHD</i>	0.92	0.46	0.46	0.23
<i>Dump truck</i>	1.34	0.82	0.67	0.33

Table 4.34: Results of engine out gas emissions input into the ventilation model for maintenance only and machines that underwent Maintenance + DPF

Gas Concentration (ppm)								
Intervention regime of TMMs in the work scenario	CO Before	CO After	NO Before	NO After	NO ₂ Before	NO ₂ After	NO _x before	NO _x after
<i>Maintenance + DPF</i>								
<i>LHD</i>	301	89	560	298	21	2	602	294
<i>Dump truck</i>	377	70	460	221	23	3	465	203
<i>Maintenance</i>								
<i>LHD</i>	298	122	460	370	26	18	530	233
<i>Dump truck</i>	344	126	569	414	31	16	655	398

Based on the above results, the air volumes, and the pollutant input data, a formula (from equation (d)), was used to calculate the total estimated EC and gas environmental concentration

loads and to determine the base-case diesel particulate concentration (Tables 4.35 and 4.36). The concentrations were then loaded into the ventilation simulation model, where the dispersion base model was constructed, showing the pollution level from the intake airways, development headings, and return airways. The base dispersion model is presented with colour codes that show the concentration levels from higher concentrations ($>1.8\text{mg/m}^3$) to the lowest ($<0.00\text{mg/m}^3$) in Figure 4.10.

4.5.1.3 Dynamic Simulation Results

Table 4.36 and Figure 4.10 present the baseline dynamic simulation. The diesel particulate concentrations were modelled with the emission tailpipe baseline data before any interventions were implemented. Table 4.35 shows the concentrations at different locations, and Figure 4.10 shows the dynamic dispersion simulation for location 3 (North development heading). The dispersion model focuses on location 3. Location 5 (South development heading) is also shown in some instances, as these are potential development headings within the district where employees are exposed to the highest levels of DPM.

Table 4.35: Dynamic simulation mass concentration for diesel particulate results (EC), the results of the base case and the ventilation alterations are presented

Location	Diesel particle concentration Baseline - before interventions (mg/m ³)			
	Base Vent	Vent +10%	Vent +20%	Vent +30%
1 – Intake South Decline	3.1	2.8	2.6	2.4
2 - Intake North Decline	2.8	2.7	2.4	2.25
3 – North Face development	4.7	4.4	4.0	3.7
4 – North development return	2.9	2.6	2.45	2.3
5 – South Face development	4.5	4.0	3.7	3.4
6 – South Development return	2.8	2.5	2.7	2.3

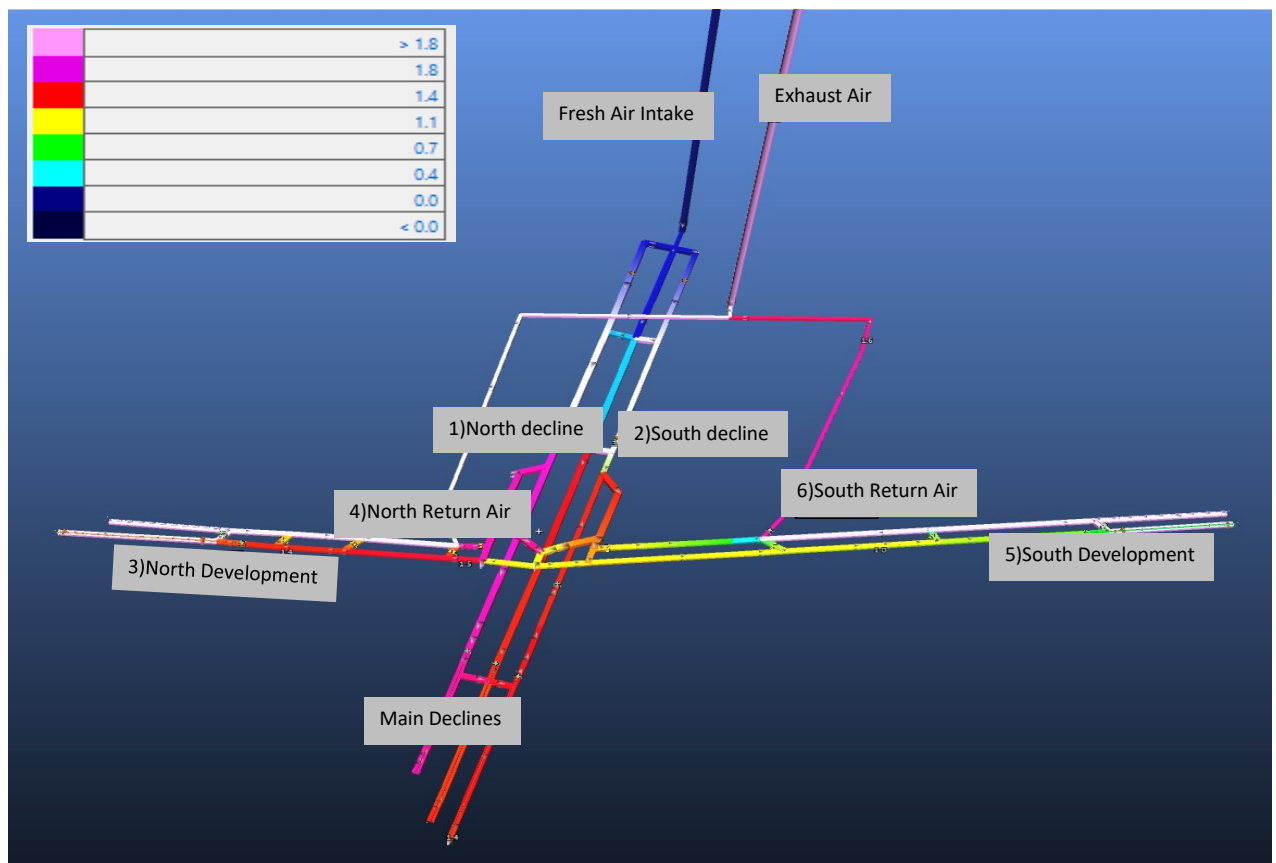


Figure 4.10: Visual dynamic simulation representation: a colour-coded diesel particulate dispersion dynamic model within the ventilation district, from the highest to lowest diesel particulate concentrations at the base case, before any intervention on the machines.

The visual presentation in Figure 4.10 shows that the particle concentration across the different parts of the ventilation district varied from above 1.8 mg/m^3 to 0.7 mg/m^3 . These concentration levels were simulated before undertaking any intervention.

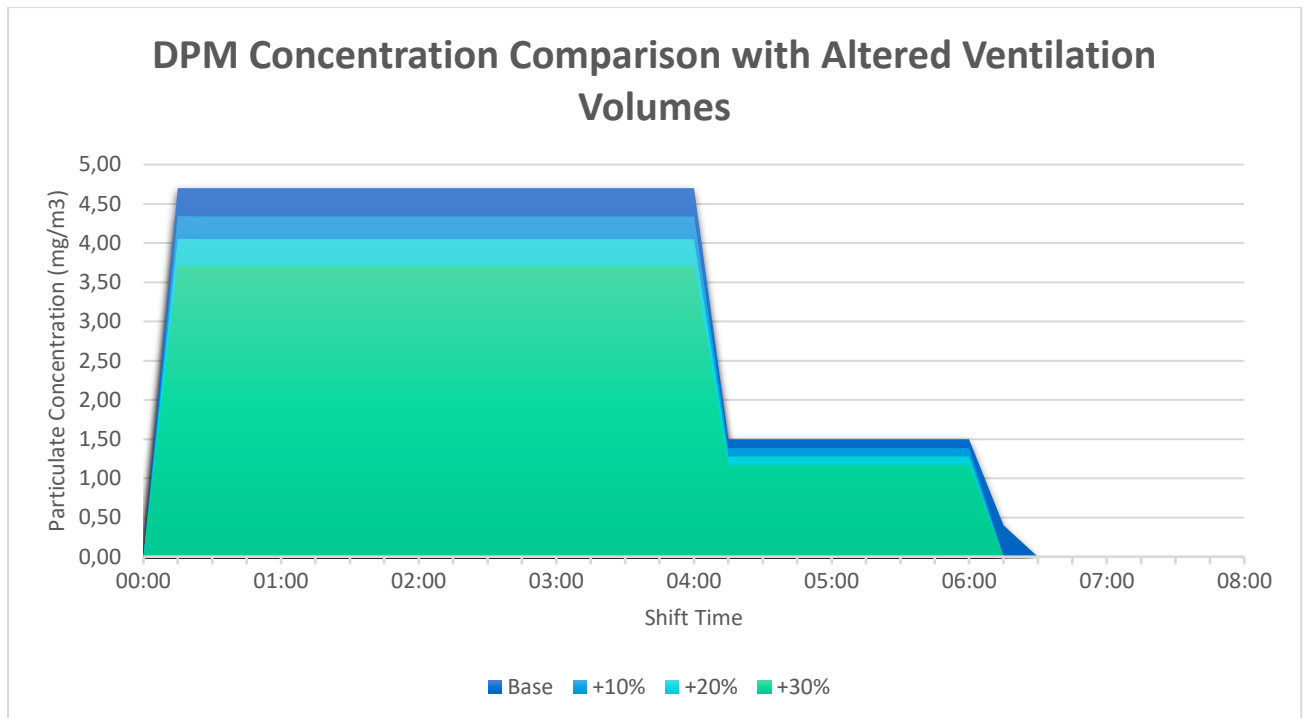


Figure 4.11: *The dynamic simulation DPM concentration at the North Development (location 3) at base case ventilation and pollutant load; simulation before any innervations.*

The simulated DPM dispersion for baseline emissions shows 4.7 mg/m³ diesel particulate concentrations at development headings (location 3). Ventilation alterations by 10, 20, and 30% reduced the concentration to 3.7mg/m³ at a 30% ventilation increase, which is a reduction of 21%.

Table 4.37 shows the dynamic simulation results for the two intervention regimes: maintenance and maintenance plus DPF. The visual dispersion for the diesel particle concentration is presented to show the particle flow through the mine ventilation district. The different colour codes represent the concentration levels of the diesel exhausts as they traverse the mine and the ventilation flow.

Table 4.36: Results for the base case dynamic simulation mass concentration for diesel particulate results (as EC) for the two interventions (maintenance only and maintenance plus DPF).

Base Case Simulation DPM Results		
<i>Location</i>	<i>Diesel particle concentration Maintenance only (mg/m³)</i>	<i>Diesel particle concentration Maintenance and DPF (mg/m³)</i>
	Base Vent	Base Vent
<i>1 – Intake South Decline</i>	2.3	0.013
<i>2 – Intake North Decline</i>	1.32	0.0076
<i>3 – North Face development</i>	2.6	0.021
<i>4 – North development return</i>	1.7	0.0124
<i>5 – South Face development</i>	2.8	0.02
<i>6 – South Development return</i>	1.5	0.0104

Note: The formula used to calculate the particle mass concentration (mg/m³) is equation (d). A similar equation was used to calculate the gas concentration in the model.

4.5.1.4 Diesel Particulate Dispersion Modelling Results

This paragraph presents the dynamic dispersion modelling results described under work scenarios in Chapter 3. The results are presented sequentially, starting with the dispersion of diesel particulate matter at base ventilation, without any alterations, and the baseline data for source emissions before any interventions. This was used as a reference point for the dispersion scenarios where machines are maintained, maintained and retrofitted with diesel particulate filters, and altered ventilation (increased ventilation from the base case).

A) Scenario 1 – Actual/implemented intervention.

Modelling scenario 1 presents the dynamic modelling for the machines that underwent maintenance only and machines that underwent machines plus retrofitting with DPF. In this section, two LHDs and a dump truck were allocated for the load and haul; the machines were diesel-powered. The two interventions at different locations were compared. The results will focus on location 3, the North development heading, and location 5, the South development heading. The results of all other areas are included as additional information on submission.

The airflow from the intake airway flowed through the haulage and split at the North and the decline development heading. At intake, the airflow already contained some contaminants from the dump trucks that operate at the primary declines.

Once it returned from the face, the air from the North development heading flowed to the return airway. However, it must be noted that the air that ventilates the Southern section development heading first ventilates the main decline development heading before returning via the South ventilation heading, where it is reused. This configuration may increase the pollutant load at the South development heading compared to the North.

Table 4.37 presents the results of the DPM dispersion simulation for the base case and the altered ventilation levels for scenarios 1 and 2. The section was simulated for diesel-powered LHDs and dump trucks, comprising two (2) LHDs and one (1) Dump truck. One LHD load on the development face the Muck bay, and the second LHD load from the Muck bay into the Dump truck, where the ore is then conveyed up the declines to the tipping point on the conveyor belts. The results are presented for the maintenance and maintenance plus DPF scenarios. Maintenance plus installation of DPF achieved lower DPM concentrations, viz; Location 3 achieved 0.021mg/m^3 compared to 2.6 mg/m^3 for machines that only underwent maintenance.

Table 4.37: Dynamic simulation mass concentration results for EC. The results of the base case and the ventilation alterations are presented.

Location	Diesel particle mass concentration Maintenance Only (mg/m ³)				Diesel particle mass concentration Maintenance and DPF (mg/m ³)			
	Base Vent	Vent +10%	Vent +20%	Vent +30%	Base Vent	Vent +10%	Vent +20%	Vent +30%
<i>1 – Intake South Decline</i>	2.3	2.1	1.9	1.7	0.013	0.012	0.0108	0.01
<i>2 - Intake North Decline</i>	1.32	1.2	1.1	1.0	0.0076	0.007	0.0064	0.0058
<i>3 – North Face development</i>	2.6	2.35	2.2	2.0	0.021	0.019	0.016	0.0154
<i>4 – North development return</i>	1.7	1.6	1.44	1.32	0.0124	0.0108	0.0104	0.0092
<i>5 – South Face development</i>	2.8	2.3	2.1	1.95	0.02	0.017	0.0157	0.0154
<i>6 – South Development return</i>	1.5	1.4	1.12	1.1	0.0104	0.0092	0.0086	0.008

Table 4.37 shows reduced diesel particle concentration for maintenance only and maintenance plus DPF intervention scenarios by ventilation dilution.

The particulate concentration for the face of the North development airway was 2.6 mg/m³ and 0.021 mg/m³ at the working face for maintenance only and maintenance plus DPF, respectively. This is a reduction of 45% with maintenance intervention only and 99.5% with maintenance plus DPF retrofitted machines. This is in line with the efficacy achieved for the two interventions. The scenarios with machines retrofitted with DPF showed DPM levels of less than 0.1mg/m³. All the different locations in the ventilation district showed a decrease.

Figures 4.12- 4.15 visually show how ventilation influences diesel exhaust dispersion within the different parts of the mine. The different colours show the diesel particulate concentration at base air volumes; 10%, 20%, and 30% increase in ventilation. The modelling results show that contaminants moving throughout the ventilation district are presented for maintenance only and DPF interventions.

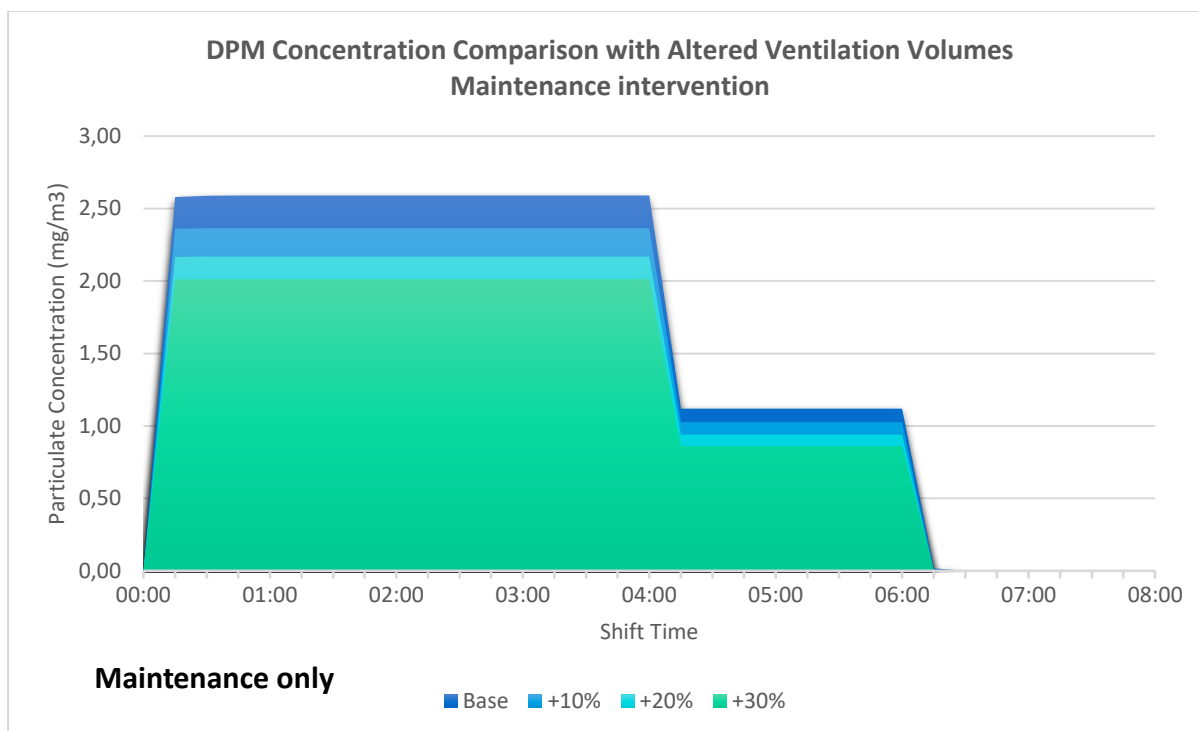


Figure 4.12: The simulation DPM concentration at the North Development (location 3) for machines that underwent maintenance only at intake. The air already contains the concentration of diesel particle emissions from locations 1- and 2-point.

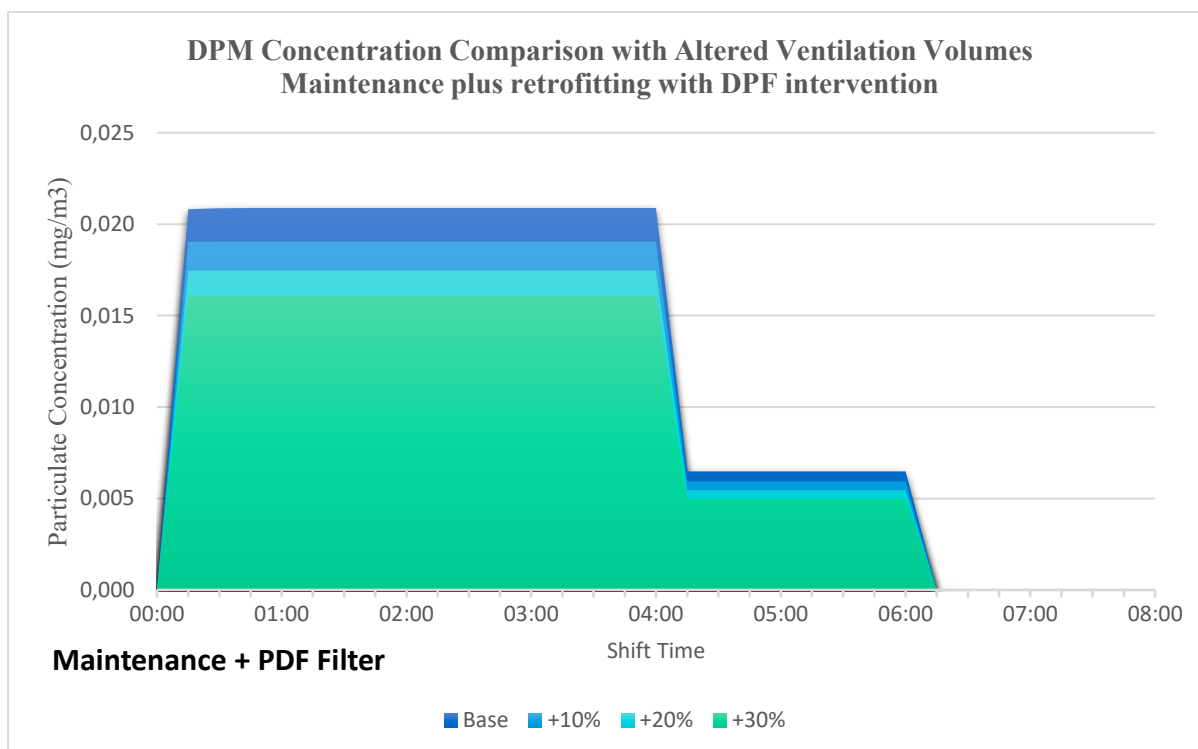


Figure 4.13: The simulation DPM Concentration at the North face development heading (location 3) for machines fitted with DPF. The air already contained a concentration of diesel particle emissions from locations 1- and 2-point sources.

The North face decline had 25m³/s available for the face, ventilated with a 75kW. The particle mass concentration at the base case was 2.6 mg/m³ for machines that underwent maintenance only and 0.021 mg/m³ for machines that underwent maintenance and were fitted with DPF. The dynamic simulation showed varying concentrations throughout the shift depending on the machines' load and the total loading time. For example, after 4 hours, the DPM decreased in the section due to the LHDs completing the loading cycle; only dump trucks were running for the remaining duration of the shift.

To test the effect of ventilation on diluting the workplace particle concentration, air volumes were increased by different percentages from the base case. A 10% increase in the ventilation flow reduced the particle mass concentration from 2.6 mg/m³ to 2.35 mg/m³ for machines that underwent maintenance only. For machines that underwent maintenance and were fitted with DPF, the concentration decreased from 0.021 mg/m³ to 0.019 mg/m³.

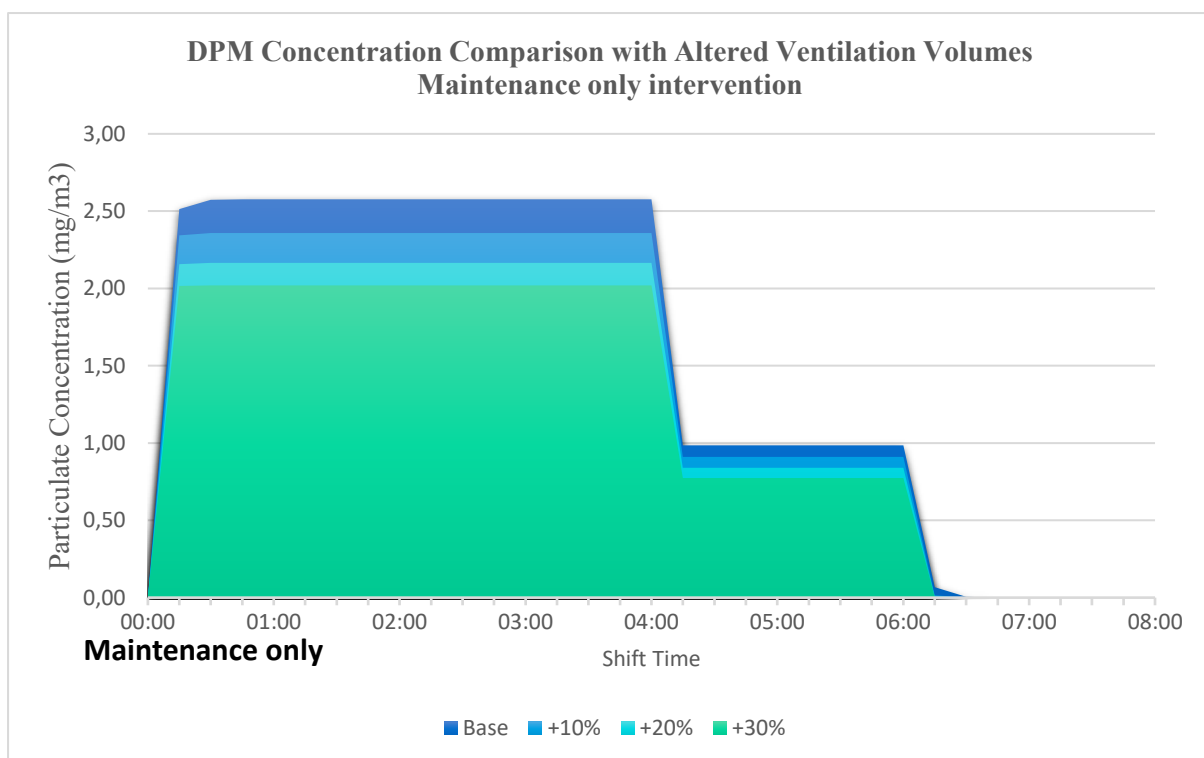


Figure 4.14: The Simulation DPM Concentration for the South face development heading (location 5) for maintenance only intervention; air already contained a concentration of diesel particle emissions from the contaminated air from the primary decline diesel emissions point sources.

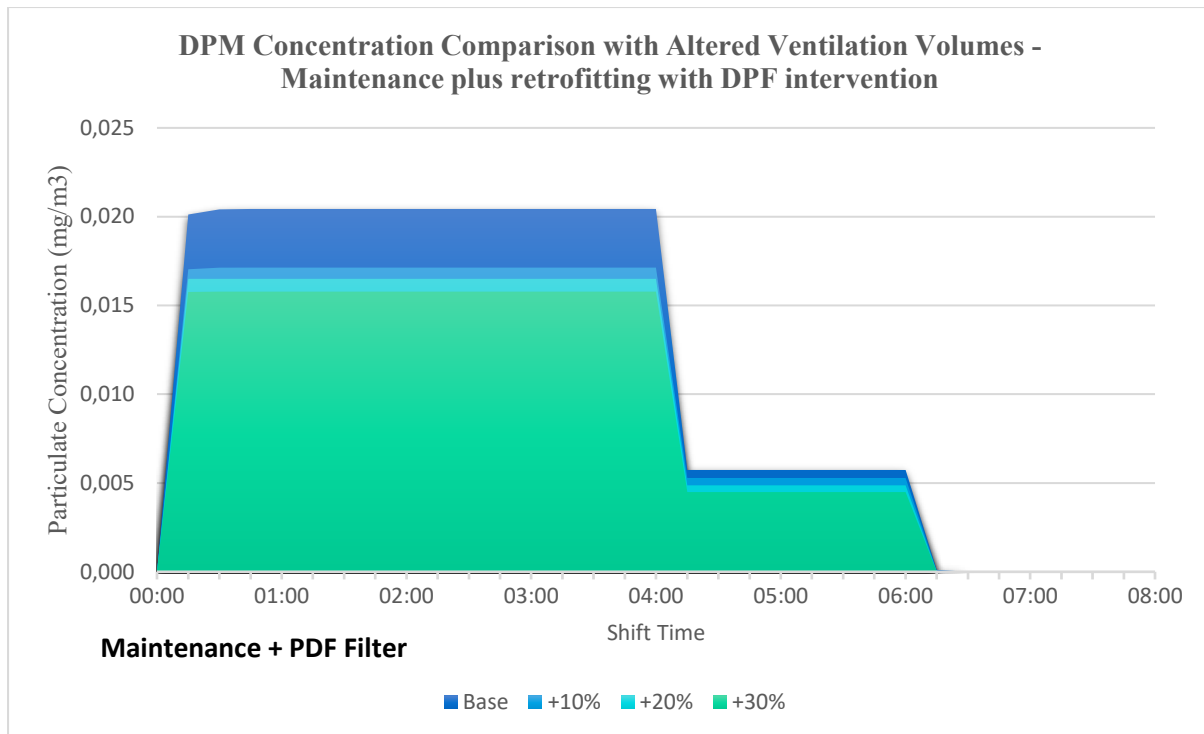


Figure 4.15: The simulation of DPM concentration for the South face development heading (location 5) shows that the air already contains the concentration of diesel particle emissions from the contaminated air from the primary decline diesel emissions point sources.

B) Scenario 3 recommended intervention – Dynamic Simulation when electric-powered machines replace the 2 LHDs in the section.

Figures 4.16 and 4.17 represent the results when the section LHDs were replaced with electric-powered machines. The results are presented for location 3 (North development heading). This translates to having 1 Dump truck within the development heading.

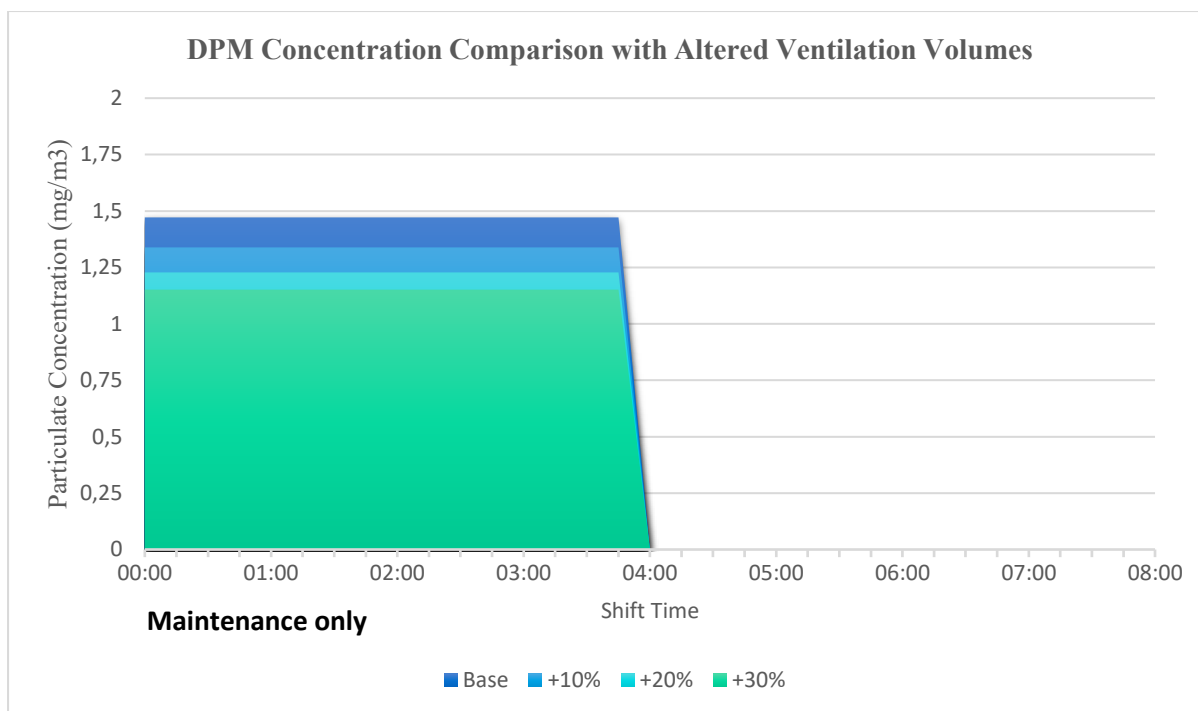


Figure 4.16: Simulated diesel particulate concentration at North face development heading (location 3) when the two (2) LHDs are replaced with electric LHDs for maintenance intervention.

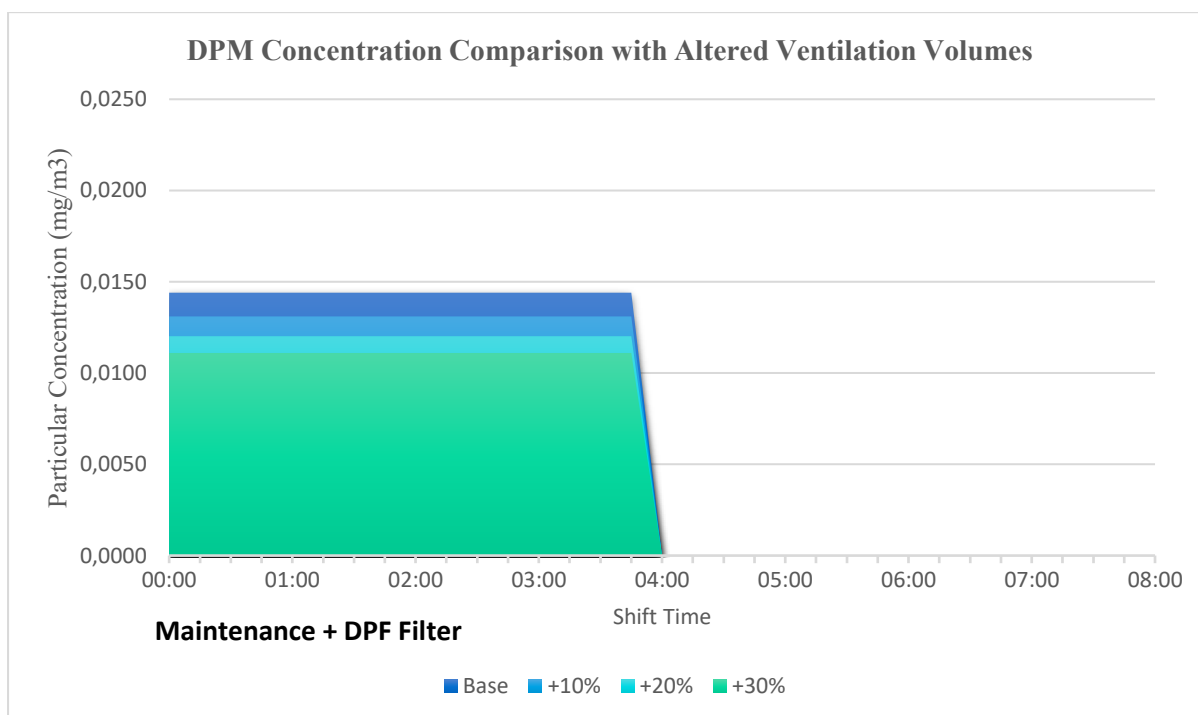


Figure 4.17: Simulated diesel particulate concentration at the North face development heading (location 3) when the two (2) LHDs are replaced with electric LHDs for maintenance plus DPF intervention.

Replacing the LHDs with electric vehicles decreased the diesel particulate concentration for the maintenance-only scenario and for machines that were maintained and fitted with DPF. The

diesel particulate concentration decreased by 51% for machines that underwent maintenance and 99.7% for machines retrofitted with DPF. It must be noted that when the electric-powered LHDs replaced diesel-powered LHDs, the recommended exposure value for EC remained above 0.1mg/m³ for machines that underwent maintenance intervention only. Machines retrofitted with DPF further reduced the diesel particulate concentration to below 0.1mg/3.

C) Scenario 4 recommended Dynamic Simulation when the Dump truck in the section is replaced by an electric-powered Dump truck.

Figures 4.18 and 4.19 represent the simulation results when the Dump trucks and LHD's were replaced with electric dump trucks and LHDs in the section.

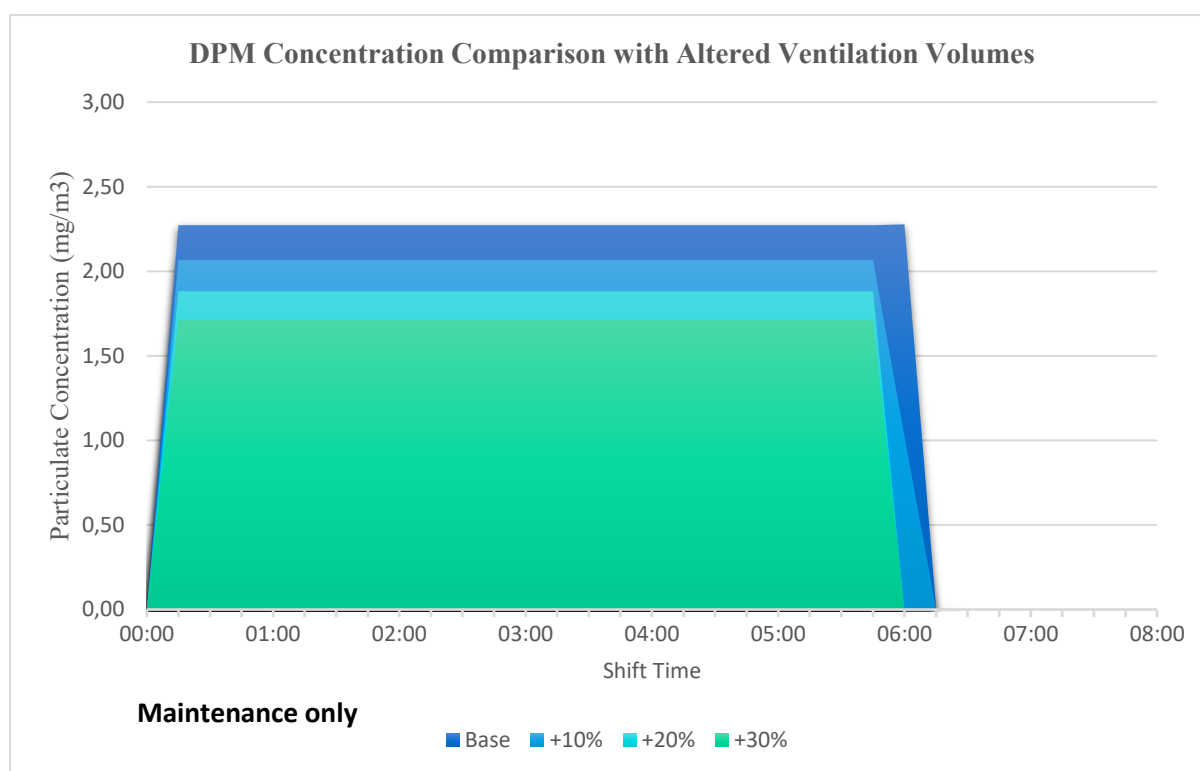


Figure 4.18: North face development heading (location 3) when the Dump trucks were replaced with electric Dump trucks; the intake air already contained a concentration of diesel particle emissions from locations 1 and 2, point sources.

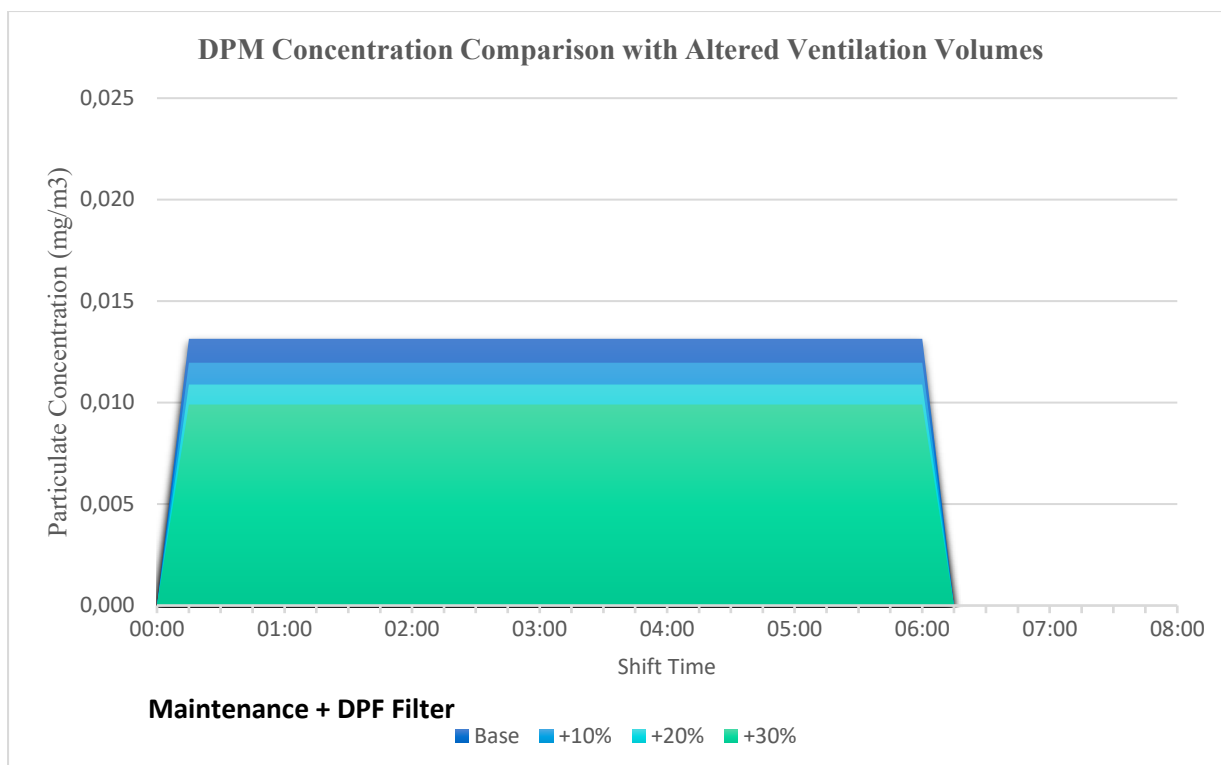


Figure 4.19: North face development heading (location 3) when the Dump trucks were replaced with electric Dump trucks; the intake air already contained a concentration of diesel particle emissions from locations 1 and 2 point sources.

The outcome of replacing the Dump truck with an electric one decreased the diesel particulate for both the maintenance and machines fitted with DPF. The diesel particulate concentration decreased by 69% for machines that had undergone maintenance and 99.7% for machines retrofitted with DPF. Machines with maintenance only were still above the 0.1mg/m^3 of EC. However, the machines retrofitted with DPF further reduced the diesel particulate concentration to below 0.1mg/m^3 .

4.5.1.5 Comparative results for workplace DPM concentrations with the recommended action limit After interventions

Figures 4.20 and 4.21 represent the simulated results of workplace diesel particulate concentration (mg/m^3) (at location 3, face development) for the two interventions: machines that underwent maintenance only and machines that underwent maintenance + DPF. Machines that underwent maintenance only showed no compliance with the recommended action limit value of 0.1mg/m^3 EC, even with increased ventilation at the workplace (Figure 4.20), wherein for machines that underwent maintenance and retrofitted with DPF, the DPM was reduced to below the recommended limit value (Figure 4.21).

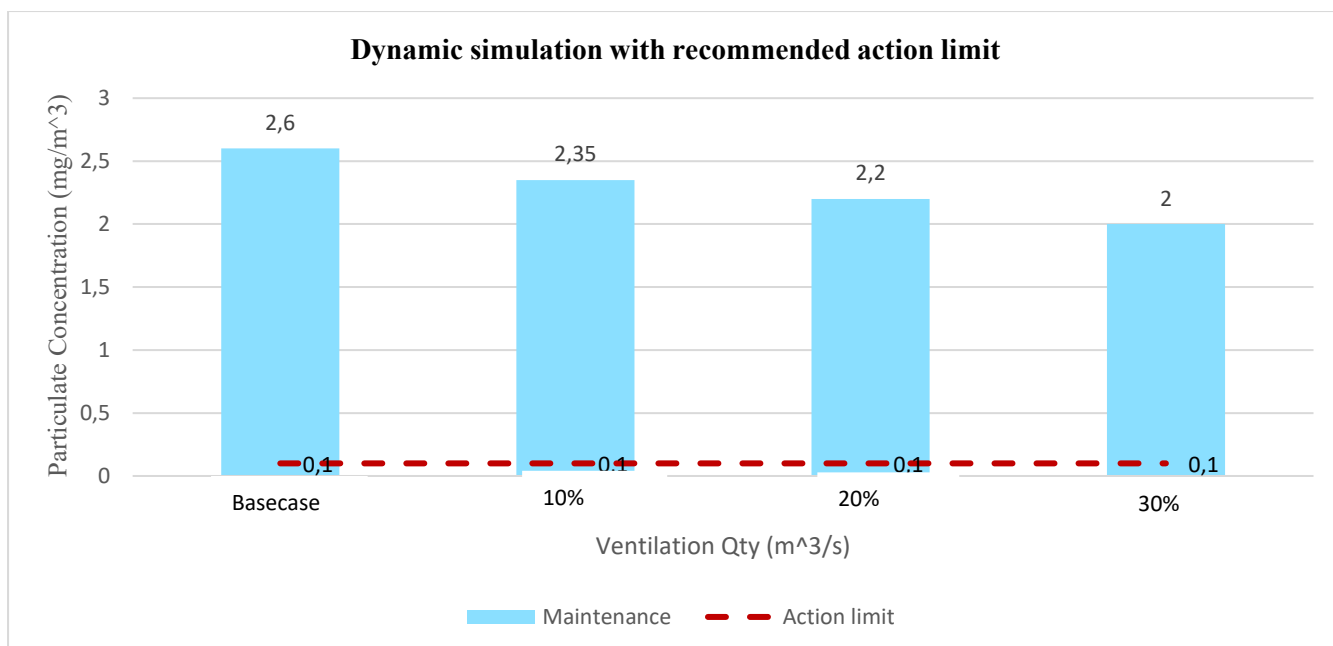


Figure 4.20: The simulated particle mass concentration at the recommended limit value of $0.1 \text{ mg}/\text{m}^3$ for the face development (location 3) at base-case and altered ventilation increases by 10%, 20%, and 30% for maintenance-only intervention, respectively.

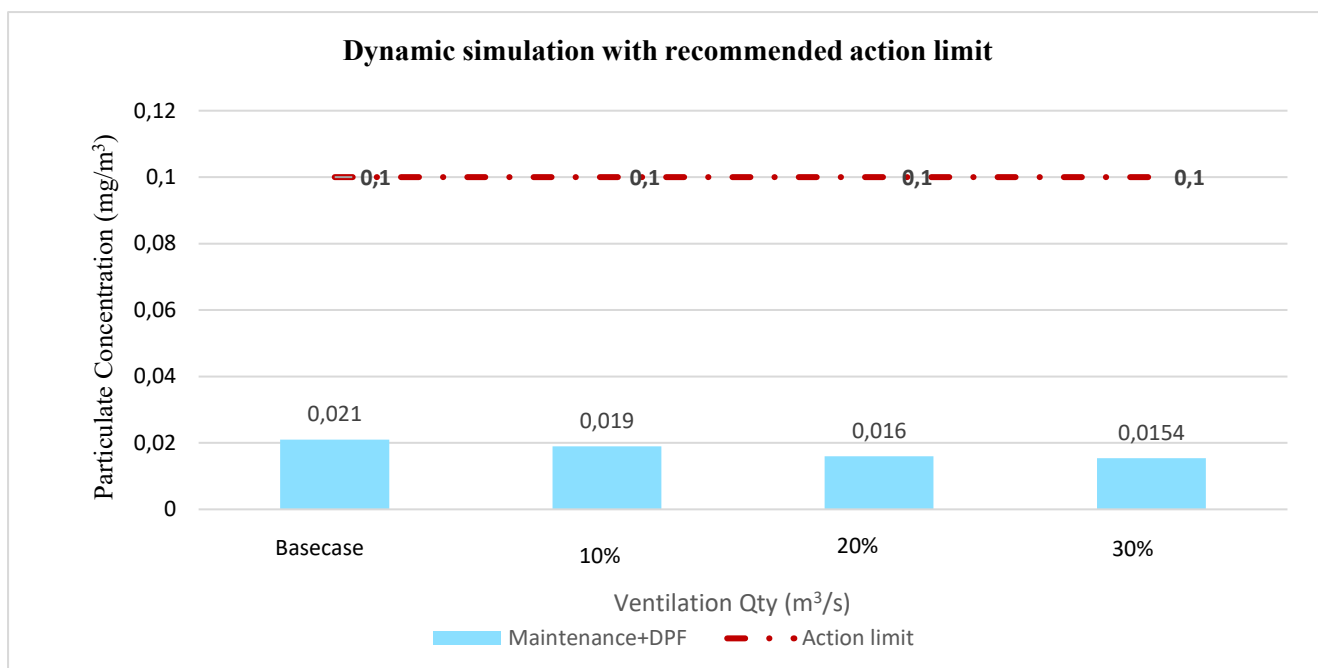


Figure 4.21: The simulated particle mass concentration on the recommended limit value of $0.1 \text{ mg}/\text{m}^3$ for the face development (location 3) at base-case and altered ventilation increases by 10%, 20%, and 30% for maintenance plus DPF intervention.

Figures 4.22 - 4.25 further demonstrate the pollutant spread for machines that underwent maintenance only. The graphs show that the DPM concentration (EC) ranges between $1.1 \text{ mg}/\text{m}^3$ and $>1.8 \text{ mg}/\text{m}^3$; when ventilation dilution and maintenance interventions are implemented, the concentrations are above the recommended action limit.

The dynamic simulations could not reproduce the visual presentation for maintenance plus DPF intervention due to the low DPM concentration.

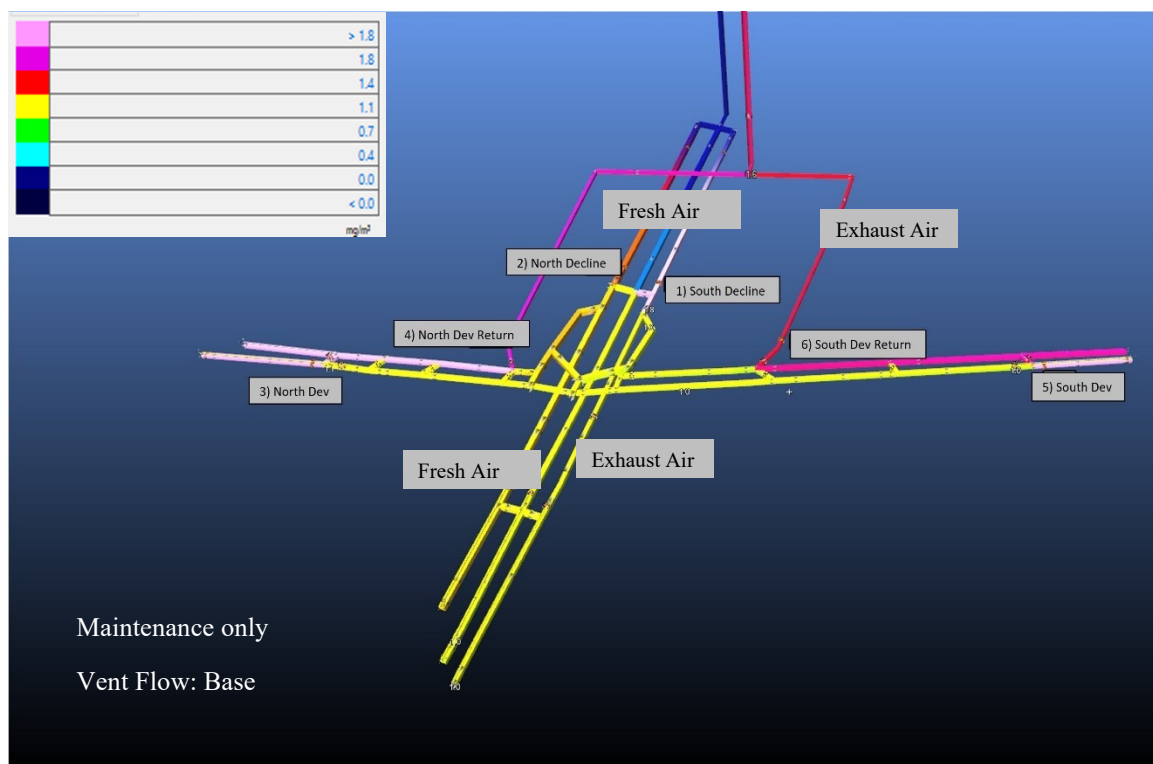


Figure 4.22: DPM concentration contamination flow at Maintenance Only base case ventilation.

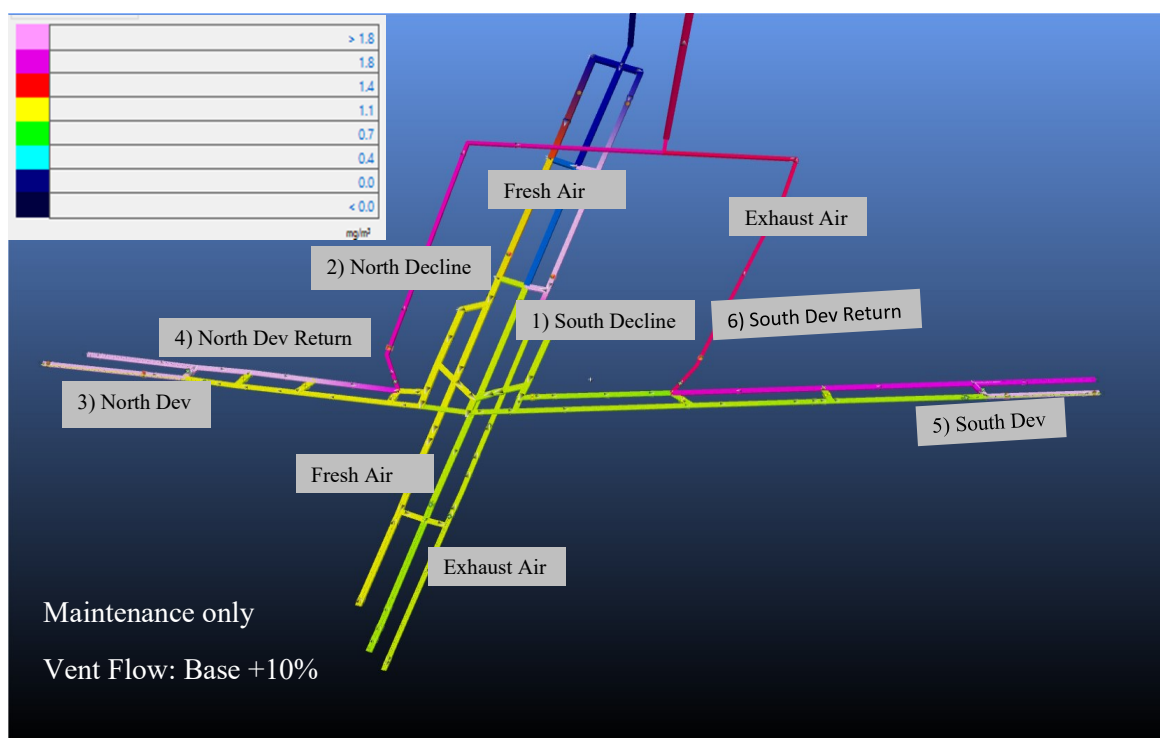


Figure 4.23: DPM concentration contamination flow at 10% ventilation increase.

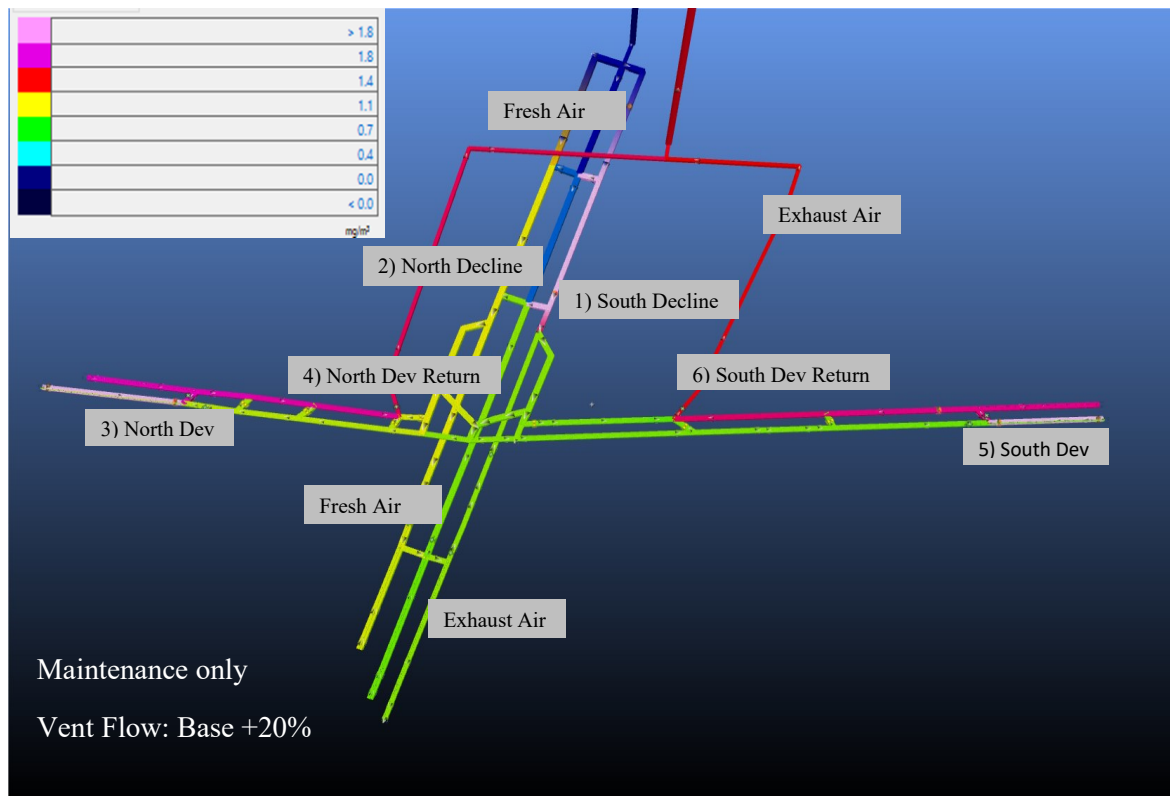


Figure 4.24: DPM concentration contamination flow at 20% ventilation increase.

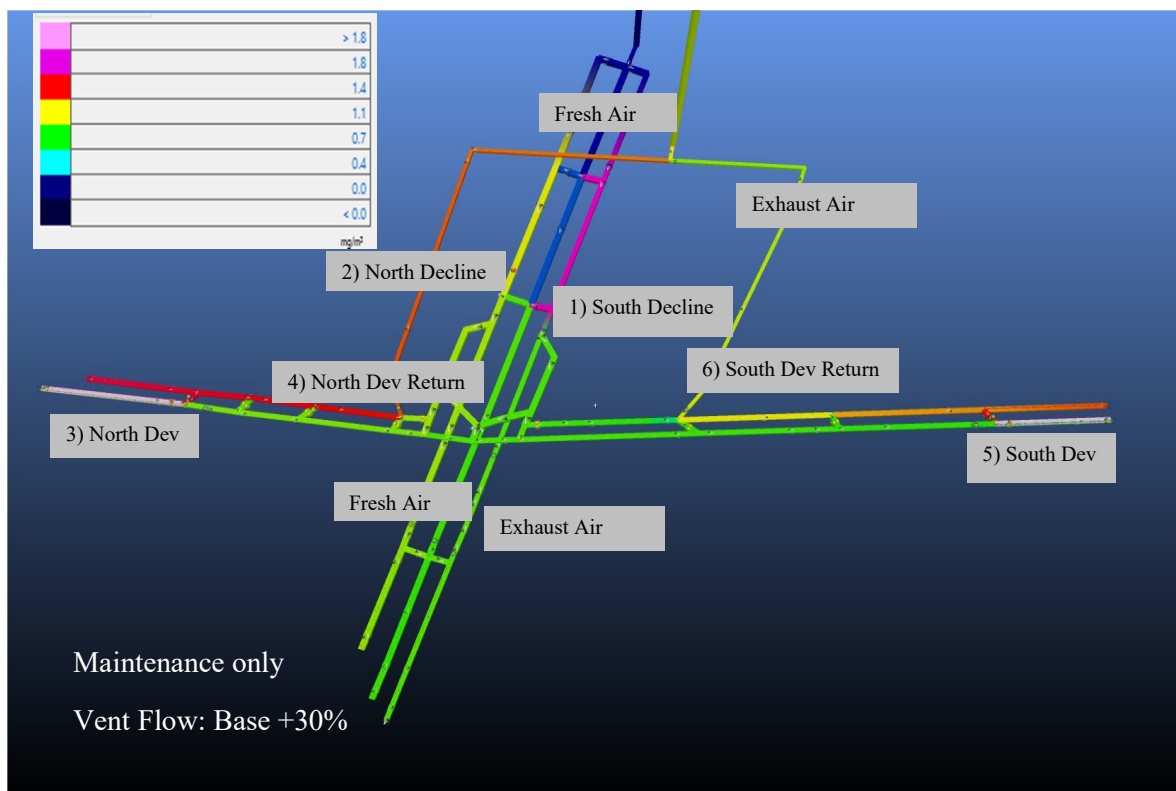


Figure 4.25: DPM concentration contamination flow at 30% ventilation increase.

The lowest DPM concentration at base case ventilation is $\leq 1.1\text{mg/m}^3$, as visualised by the dominant yellow colour. The DPM slightly decreased as ventilation increased from 10-30%. At a 10% increase, a slight green shift was observed, showing a concentration reduction towards 0.7mg/m^3 . However, the pollutant concentration reached its limit at 0.7mg/m^3 , which is still higher than the recommended action limit for DPM. It must be noted that although other areas showed some reduction in DPM concentrations, the DPM concentrations at both the North and South sections development headings remained high at 1.4mg/m^3 to $\geq 1.8\text{mg/m}^3$.

Overall, the dynamic simulation dispersion showed that controlling DPM at the source by maintenance and retrofitting the machines with DPF effectively reduced the DPM to below the recommended action limit value of 0.1mg/m^3 . Other interventions, such as maintenance, ventilation, and partial replacement of some machines with electrified vehicles, showed a reduction, although the DPM concentration was still above the action limit. Increasing ventilation showed some reduction in the concentration of pollutants in other parts of the mine. However, it was not effective in reducing DPM when implemented as a single intervention or when only combined with maintenance.

4.5.1.6 Dynamic dispersion results for tailpipe gases

Tables 4.38 and 4.39 present simulated gas results at the working places based on the tailpipe emissions at the source due to the interventions. The dynamic gas simulation was only done for maintenance and maintenance plus DPF interventions. Overall, there was a slightly higher reduction in gas concentration for machines fitted with DPF compared to machines that only underwent maintenance. The concentration was also calculated based on emission strength, development volume, and airflow requirements. The results are reported in ppm for CO, NO, NO_x, and NO₂. A graphical presentation of the reports on the base case for each intervention and the ventilation increase scenario is presented (Figures 4.26 - 4.29).

Table 4.38: Dynamic simulation Tailpipe gas concentration. The results for the base-case ventilation with no interventions are presented.

Maintenance Only - Base Ventilation				
Location	CO	NO	NO _x	NO ₂
1 – Intake North decline	143.4	148.3	149.6	7.6
2 – Intake South Decline	128.1	131.6	131.3	6.7
3 – North Face development	164.3	115.9	115.6	4.9
4 – North Dev Return	195.6	119.3	128.5	5.0
5 – South Facdevelopment	201.6	117.5	127.7	5.1

$$Q_v [\text{m}^3/\text{s}] = \frac{Q_E [\text{m}^3/\text{s}] \times (C_E [\text{ppm or } \mu\text{g}/\text{m}^3] - C_T [\text{ppm or } \mu\text{g}/\text{m}^3])}{C_T [\text{ppm or } \mu\text{g}/\text{m}^3] - C_B [\text{ppm or } \mu\text{g}/\text{m}^3]}$$

Table 4.39: Base case simulation results for tailpipe gases when diluted with workplace ventilation for maintenance only and maintenance + DPF.

Maintenance + DPF Base Ventilation				
Location	CO	NO _x	NO	NO ₂
1 – Intake North decline	62.7	143.3	146.4	3.9
2 – Intake South Decline	56.0	128.0	130.8	3.4
3 – North Face development	87.6	84.7	88.6	4.0
4 – North Dev Return	107.6	112.0	115.4	3.5
5 – South Face development	118.0	115.4	118.6	3.3

$$Q_v [\text{m}^3/\text{s}] = \frac{Q_E [\text{m}^3/\text{s}] \times (C_E [\text{ppm or } \mu\text{g}/\text{m}^3] - C_T [\text{ppm or } \mu\text{g}/\text{m}^3])}{C_T [\text{ppm or } \mu\text{g}/\text{m}^3] - C_B [\text{ppm or } \mu\text{g}/\text{m}^3]}$$

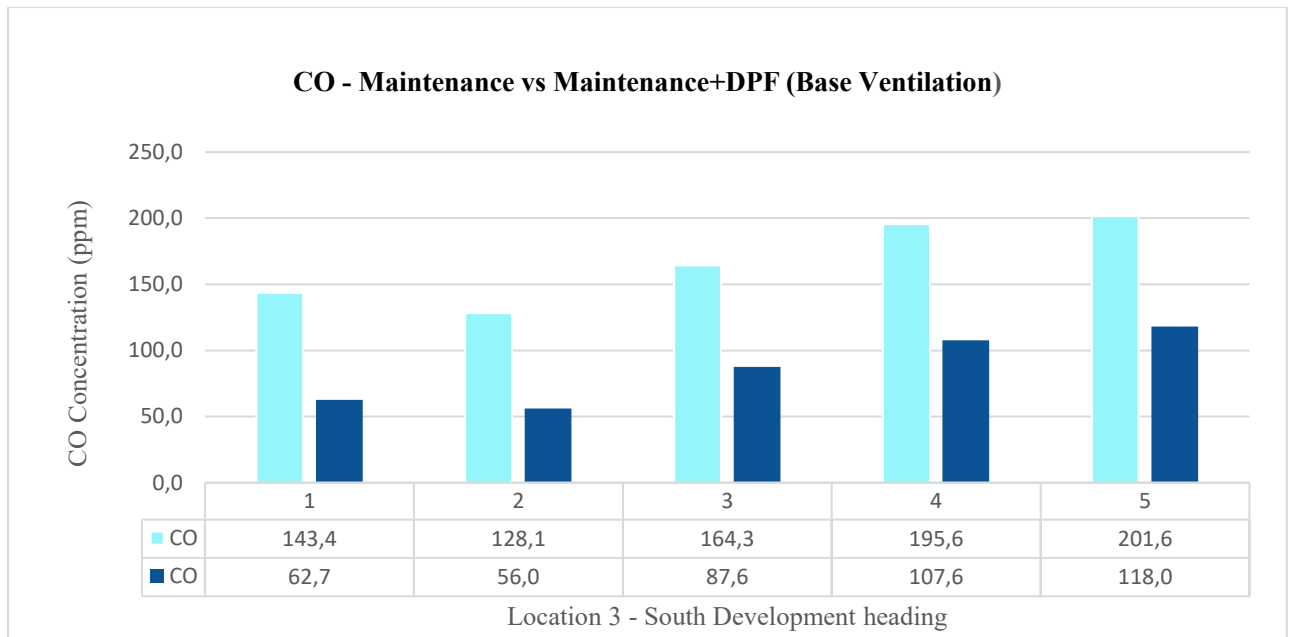


Figure 4.26: Dynamic simulation results showing carbon monoxide concentration; the results show the CO concentration for the face development (location 3) at the base case.

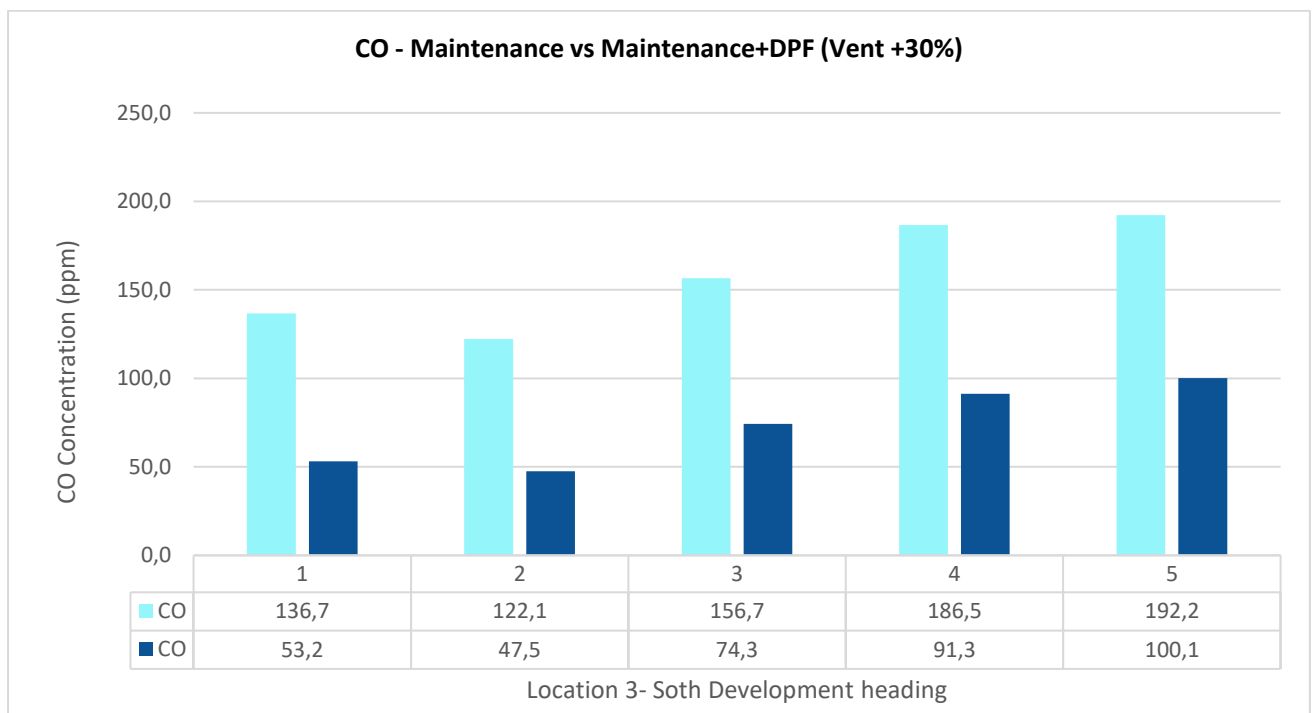


Figure 4.27: Dynamic simulation results show that carbon monoxide (CO) concentration at the face development (location 3) is at a 30% ventilation increase.

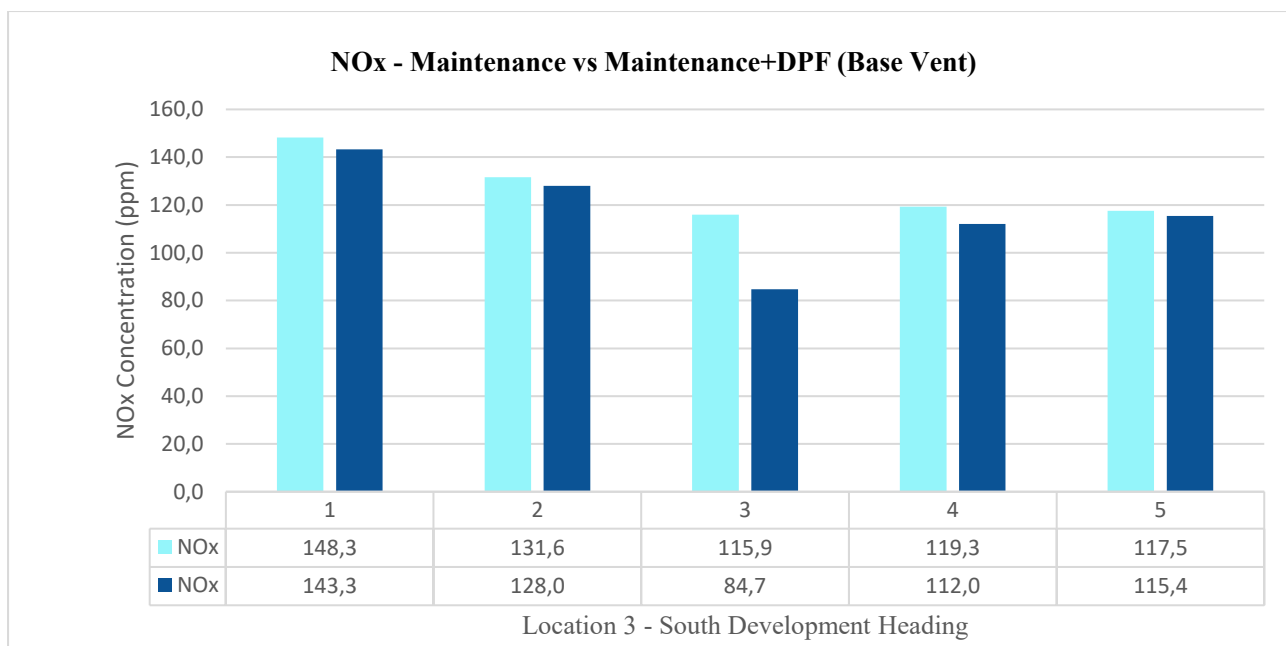


Figure 4.28: Dynamic simulation results in Nitrogen Oxide (NOx) concentration at the face development (location 3) at base-case.

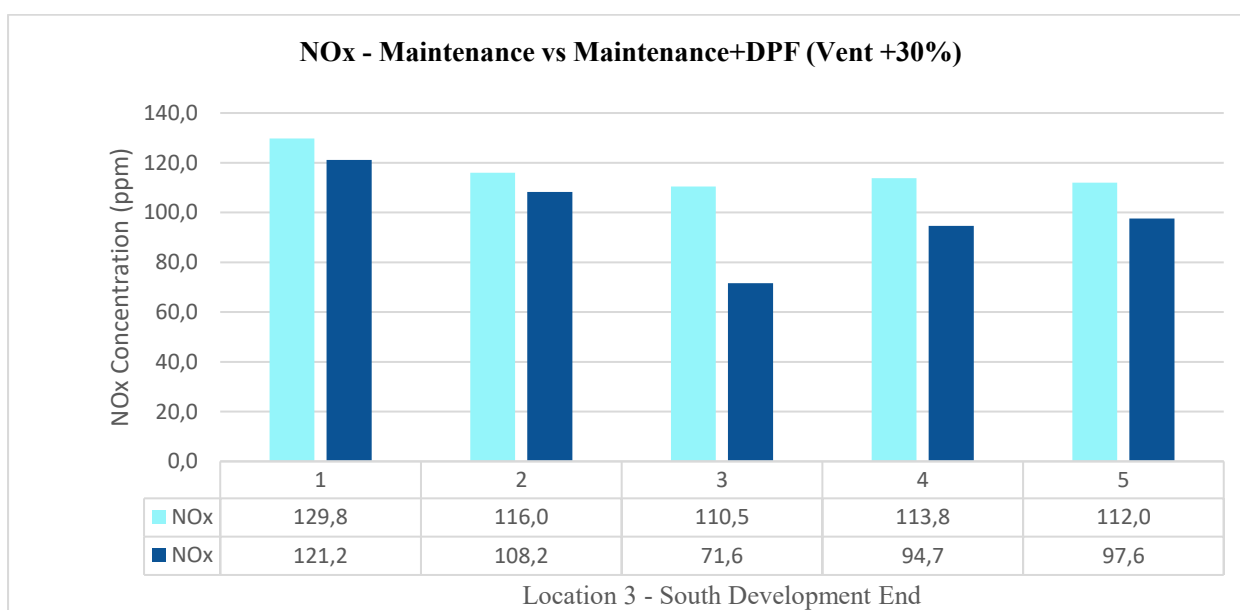


Figure 4.29: Dynamic simulation results Nitrogen Oxide (NOx) concentration at the face development (location 3) at ventilation increase at 30%.

When comparing the machines fitted with DPF and those with maintenance only, the simulated exhaust gas concentrations for CO decreased by an average of 50% from the base case. There was, however, only a very slight reduction with NOx (at an average of 15% when ventilation was increased to 30%). The reduction of exhaust gases was generally lower than that of diesel exhaust particles.

4.5 Cost Evaluation Results

A cost evaluation determined the viability of using ventilation dilution to reduce workplace diesel engine exhaust. This was done by assessing the required ventilation to run the primary and secondary ventilation fans for the 10 operational half-levels at the mine. Direct ventilation information is presented in Table 4.40, showing the development heading air volumes, the thru ventilation volumes, and the diesel particulate concentration for maintenance only and maintenance plus retrofitted DPF. The total available quantities for both primary and secondary systems were used to calculate the absorbed power and the total running power costs for the required ventilation, presented in Tables 4.40 and 4.41.

Table 4.40: Summary of the development airflow quantities and diesel particulate concentrations in a development end; the results are presented for both interventions with ventilation increase intervals of 10%, 20%, and 30%.

Intervention Cost Benefit Assessment by Available Ventilation					
Scenarios	<i>Dev volume (m³/s)</i>	<i>Thru Vent (m³/s)</i>	<i>Time (s)</i>	<i>Simulated DPM concentration Maintenance only (mg/m³)</i>	<i>Simulated DPM concentration Maintenance + DPF (mg/m³)</i>
Base	25.0	50.0	3600	2.6	0.021
10%	27.5	55.0	3600	2.35	0.019
20%	30.0	60.5	3600	2.2	0.016
30%	32.5	66.6	3600	2.0	0.015
Reduction by dilution %				25%	23%
Reduction by dilution + DPF					98.8%

Table 4.41: Power consumption rate based on absorbed power (kW)

<i>Absorbed Power (kW)</i>					
<i>Scenario</i>	<i>Auxiliary fan (kW)</i>	<i>Main Fan(kW)</i>	<i>Total (Annum)</i>	<i>Rated Kw/h (USD)</i>	<i>Estimated running cost (USD)</i>
<i>Base</i>	66,5	1773	15 535 344,08	0.692 USD	9 771 967,30 USD
<i>10%</i>	88,6	2360	20 677 542,98	0.692 USD	13 006 489,03 USD
<i>20%</i>	115	3064	26 845 084,45	0.692 USD	16 885 960,05 USD
<i>30%</i>	139,6	3896	34 131 240,81	0.692 USD	21 468 971,27 USD
<i>Power Consumption %change</i>	52.4%	54.5%			

Table 4.42: Summary of the once off cost for the installation of diesel particulate filters

Investment - Diesel Particulate Filters			
<i>Machine type</i>	Unit Price	Number of Machines	Estimated installation cost
<i>LHD*</i>	8,500 USD	32	272,009 USD
<i>Dump trucks**</i>	14,691 USD	41	602,367 USD
<i>Total</i>		73	874,376 USD

***LHD** – Fitted with 1x DPF.

****Dump truck** – Fitted with 2x DPF.

The ventilation dilution decreased the diesel particulate concentration by 25% for the machines which underwent maintenance only and 98% for machines with maintenance plus retrofitted with DPF, at a 30% ventilation increase. However, to achieve this, the absorbed power for the secondary ventilation system increased by 52% from the base case and the primary ventilation by 54.5%, which increased the ventilation operational running costs from 9 771 967,30 USD to 21 468 971,27 USD per annum.

On the other hand, installing DPF on the 73 machines for the entire shaft costs 874,376 USD in capital. DPF does not require complex maintenance but is cleaned monthly with highly pressurised water. Continuous maintenance for the TMM fleet forms part of existing operational maintenance costs; there is no additional maintenance cost when machines are retrofitted with DPF.

CHAPTER 5 – DISCUSSION

The overarching aim of the research was to determine the characteristics of diesel engine exhaust (DEE) at source during the operation of trackless mobile machinery and to evaluate specific control strategies to prevent and control workplace exposure to DEE in South African underground Platinum Mines. The outcomes of the research findings support the aim and objectives of the study. This section will integrate the findings of the study aim and objectives by logically synthesising the outcome of objectives 1, 2, and 3 in line with the reported findings to evaluate the impact of different control strategies to prevent and control the exposure of diesel exhaust emissions to employees. High-level findings are summarised and discussed accordingly.

5 Discussion

5.1 Research Findings by Objectives

Evaluate the efficacy for the reduction of engine exhaust emission of diesel-powered trackless mobile machinery by 1) the introduction of the OEM maintenance program and 2) the introduction of the OEM maintenance plus retrofitting with diesel particulate filters.

5.1.1 Objective 1

In this study, we evaluated the effectiveness of maintenance strategy and maintenance plus retrofitting machines with DPF by measuring particle number concentration, particle mass concentration, particle size distribution, gas concentration, and personal exposure to DPM—by measuring all parameters before any interventions (baseline) and post-interventions. The results of tailpipe measurements showed that particles associated with diesel exhaust emissions (DEE) are characterised by particles of aerodynamic size fraction of around 0.1 – 1.0 μm , comprising a higher range of ultrafine and fine size fractions. In contrast, the concentration in the respirable size fraction (aerodynamic size range of $\geq 2.0 \mu\text{m}$) was very low. Overall, there was a marked reduction in PNC and PMS after the two interventions: engine maintenance and maintenance plus retrofitting the engine with DPF. The total PNC and PMC were assessed by size fraction, type of intervention, and engine age at 250, 500, and 1000 hours.

Results from the tailpipe emissions tests have shown that the interventions on the diesel-powered machines reduced overall tailpipe diesel engine exhaust emissions. Both maintenance and maintenance plus retrofitting machines with diesel particulate filters significantly

decreased the tailpipe emission, with the latter combination showing the highest reduction levels. The highest total particle number concentration was found in the defined ultrafine and fine size fraction, whereas the concentration in the defined respirable size fraction was lower. During pre- and post-intervention tailpipe measurements, most of the particle size mode was concentrated around the 0.1 μm region. The total particle number concentration showed a significant overall reduction by size fraction compared to the baseline measurements.

Machines that underwent a maintenance intervention achieved an overall reduction of 40% in particle number concentration and 34% in total mass concentration from the baseline. Retrofitting similar machines increased the efficacy by 96% for particle number concentration and 90% in total mass concentration. Further, the correlation between the total particle number concentration difference before and after intervention showed a positive correlation with the engine age and a negative correlation with engine power (kW). Older machines with higher engine operating hours generated higher PNC and PMC regardless of intervention type, whereas a negative relationship was established for power.

When evaluating the machines that had higher engine power (Engine size of more than 389 kW), it was observed that 24 machines had kilowatt ratings of above 392 kW. Of the total machines, $n=(10)$ were in category A (engine hours of <4000 , $n=(7)$ was in category B (Engine hours of $>4000 \leq 8000$) and $n=(7)$ was in category C (≥ 10000). Although machine rating directly influences increasing emissions, machines under category A may emit low emissions due to good engine health and effective maintenance when the engine hours are still low. This could have led to a negative correlation. Also, it was observed that five (5) machines with a power rating of $\leq 250\text{kW}$ showed higher emission output, which could have been influenced by older age. It can be concluded that the influence of power rating against emissions may be affected by other external factors such as wear and tear, engine age, and overall engine health rather than power output alone. Further studies are required to address this highlighted gap.

Bimodal and multimodal size distributions were observed when particle size distribution was assessed, with bi-modal distributions for the 250 and 500 maintenance schemes. However, the machines with the highest engine hours above 8000 showed multi-modal size distribution. The interventions have shown that when machines were subjected to all three maintenance categories (250hrs, 500hrs, and 1000hrs), the tailpipe emission concentration was further reduced even on the older engine machines. This was assessed using simple linear regression, and the results showed that machines that underwent maintenance at 1000 hours showed a significantly increased reduction ($p\text{-value} = 0.001$) than machines that underwent maintenance

at 500 hours (p-value 0.05). Tailpipe exhaust gasses measurements showed a significant % reduction post maintenance (only) intervention by 40% and more than 70% reduction for maintenance plus DPF for CO, NO, NO₂, and NO_x. This supports the focus on reducing the diesel exhaust emissions at the source as the primary exposure reduction intervention.

5.1.1.1 *Characterisation of Diesel Engine Exhaust*

When the characteristics of diesel particle emission were assessed in this study, it was found that the highest total particle number concentrations for both pre-and post-intervention tailpipe measurements were mainly in the ultrafine and fine particles aerodynamic size bins; these are the size bins with aerodynamic size diameters between $\geq 0.0019 < 0.3123 \mu\text{m}$ and $\geq 0.312 < 2.002$. Exposure to this aerodynamic range is said to cause health effects (12). There was a significant reduction in the PNC after the interventions. On the other hand, the defined respirable size fraction bins ($\geq 2.002 < 7.259 \mu\text{m}$) contained lower particle number concentrations, and no significant reduction could be demonstrated for this size fraction post the interventions. A total overall concentration of 0.42 mg/m^3 was recorded when particle mass concentration was assessed for the baseline measurements; this concentration includes all the size fractions (ultrafine, fine, and respirable concentration. After the interventions, PMC was reduced to 0.06 mg/m^3 , showing the effectiveness of the interventions (Table 4.16). The reduction was recorded at 90% for machines that underwent maintenance and retrofitted with DPF and a 40% reduction for machines that underwent maintenance only (Figures 4.7 and 4.8). A previous study that reported on comparable particle size fractions from combustion activities is the study by Myung and Park (2011), which evaluated particle emissions behaviour during combustion; their results showed a relationship between particle number, surface area, and particle mass in lung deposition efficacy (Figure 2.3). They reported the highest particle numbers in the ultrafine (nucleation) mode, with particle diameters smaller than $0.1 \mu\text{m}$; the percentage of the mass represented by this size range was low at 1-20 % of the total engine mass emissions. They further reported that the higher particulate mass was found in the fine (accumulation) mode, with particle diameters between $0.1 \mu\text{m}$ and $1.0 \mu\text{m}$ (42). Although the particle number concentration of the respirable (coarse) mode was minor, the particle mass in this mode represents 5-20%. De Jesus et al. (2019) also reported similar findings; they found that particle number concentration (PNC) was dominated by UFP and mainly affected by local sources, especially combustion processes, with a significant contribution from vehicular exhaust. Similarly, the particle mass was dominated primarily by fine particles (44). Our study also showed a similar characterization trend for the particles within the aerodynamic size range

of 0.01 μm to 1.0 μm as defined by other authors; it also showed that the respirable size fraction containing larger particles was smaller when compared to the ultrafine and fine size fractions; this indicates that the current literature review supports the findings from our study.

Diesel particulates have a bimodal size distribution, including small nuclei mode particles and larger accumulation mode particles (14). The particle size distribution in our study showed that more particles were confined within the aerodynamic size fraction between 0.01 μm < 1 μm in a bi-modal pattern before interventions for machines with engine hours of <8000 (Figures 4.4 and 4.5). However, a multimodal distribution was evident for machines with engine hours >8000 (Figure 4.6). It must be noted that this study differs from other studies, which showed only bi-modal distribution; one such study that supports the bi-modal size distribution is the one conducted by Bugarski et al. (2009) (10) and McGinn et al. (1998) (73); in their studies, they evaluated the performance for DPF and other technologies such as the diesel effectiveness of oxidative catalyst (DOCs), and the results showed a bimodal size distribution for the DPF technology. They also reported that the aerosol concentrations were found to be primarily in the nucleation mode when the engine was operated at a heavy load and high exhaust temperature conditions, whereas in the accumulation mode, when the engine was operated in a light load and lower temperature conditions (10). Furthermore, depending on the engine technology and particle sampling technique, the nuclei mode typically contains only 0.1-10% of the total PM mass. Still, it often includes more than 90% of the total particle count. Sometimes, the nuclei mode particles present as much as 99% of the total particulate number (14). The low idle and high transient were tested in our current study and showed bi-modal distribution, except for the older age machines. We conclude in the present study that the multimodal particle distribution could result from increased coarse size fraction generated due to wear and tear of the engine and its components, relating to the machine's age and state of engine health (10,14); we assessed the PSD of machines in category C, e.g., engines whose running hours were above 10000. A total of six machines showed size modes above 1 μm (the defined respirable size fraction). The machines included three dump trucks and three LHDs. The engine hours and rated kilowatts of the six machines were as follows: 10 060hrs (392kW), 11 769hrs (256kW), 12 400hrs (392kW), 13 271hrs (354kW), 11 934hrs (392kW), and 11 977hrs (256kW). Based on previous research and considering that only the six machines' engine exhausts had relatively larger size modes out of 41 machines, it can be concluded that engine age may have resulted in wear and tear of the engine. Further studies are recommended to

reproduce the results and to link the distribution to specific maintenance requirements to minimise wear and tear.

Further, it is essential to note that control strategies tested in this study effectively reduced the diesel exhaust's fine and ultrafine fractions for both the PNC and, subsequently, the PMC. These findings are similar to the study that Kumar and his colleagues did in 2011 (112); they studied the particle size distribution and number concentrations from engine tailpipe emissions under different operational loads. They reported that the size range of the particles increased as the engine load increased because the machine operated under the high transient mode. Smaller particles in the size range of 40–50 nm dominate at no load, while at full load, particles in the size range of 60–70 nm dominate; they further reported that coarser particles dominate the mass spectrum at the higher engine loads (2,112). They also reported a direct bearing on the residence time of the particles in the atmosphere and their toxicity, therefore demonstrating enhanced toxicity. Their study emphasised the need to understand the characteristics of PM as these play a significant role in toxicity. The study recommended effective maintenance to improve road conditions, as poor road conditions contributed to the higher engine load. A recommendation was to consider minimising uneven underground road surfaces and an optimised selection of machines by rated power to minimise emissions (2,112).

Ultrafine particles are said to have adverse health effects. In this study, the particle size distribution shifted towards the smaller size ranges. Consequently, the PMC was significantly reduced since many larger-size particles were removed during the interventions, which were the particle size range that mainly contributed to the overall PMC. This remains an area of concern regarding DPM personal sampling methodology and implementing preventative controls. The health effects resulting from exposure to DEE are mainly caused by these minor size fractions (< 100 nm diameter) (5,12); therefore, it is recommended that the controls and sampling techniques focus on the particle size fractions of concern. The exposure pathway must be fully understood when control measures are implemented. The outcome of this study highlights that mass concentration or gravimetric sampling alone may not be an ideal metric to assess the hazard measure for DPM. There is a need to determine an appropriate measuring metric for DPM particle size distribution to support the current gravimetric sampling and to ensure that all the aerodynamic size fractions are included. Our study findings demonstrate that in addition to gravimetric sampling, real-time aerosol measuring technology could be implemented to determine the aerodynamic size fractions.

It is important to note that control measures aiming to reduce particle mass concentration do not automatically reduce particle number concentration and vice versa. In the DEEP study

conducted in 2002 (119), the authors highlighted the need to address sampling issues based on the understanding of the DEE characterisation profile, i.e., The DPM. From the technology point of view, they noted that it is essential to emphasize the existence of particle sizing instruments having significantly better sensitivities than the gravimetric measurement. Thus, it presents an attractive alternative for the DEE emission measurement in future engines, provided that standardized measuring methods are developed. The studies by de Jesus et al. (44) also concluded that PNC and PM 2.5 measurements are not representative of each other and that regulating particle mass (PM2.5) did not reduce PNC. This highlights the need to establish regulatory approaches and control measures to address the impact of elevated UFP concentration (43).

5.1.1.2 Maintenance and retrofitting strategies

Maintenance forms an integral part of mining equipment services. Machines require continuous maintenance for optimal performance, preserving lifetime, and minimising tailpipe emissions. This study employed two interventions: Maintenance and maintenance plus retrofitting machines with DPF. The interventions were categorised by engine hours: category A for machines with ≤ 4000 hrs, category B for machines with engine hours $\geq 40000 \leq 8000$ hrs, and category C for machines with ≥ 8000 hrs. The interventions significantly reduced DEE; machines with fewer engine running hours achieved more reduction. The results showed a significant decrease after the maintenance protocol for 250 hours of maintenance (p-value = 0.005); significance was also observed for 500 hours (p-value = 0.005) and 1000 hours (p-value = 0.004) for machines that underwent maintenance only. It was demonstrated that when OEM maintenance was followed, the overall reduction efficacy for the particle number concentration was 31%. The higher reduction for category A machines could have been influenced by lower engine hours (less than 4000) compared to categories B and C. For machines that underwent maintenance and were retrofitted with DPF, the higher reduction of DPM (96%) for all engine categories can be linked to the retrofitting of the DPF, as the sintered metal wall flow filter is designed to remove the particulate matter portion.

Tailpipe gases measured in this study also revealed significant reductions when compared before and after interventions. The gaseous emissions for retrofitted machines were significantly reduced by 82% for CO, 72% for NO, 86% for NO₂, and 72% for NO_x during idling. The reduction was also significant during high rev/transient mode: 95% CO, 85% NO, 88% NO₂, and 85% NO_x (n=21). The reduction in gas emissions will be due to the diesel

oxidative catalyst (DOC) function of the DPF, where the ceramic part oxidises the gases. Kitchen (2018) (75).

Results for machines that underwent maintenance only also showed a significant reduction of 77% for CO, 40% for NO, 27% for NO₂, and 36% for NO_x at the idling mode, and for the high rev/transient mode, the reduction was also significant as follows; 76% for CO, 35% for NO, 26% NO₂ and 40% for NO_x, (n=20). These findings are similar to those Hines (2019) reported in her study, where CO showed a higher reduction. In the present study, however, there was a significant slight reduction in NO, NO₂, and NO_x post-maintenance intervention only.

In the study by Hines in 2019, significant improvements were achieved in reducing tailpipe emissions by implementing an emission-based maintenance (EBM) program. The study was a maintenance intervention focused on diagnostic methods to assess diesel-powered machines and improve the blockage in the exhaust pathway and the seals on the filter houses to reduce incomplete combustion. This was done using an emission-based fault-finding software with diesel emission measuring equipment (Checkmate). This guided the maintenance team in identifying the faults and applying a correct maintenance protocol to improve the emissions and machine performance. The EBM project reduced the diesel particulate matter on employees' exposure by 47% and reduced fuel by 7-20% at the intervention site (11). One of the supplementary findings in Hines's study of two coal mines was poor machine performance due to the failure of the mines to follow the OEM maintenance standard. This concurs with the results from our study, where at the beginning of the study, we observed that management did not comply with the OEM maintenance standards to avoid taking machines out of production; this resulted in an increased number of breakdowns on the machines.

In terms of gases, Hines reported a reduction in carbon monoxide (CO) emissions by more than 80% when the blockage on the pathway was removed, and the seals were fixed, as well as with excess fuelling; however, when it comes to NO and NO₂, there was no reduction. Further, personal exposure results to NO₂ did not show any difference before or after the intervention. In instances where the NO₂ was observed to be reduced from tailpipe measurements when exhaust passed through a catalytic converter at lower temperature exhausts below 250 °C, NO₂ could decrease by as much as 77% and increase with temperatures above 250 °C (10). Hines's findings are confirmed in the current study regarding tailpipe exhaust gasses reduction post maintenance, especially for CO at above 75% in both interventions, indicating that proper maintenance programs positively impact tailpipe gases. Although there was a significant reduction for the NO, NO₂, and NO_x, the reductions were much lower than the reduction of

CO; further studies are recommended to find ways and methods to improve the NO_x gasses during maintenance.

In the study that was conducted by Bugarski et al. (2020), where they tested EPA Tier IV and Tier II engine machines, they found that the Tier IV engine contributed substantially less to the mass concentration of EC and OC, to number concentrations of aerosols, and to concentrations of CO, NO, and NO₂, compared to the US EPA Tier 2 machines (71). Based on these findings, it is essential to note that introducing higher Tier Engines (Tier III and above) and repowering machines by retrofitting strategies to reduce overall DEE remains a priority.

McGinn and his colleagues (1998) conducted a study at the Brunswick mine as part of the Diesel Exhaust Emission Program (DEEP) consortium. They evaluated the overall performance of the latest DPF technology regarding their ability to reduce tailpipe emissions, concentration of DPM and noxious gasses in mine air, regeneration efficiency, maintenance requirements, reliability, and acceptance. The outcome demonstrated the efficiency of DPF in reducing DPM in the environment with recommendations of continuous maintenance of the DPF, ensuring that there are no leakages in the DPF itself. Poor maintenance of DPF may result in soot accumulation in the filter, resulting in increased filter back pressure and overheating of the engine, ultimately resulting in engine failure or introducing a fire risk in underground mines. Therefore, training of the engineering maintenance team and operators, strict scheduling of DPF maintenance after installation, and overall machine maintenance are critical in maintaining the efficacy of the controls (23,71).

Similar findings that support this study were reported by Lebaka et al. (2023) in a study using similar metal-sintered diesel particulate filters DPFs in an underground Platinum South African mine, in which the authors concluded that DPFs reduce particulate matter concentrations by more than 96%. The reduction of the PNC and gases could be attributed to the technological aspects and the functional design of the DPF (116). Another study by Watrus et al. (2016) also tested the effectiveness of DPF in a simulated environment where they retrofitted machines with DPF and demonstrated a 98% reduction in exhaust emissions compared to the measurements before intervention (121).

Studies conducted by Bugarski and colleagues on engine technology have shown positive improvements in reducing machines. In 2009 and 2020, they assessed the effectiveness of DPFs, disposable filter elements (DFEs), engine intake air cleaners, and diesel oxidation catalysts (DOC) in removing aerosols by particle number and particle mass concentrations. They found that the engine operating mode strongly influenced the increase in particle number

concentration when machines operate in high transient mode (10,71). They also found that particle mass and the number decreased when control strategies were in place; the 2020 study examined the potential of diesel emissions control strategies based on retrofitting existing power packages with exhaust after-treatment devices and repowering with advanced power packages. The retrofit systems, a diesel oxidation catalyst, and a diesel particulate filter were evaluated individually using the US EPA tier 2 engine, operated under four steady-state conditions and one transient cycle. The underground conditions where TMM operates may significantly increase the total emission loads in areas such as the inclines or where road conditions have undulations. It is essential for the employees operating the machines to understand the conditions where they work so that they can report conditions requiring maintenance (71,72).

Machine maintenance is an administrative control and can be very much dependent on the person conducting the maintenance, i.e., the knowledge and experience of the technician to maintain the machine. During the study, it was noted that the currently employed technicians were not from the OEM teams; they were new artisans (apprentices), and their training to work with the different machines was still in process (post retrenchments and change of contracts). Further to note was that mine B had deviated from the OEM maintenance procedure requirements by implementing their maintenance called “usage-based maintenance,” meaning that they were not following the OEM hourly maintenance for a more extended period (over 12 months). The usage-based maintenance aimed to optimise the availability of machines for production purposes. However, this resulted in more mechanical breakdowns and higher emissions due to poor maintenance. In addition, the oldest machines experienced mechanical wear and tear on components. In many cases, it was difficult to readily find spare components due to an ineffective rotary management system for spares that require refurbishment. Further, the inspection breakdown reviews also reported many more hydraulic system failures.

A walkabout was done after the DPF installation to assess the current study's success and identify possible knowledge gaps during implementation. To effectively monitor the DPF, all machines are fitted with a service check digital electronic control unit (ECU) screen that reports when there is back pressure in the fitted DPF or increased engine temperature. In some instances, the ECU was not working; in some cases, it was working, but the operator took no report or action. When further assessed, some machines had damaged ECU coupling cables due to poor conditions in underground roadways, such as undulations and water accumulation; this damaged these coupling cables, resulting in data not being sent to the ECU. This was recorded as poor maintenance post-DPF installation and inadequate training for operators and

the maintenance team. In many instances, there was a gap regarding training knowledge application by the operator or Engineering team; only the Ventilation/Occupational hygiene teams understood the strategy well, not the process owners.

Continuous clogging of filters may result in increased heat load where an engine can overheat, potentially causing premature engine failure and a higher engine replacement cost. Therefore, adequate training was identified as a critical success factor for the project; the training program should include the mine engineers, ventilation engineers, maintenance team, operators, and even the suppliers of diesel engines and related equipment, with follow-up to make them aware of new tools and other developments. It is also essential to ensure that the condition of filters is added to the planned maintenance scheduled for cleaning and maintenance, as prescribed by the OEM, to ensure that non-combustible materials are removed, and back pressure blockage is prevented at all times. The best way for an engine and DPF supplier to improve the relationship with the mine is to provide solutions to problems by service representatives providing hands-on instruction with small groups or one-on-one, as described by train-the-trainer sessions, to ensure continuous improvement at the mine.

It is recommended that a program to test undiluted exhaust gasses' tailpipe emissions on underground vehicles be implemented as part of planned maintenance before and after any scheduled maintenance. The tests must be integrated into a structured maintenance planning system. The System Application and Products (SAP) is currently used at the mine to schedule maintenance, and it can be optimised to suit the needs for diesel emission control. A maintenance program to track emissions before and after maintenance should be developed to allow the maintenance team to respond to the emissions set action limits, ensuring appropriate technical responses to the problems detected. Further, an annual maintenance audit plan to follow up on the effectiveness of scheduled maintenance must be implemented to check the efficacy of controls. One significant learning from Hines's study (11) was the ability of the maintenance teams to conduct diagnostic assessments on the machines and to apply the specific maintenance protocol to address the technical issues (10). The mines can adopt a similar methodology; that way, all levels of control and systems are integrated. Further, if well implemented, it will improve the tracking of machines and ensure that the health of the engines is monitored at all times.

Inferential statistics were done to assess the relationship between diesel emissions further when the TMM operates and factors that may affect emission levels. Spearman correlation test was done to evaluate the association between pre and post-intervention particle number concentration differences for the 41 machines and engine age (in hours) and the rated engine

power. There was a positive association between total particle concentration and machine age. The total-particle number increased as the entire engine hours increased. This could be due to the expected engine wear and tear as the machine ages, the mechanical breaking of components, non-adherence to maintenance schedules, poor quality maintenance, poor working conditions, and damage to the machine components, resulting in machine deficiencies. There was a negative correlation for the machine-rated kilowatt, i.e., the difference before and after intervention on particle number concentrations decreased with increasing machine power. However, this could be attributed to the considerable variation in rated power between the three categories and the small sample size for each category. In addition, it should be noted that machines with higher-rated power were fitted with two DPFs (mainly Dump trucks) and one DPF for lower power-rated machines (Figures 3.1 and 3.2). This could have dominated the particle number concentration difference before and after the intervention, overruling the association between power rating as the independent variable and particle number concentration difference as the dependent variable.

Simple linear regression for engine age and power was done to explore the possibility of a predictive emission model. Significance was achieved in predicting engine tailpipe total number concentration by engine age (p-value=0.03), for 500 maintenance (p-value=0.05), and for 1000 maintenance (0.001). However, engine power was not significant (p-value=0.73). It must also be noted that although significance was achieved for engine age and maintenance, the low R-squared values of ($R^2 = 0.13$ for engine age and $R^2 = 0.37$ for 500 maintenance) were achieved. All parameters indicate that other variables not assessed in this study will affect the independent variable (total particle concentration for the pre- and post-measurements). Also, the small sample size could have influenced the high p-values observed. This study comprised three categories with a sample size of less than 20. However, their categories were well-defined for maintenance and engine age per category; there was a wide variety of engine power ratings within each category. An increased number of samples is required to improve model prediction with a proper machine pairing of power rating. Additional studies must be conducted to address this study's shortcomings and establish an ideal predictive model for the mine fleet to assist in proactive diesel emissions management and better understand the variable factors that influence total particle emissions.

5.1.2 Objective 2

To evaluate the effectiveness of interventions in objective one (1), personal exposure to Elemental Carbon (EC) and CO concentrations was measured in underground development

heading sections. Personal exposures were measured before and after all the primary machines (LHDs and Dump trucks) were maintained and fitted with DPFs. There was a significant reduction in exposure to personal monitoring for elemental carbon, total carbon, and CO for all the occupations measured. Although the comparison baseline had limitations, the reduced personal exposure to EC and CO showed that the interventions to reduce DEE at source were successful. The study demonstrated that maintenance and retrofitting machines with DPF significantly would reduce personal EC and CO concentrations (n=34) by 97% compared to the personal exposure of EC and CO assessed in 2019 before interventions. The results align well with the tailpipe measurements, where the DPM reduction was over 96% after DPF fitting. The results of personal monitoring for EC indicated that the night shift was more exposed to DPM than the morning shift by 27%; this may be a result of mining planning where most panels are drilled and blasted during the day shift, and priority cleaning is done during the night shift to prepare for the morning shift blasts. Further, only a few working areas are targeted to be cleaned during the day shift to optimize drilling opportunities.

Personal exposure to CO showed a significant reduction of 46% for the morning shift and 54% for the night shift, respectively. Further, the load and haul activities are higher during the night shift because cleaning blasted faces forms part of night shift preparation to make the drilling and blasting activities easier during the morning shift. Future strategies to reduce exposure to underground mines must consider the blasting and cleaning cycle. Although many studies have been published in the literature, very few relate to underground platinum mining. Findings from this intervention study offer the basis to develop effective strategies to measure the effectiveness of intervention outcomes (maintenance or maintenance plus retrofitting machines with DPF) by assessing workplace exposure. It also sequentially addresses the occupational setting exposure pathway, which is crucial in developing an exposure profile and occupational hygiene program. Similar findings were reported by Lebaka et al. (116).

The study by McGinn and his colleagues in 1998 (23) evaluated the overall performance of the latest diesel particulate filter technology (DPF) at their Brunswick Mine in Bathurst. They assessed the performance of the filtration systems concerning their ability to reduce tailpipe emissions and concentrations of diesel particulate matter (DPM) and noxious gases in mine air, the efficiency of the filter regeneration process, maintenance requirements, reliability, and acceptance. The efficiency of the filters was also evaluated based on tailpipe measurements, ambient DPM measurements, and ambient particle number/mass concentrations. They reported reduced ambient DPM concentrations and removing personal elemental carbon particles in the

98-99% range for total and elemental carbon. This correlated very well with the measured TC/EC from the raw exhaust. The ambient measurements for particle size distribution emitted by vehicles retrofitted with DPF were bimodal, with higher concentrations of the ultrafine particles below 0.05 μm (14,10). Our study observed a bimodal distribution for machines with lower engine hours, but a multimodal distribution was achieved for machines with the highest engine age. The multimodal distribution is associated with wear and tear of machines, which is validated by observing machines with engine hours of more than 10000 hrs (14).

The previous studies, which assessed the impact of technology in reducing worker exposure, found a direct effect in reducing worker exposure when the diesel emissions from the source were reduced. Bugarski et al. (2002) reported field tests of an underground metal mine, where LHD and trucks were examined to observe the effect of retrofitting machines with DPFs and DOCs on personal exposure to EC. The results showed that DPFs could significantly reduce EC concentrations compared to the DOC test, but all results still exceeded the DPM exposure limit (3). This study showed a significant reduction to below 0.1 mg/m^3 of EC (EC used as a surrogate marker for DPM), showing an ongoing improvement in the engine technologies.

Hines 2019 (11) reported a 47% reduction in worker exposure to EC compared to the 58% on the controlled site (this was assessed by comparing it with a controlled mine where EBM was not done). In addition, the fuel cost was reduced by 7% for machines for light-duty personnel vehicles and 20% for LHDs. In the present study, retrofitting machines with DPF directly impacted the underground workplace environmental conditions where personal measurements were taken post-installation of DPF, showing a significant reduction in personal EC, TC, and CO. These study findings matched with those reported for Mine A on the small-scale study to assess retrofitting where personal exposure to EC showed over 96% filtration reduction and reduction of EC to below 0.1 mg/m^3 (115). Bugarski et al. 2015, also found a substantially higher reduction of OC and EC mass concentration, and an overall reduction in the total workplace aerosol concentration was achieved by retrofitting the Tier 2 engine with a DPF system (76). It is also important to note that personal EC measurements were mass-based using a cyclone with a D50 of 4 microns, meaning that the aerodynamic range stretched from 10 μm to the submicron range. This may have underestimated the mass contributions from particles with sizes under the ultrafine range, which is the one that poses more health/toxic effects on exposure. Further studies must be conducted to evaluate sampling techniques for personal exposure to cater to the ultrafine particle range.

Toxicological studies done by Ristovski et al. (2012) evaluated various model/surrogate particle proxy, such as carbon black, and findings have suggested that the particle surface area is the most critical determinant of the health effect of ultrafine particles (diameter less than 100 nm). In contrast, chemical composition may be more important for larger particles (17). This study again indicates that personal sampling methodologies remain challenging because the size distribution is not well determined during monitoring and exposure assessment. Further exploration of the possible monitoring technique for ultrafine particles is recommended, as these smaller particles have higher toxicity regarding DPM exposure.

5.1.3 *Objective 3*

In objective 3, we used numerical simulations, such as fluid flow dynamic systems, to model diesel exhaust emission dispersion patterns and predict the spatial and temporal risk of (over) exposure to diesel particulate matter (DPM) in underground workplaces. The input pollutant concentrations were derived from the tailpipe measurements, converted to EC concentrations, and adjusted to the environmental concentrations of a shaft section using emission strength calculations and dispersion modelling.

The dynamic dispersion modelling for the considered scenario at location 3 for the base case, i.e., without any interventions, was 4.7mg/m^3 of EC. When the dispersion was altered by increased ventilation up to 30%, only 21% reduction was achieved, indicating insufficient ventilation in the section to dilute DPM to the recommended exposure limit of 0.1mg/m^3 (EC) at the current mine design.

At the Southern intake section, EC was 2.3 mg/m^3 for the scenario where machines underwent maintenance only and 0.01 mg/m^3 for machines that underwent maintenance and installation of DPF. The levels for the North intake section were 1.32 mg/m^3 and 0.0076 mg/m^3 , respectively. The EC concentrations were further reduced when the air volumes were altered to increase by 10%, 20%, and 30%. The concentration levels at the intake sections already indicate some level of air contamination before the air reaches the specified workplace due to the continuous movement of machines at the intake decline sections.

The current ventilation mine design for development headings uses a 75kW fan size, which supplies a quantity of $25\text{m}^3/\text{s}$, and 90kW fans for decline development headings, which supplies a maximum of $30\text{m}^3/\text{s}$. The development heading air volume per haulage surface area standard

at the mine is planned at $0.2\text{m}^3/\text{s}/\text{m}^2$, and a ventilation dilution rate of $0.06\text{m}^3/\text{s}/\text{kW}$ was adopted. For the load and haul activity scenario, two (2) LHDs and one (1) dump truck for loading, mucking, and hauling are required, which is equivalent to 850kW rated power in the section. When a ventilation dilution rate of $0.06\text{m}^3/\text{s}/\text{kW}$ is used, the total air quantity needed to ventilate the flat development headings (North and South sections) is $51\text{m}^3/\text{s}$. This means the current ventilation planning of $25\text{m}^3/\text{s}$ or $30\text{m}^3/\text{s}$ for flat development headings (South and North sections and the capital decline development headings) is inadequate to effectively dilute the DPM emissions to the sections. These findings highlight a concern that without any technological interventions, such as DPF retrofitting, there is insufficient underground ventilation and a possible over-exposure to DPM on daily working shifts underground. Therefore, a total redesign of the ventilation system that will enable adequate dilution is always required to improve underground conditions.

To summarize the ventilation modelling output findings, diesel particulate concentrations increased in the workplace/ mine section as the number of operating machines increased for load and haul activities. It also increased as the air was re-used in the downstream working areas of the development sections. Ventilation alterations have shown that particle emissions can be diluted if mixed with an air stream, reducing the exposure to the affected employees. However, it must be noted that ventilation alone, even at the highest percentage (30%) increase, is inadequate to mitigate the exposure levels for the emission scenario deploying machines that had maintenance only.

This was demonstrated by the results of base case ventilation modelling (Figure 4.9), which shows that machines underwent maintenance only and machines that underwent maintenance were also fitted with DPF. Machines equipped with DPF achieved a recommended reduction of DPM workplace concentrations to less than $0.1\text{mg}/\text{m}^3$ EC at base ventilation. However, machines with maintenance intervention could not reach the recommended limit even with the highest ventilation increase. Dispersion modelling in the case of a scenario with a partial replacement of diesel-powered machines with electrical machines, there was a marked reduction in the EC concentration; however, the action limit still could not be achieved if the diesel-powered machines underwent maintenance intervention only. In the latter case, a reduction of 51% could be observed, whereas in the case the diesel-powered machines underwent maintenance and were retrofitted with DPFs, the reduction was 99.7% (Figures 4.16 and 4.17). If the diesel-powered Dump truck was replaced with an electric model, a decrease in diesel particles of 69% was achieved if the remaining diesel-powered machines only

underwent maintenance and 99% for machines that underwent maintenance and retrofitted with DPFs (Figures 4.18 and 4.19). These results show that mechanised mining needs to shift the focus and invest in the energy-efficient strategic replacement of diesel-powered machines to curtail the DEE underground. The drive to use clean energy should be supported by the high-risk evidence of lung cancer risk amongst DPM/DEE-exposed operators from previous research (5). In addition to the above findings, when the cost of altering the ventilation system was assessed, there was a notable cost-benefit relationship in eliminating DEE from the source (by improving exhaust technology such as retrofitting with DPF or replacing machines with higher tier engines) rather than using ventilation dilution only. An integrated control strategic approach has great potential to eliminate, reduce, and prevent employees' exposure to DEE. Also, a shift towards replacing diesel-powered machines with electrical machines will eliminate the risk of exposure to DEE in underground working places with the added benefit of reducing the environmental carbon footprint.

The findings of this study highlight a need for the industry to ensure that ventilation planning is integrated into the mining mineral resource planning models from the outset. This can be proven by the fact that in this study when load, muck, and hauling processes were reviewed against current ventilation design requirements, there was under-resourcing of ventilation requirements; for example, fan size and airway size were found to be small for the ventilation air quantities required in development headings. To further elaborate, the mine under study (B) requires $51\text{m}^3/\text{s}$ of total air volume to effectively dilute DPM to a $0.1\text{mg}/\text{m}^3$ level, wherein the current infrastructure can only cater for $25\text{m}^3/\text{s}$. Mine planning systems need to be improved to build the health aspects and implement a preventative approach to managing health hazards by ensuring that the infrastructures are appropriately designed; further, this must be addressed during the early design phase because modification of infrastructure blasting of airways to increase the size at a later stage may require high capital costs, and may potentially affect the mining cycle, leading to inherent noncompliance. This gap needs to be closed by Ventilation Engineers and Mine Management during the early planning phase of the mining project.

The South African mining industry previously used an air volume dilution factor of $0.012\text{ m}^3/\text{s}$ per kW ($\text{m}^3/\text{s}/\text{kW}$) during the planning and design of ventilation systems to determine effective ventilation quantities required over the diesel-powered equipment and to have a healthy, safe working environment (102). In recent years, many mines have adopted a dilution factor of $0.06\text{ m}^3/\text{s}/\text{kW}$. These factors are used when planning mine ventilation design to determine total air quantities based on the number of machines required for load, muck, and hauling activities in

the development heading section. This factor has, however, shown that it is inadequate for diluting DPM in underground mechanised mines. There is an urgent need to review this factor and adjust it to $0.1\text{m}^3/\text{s}/\text{kW}$ to ensure proper dilution, especially where technological interventions are impossible. A value of $0.06\text{ m}^3/\text{s}/\text{kW}$, which is currently being applied, is misleading since it is unlikely that all of the diesel vehicles in the mine will have a similar power rating or be in use simultaneously (90). Therefore, the ventilation rate value must be applied and adjusted based on the mine design requirement.

This study assessed ventilation modelling using a single dimension software (VentSim) to predict DPM dispersion in underground workplaces. This is the first study to detail dispersion using the single dimension software. The results are validated and correlate well with the tailpipe calculated emission strength used as an input parameter and the personal measurements taken after DPF retrofitting. This study adds knowledge of step-by-step methodology to assist Ventilation professionals in quantifying the emission strength of the pollution source as input to the VentSim program. It is important to note that an emission strength is essential to correctly estimate environmental exposure and for correct output from the program that will harness making proper decisions for the mine ventilation planning. The added benefit of using single dimension is that Ventilation Engineers are trained to use VentSim rather than two and three dimension CFD modelling, which requires programming Mathematical Engineers. The single-dimension method can be used to validate high-level CFD modelling.

Previous studies have demonstrated that computer-based fluid dynamics methods have successfully investigated and solved ventilation-related issues, such as underground dilution of ambient gases, dust, fires, and heat load. Further, literature has shown that a ventilation strategy successfully managed exposure to gases and particulate matter, especially in coal and hard rock mines (97,98). Xu and his colleagues conducted a study in 2016 to characterise ventilation systems using tracer gas and CFD. They noted that underground airborne pollutants' dilution largely depended on the particle size distribution of the contaminant being moved. Therefore, it is essential to measure and control the particle size and fully understand how the flow of these particles behaves through the available ventilation (101). In other studies conducted in 2011 by Zheng et al. (15,96) and Yi et al. in 2022 (102), the results obtained from DPM propagation using the 2-dimensional CFD method showed that DPM tends to accumulate near the roof and top area in the tunnel due to the influence of buoyancy which was in concordance with the results with experimental and field measurements. This knowledge is critical in integrating into a real-time monitoring system or when experimental studies are conducted to

validate the modelling results. Additional studies to further conduct experimental studies to validate single-dimension study results are recommended.

The findings from this CFD for gases would apply to the dynamic simulation of diesel exhaust particles because of their small surface area. The conclusions of this study have shown that diesel engine exhaust are concentrated within the smallest aerodynamic size, being ultrafine and fine particle sizes. Gasses exist in very small sizes; tailpipe emissions particle distribution from the current study indicates a vast of very small particles, which gives evidence that dispersion modelling can assume a gaseous behaviour of the DPM particles. Therefore, the behaviour of the particles dispersion will move towards the highest part of the haulages similarly due to the gas's buoyancy.

The present study applied the recently implemented module to simulate the DPM dispersion in an underground environment. The tool does not require specialized skills as the 2D/3D CFD requires; ventilation engineers can be trained to use this tool easily for day-to-day planning and monitoring. However, validating the module for the specific mine ventilation conditions by experimental measurements is also recommended to ensure that the module output is reliable for planning and responding to the pollution load. Although advanced CFD analyses are more cost-effective than experimental tests, it is still expensive (121); single-dimension numerical modelling may be a solution to a cost-saving solution.

Most studies have been conducted to understand how DPM behaves underground using CFD, either in a 2-dimensional or 3-dimensional approach since these approaches offer much more accurate predictions. However, the single-dimension numerical simulations have successfully predicted heat loads, dust loads, and ventilation flows in underground hard rock and mechanized mines on a larger scale. In addition, mining houses typically use 3D for small-scale modelling and then apply single-dimension numerical modelling for larger-scale modelling. Therefore, using single-dimension numerical simulation may add a simplified benefit to ventilation design planning for DPM management.

Another benefit of this study is the possibility of introducing real-time monitoring for DPM by linking it to a VentSim program through the Supervisory Control and Data Acquisition (SCADA). 2-D and 3-D dimensional CFD is best for developing predictive models for DPM, but it is used to study smaller sections of the mine, mostly during feasibility studies. Moreover, it cannot easily be linked to a real-time system because of its complexity. In contrast, the single-dimension numerical simulation method can be linked to mine digital networks to monitor the pollutant load as the dynamics change in a workplace in real-time. Some platinum mines

already use VentSim systems, which are linked to the SCADA systems in control rooms to environmental parameters such as air velocities and gases in the tunnels. Action command controls are automatically activated when a set value of a parameter is exceeded, and corrective actions are taken immediately. If a real-time monitoring of DPM or a proxy can be linked to the system, it can potentially manage the DPM concentration. Previous studies done by Noll et al. have shown a strong relationship between EC and TC, EC and NO₂, and a moderate correlation between EC and CO (32,34). A study by Hedmer et al. 2017 (33) for tunnel construction activities reported a correlation between personal EC and particle number concentration ($r=0.76$). These studies can be used to evaluate an ideal real-time monitor for DPM (or a proxy/marker such as EC), which will assist in assessing the effectiveness of workplace controls in a real-time scenario (30,32,33).

VentSim program is equipped with capabilities to be linked to monitors to detect particle mass concentration, gasses using the detection sensors, and air velocities. In addition, it can be used to check the effectiveness of ventilation controls, such as if ventilation doors are adequately closed within the ventilation districts and sections to maintain air quantities in workplaces. Other systems that monitor blasting fumes are currently in place in mechanised mines; these systems monitor gas levels at specified points to ensure that employees can only go underground when the gases and fumes are cleared, and a similar interface can be used with VentSim to measure and manage the diesel particles number concentration and diesel particulate mass underground. Since diesel particulate emissions and smaller-sized particles are of concern in underground workplaces, it is recommended that further studies be done to evaluate a possible tracking of both particle mass/number concentrations in a real-time scenario to prevent employees from over-exposure to DPM effectively.

5.2 Integrated Findings from the Study

Underground platinum mine employees are exposed to diesel exhaust emissions, including particulate matter and gasses, during their day-to-day activities, especially employees working in development headings and operating the load and haul machines. Platinum mines have moved towards mechanisation in the past few years, and the trend continues to grow. Mechanisation improves the cost curves regarding production and profits and holds the future for mining in SAMI. However, this transition has left employees exposed to DEE. At a global level, there have been many interventions to address issues related to engine emission control reduction strategies, such as regulations for implementing clean engine technologies,

ventilation design ratios per rated machine size, and even mandatory technologies to reduce exposure to employees. South African mines have not yet been regulated towards DPM after IARC declared DPM carcinogenic by inhalation in 2012 (5). However, many efforts have been made to address these shortcomings, including baseline studies to understand exposure profiles for the different commodities, simulated studies to test the efficiencies of using DPF technologies, and voluntary DPM exposure limits introduced since 2013 (6;55).

Mine employees working in underground sections are exposed to DEE daily during their shifts where diesel-powered machines operate (1). Diesel-powered machines are most preferred because of their high energy efficiency and low carbon dioxide (CO₂) emissions, ease of maintenance, and durability compared to gasoline equipment (2). However, they are a significant source of underground pollution, as diesel engines emit diesel combustion products containing toxic gases and particulate matter (12,13). Further to note is the lack of regulations regarding DPM in SAMI. The risk of over-exposure to DEE underground development headings is increased due to confinement. This leaves a lot to be desired regarding identifying the hazards and preventing and managing the exposure thereof.

This study hypothesised that the maintenance of TMM could reduce diesel exhaust emissions. The study further hypothesized that point source technological control strategies could be linked to reducing workers' exposure to diesel engine exhaust. First, baseline measurements, i.e., pre-intervention, for the diesel (tailpipe) emissions, were conducted to assess particle-size distributions, particle number, and particle mass concentrations to characterise DEE. Two interventions were identified and implemented, including maintenance and maintenance plus retrofitting the machines with diesel particulate filters. Tailpipe measurements were repeated after the interventions.

Machines were divided into three maintenance categories, including 250-hour maintenance, 500-hour maintenance, and 1000-hour maintenance schemes. The effect of engine age and rated power on total particle concentration pre (before) and post (after) interventions were evaluated, and the efficacy of the interventions was calculated. Ventilation numerical modelling was done to determine DPM dispersion in the development headings and to assess the effect of the ventilation dilution control strategy. Different scenarios were developed to determine the behaviour of DPM when each was modelled; this included ventilation alteration, where air volumes were increased by 10%, 20%, and 30%. Other scenarios included the partial replacement of diesel-powered machines with an electrical LHD and the replacement with an

electrical Dump truck. The simulations revealed that only for the scenarios with DPF-fitted machines, the estimated DPM was below 0.1 mg/m^3 of EC. Key findings from the research study are summarised below:

The overall findings from this study have demonstrated that DEE is characterised by a range of particles from ultrafine, fine, and coarse particle sizes, with the lowest number concentration for the latter size fraction. It has also been observed that these particles are emitted in underground sections where employees work and travel. This study employed three interventions: emission-based maintenance, retrofitting machines with diesel particulate filters, and ventilation dilution. The first two interventions were targeted to reduce particles at the source, wherein ventilation was aimed at diluting the DEE to lower exposure once it has been emitted into the environment. Emission-based maintenance (EBM) showed a filtration reduction efficacy of 31% when assessed post the EBM. When similar machines were maintained and retrofitted with DPF, a marked increase in reduction of DPM from the source was observed, i.e., above 96% filtration efficacy, which also translated to lower personal DPM (EC) of less than 0.1 mg/m^3 . These findings align with previous research findings on the impact of EBM and DPF on diesel-powered machines. Lastly, numerical modelling showed a reduction in EC concentrations (DPM proxy) when machines underwent EBM and retrofitted with DPF; minimal improvement was observed for machines that underwent EBM only. It was further shown that reducing DPM using ventilation only has inherent cost implications because increased ventilation requires increased power from the overall ventilation systems (such as fans) and can quickly increase the overall running cost of electricity. Ventilation system alterations may also require more extensive excavations to fit larger fans and ventilation columns outside the mine designs, requiring higher capital investment costs to redesign the infrastructure needed. Based on these findings, a conclusive decision was considered on an integrated approach to curb the DPM-related issues in underground mines. An integrated control and management strategy is required to find progressive and sustainable solutions to the current challenge.

When controls are evaluated to manage occupational health and safety hazards in the workplace, a holistic approach must be followed in a sequence that will ensure that elimination is prioritized, isolation or substitution, evaluating engineering controls, administrative controls, and, as a last resort, the use of personal protective equipment (8). When it comes to DEE, a combination of control strategies is required to prevent employees from being exposed to gases

and DPM. The hierarchy of control framework is presented in Figure 2.6, which details the different risk control steps accordingly.

5.2.1 Integrated Prevention Management Systems to Control Exposure to DEE Elimination

Diesel-powered machines add to the burden of DEE exposure in underground mines. Eliminating hazards ranks high in addressing workplace occupational health and safety issues. However, this is currently impractical because South Africa is a developing country, and eliminating diesel-powered machines might have negative financial implications if not correctly implemented. One major challenge that complicates matters is the power/electricity-related issues that SAMI faces; electrically powered machines still require electrical energy to operate, and renewable energy and solar plants are not widely available in South Africa. Efforts to reduce DEE at source must continue while awaiting a long-term strategy to replace diesel-powered machines with energy-efficient electric or battery-operated vehicles.

In SAMI, the governing legislation requires that the employer assess the risk and employ systems to address such risk in the workplace (6,55). Regarding DPM, SAMI's regulations are still not in place; however, different efforts are ongoing to address this challenge. Most mining employers have replaced Tier 1 engines with Tier 2 engines, and ongoing efforts to replace these with Tier 3 engine standards are progressing well. Another area being investigated is the introduction of electric and battery-powered machines. The introduction of electric-powered and battery-powered mining fleets will eliminate DEE. This option has not been widely implemented in SAMI, but multiple studies and trials are underway. Further, it must be noted that global efforts are being made to move towards this transition. International mining companies have started investing in cleaner energy LHDs and Dump trucks to align with the climate change strategy. The Global data shows that as of March 2022, 157 electric loaders (LHDs) and 45 electric trucks are operating in underground mines globally, with the largest combined population of electric LHDs and trucks in Canada, Russia, Sweden, and Australia (117). Although the focus is mainly on reducing greenhouse gases, the health benefits could not be less important. On the contrary, South Africa faces technological challenges regarding the availability of these technologies, and a transitional approach is required to meet similar international standards. Although continuous research for these new technologies is being conducted in South Africa to assess their feasibility, current mechanized mining methods do not have technologies available for mechanized low-profile machines. It is anticipated that such technology will only be fully available in South Africa from 2027 onwards (117). Mining research on this technology also reports other benefits over the reduction of greenhouse gasses,

including less ventilation and lower cooling requirements, resulting in a substantial reduction in ventilation costs of about 40-50%, less noise pollution, and lower maintenance costs since battery vehicles having 25% or so fewer parts compared with diesel propulsion systems (118). According to the dynamic dispersion model simulations, Partial replacement of either LHDs or dump trucks within the mine section reduced the estimated DPM concentrations positively. A strategic phased-in approach can be considered post-2027 for replacing the current diesel-powered fleet with electrical-powered machines.

Operator cabins have been used to isolate employees from exposure to DPM. Previous research by DEEP 2001 and Bugarski 2009 showed that this directly reduced operators' exposure (10,119). Nonetheless, this option still leaves the employees working at the development heading exposed to DPM; hence, the control is only partially effective.

Diesel-powered machines can be substituted by replacing older engines with the newest technology engines, such as rebuilt engines, when they reach a specific age. It can also be achieved by partially replacing diesel-powered machines with electrically powered machines; this has great potential to reduce exposure. Substitution can also be achieved by progressively replacing Tier II with Tier III and IV engines. Bugarski and his colleagues (2020) tested EPA Tier IV and Tier II engine machines; they found that the Tier IV engine contributed substantially less to the mass concentration of EC and OC, to number concentrations of aerosols, and to concentrations of gases when it was compared to the US EPA Tier II machines (71,119). Based on these findings, it can be concluded that introducing higher-tier Engine technologies (Tier III and above) has a great potential to reduce the DEE emissions right at the source. The outcome of this research further demonstrated that as engine age increases, the wear and tear of the engine components were evident, resulting in an increased level of emissions; therefore, it is of critical importance to ensure that a complete replacement program for machines when they reach a certain age is vital and a formal program for either engine rebuilds, or overhaul engine replacement is done. Different substitution strategies should be considered when evaluating DEE control strategies at the mines.

Engineering solutions have been the most studied area for managing DEE. They are the most preferred type of control in underground mines. However, administrative control requirements can sometimes compromise engineering controls. This study considered two engineering controls: retrofitting DPF on the engines and using ventilation to dilute the DPM concentration to the lowest levels.

Retrofitting the machines with diesel-powered machines has reduced total particle number concentration by 96% and more than 70% for the gases. These results show the capabilities of DPF in reducing the total number concentration, mass concentration, and gases by oxidizing the gases with DOC and trapping soot as the emissions flow through the filter. This shows that reduction at source should be a strategic objective for the South African mining industry, especially in the absence of immediate technology for replacing diesel-powered machines with electric/battery-operated machines. Two South African studies reported similar findings, which showed 96% and 98% filtration efficacy. Watrus et al. (2016) tested the effectiveness of DPF in a simulated environment set up where they retrofitted machines with DPF and demonstrated a 98% reduction in exhaust emissions compared to the measurements before intervention (120). The study conducted by Lebaka et al. in 2023 in a real-life experiment in an underground Platinum mine showed a reduction rate of 96% (115).

Ventilation is the life support system for underground mining. It is a critical control for providing adequate oxygen to working areas in underground mines, reducing dust concentrations, radiation exposures, and hazardous gas concentrations from the ore body and from blasting where employees work and travel (Bugarski 2006). In addition, ventilation plays a vital role in controlling diesel-generated gas and particulate concentrations. CFD methods can effectively simulate the airflow patterns for the entire mine and a single long heading. However, the accuracy and detail of each depend on the accuracy of the input data (Zheng et al. 2015) (100). Ventilation system alterations (increase airflows) were considered when dispersion models were done; when dynamic DPM dispersion simulation was conducted on base case conditions, i.e., before the intervention, a maximum reduction of the EC concentration in the mine section of 23% was achieved, whereas, in the scenario where on machines that underwent maintenance only were used, a maximum decrease of 30% was achieved. When the simulation was done in the scenario where the machines were retrofitted with DPF, a 99.7% reduction was achieved; further dispersion simulations where machines were partially replaced with electrical LHDs and dump trucks showed a total decrease of 51% and 69%, respectively. Optimising the ventilation system can reduce DPM concentration in underground mines. To optimise the ventilation system, one needs to determine the required airflow, evaluate the present ventilation system, investigate steps to improve ventilation in the working areas, and identify the costs of these improvements (Bugarski 2006). Once the mine collects all the necessary information, the amount of ventilation that is technically and economically practical can be determined. Efficient ventilation and cooling designs can

significantly improve sustainability and reduce energy costs and carbon footprint (26). Ventilation modelling in this study showed that ventilation control alone is ineffective in lowering DPM concentration in working places. However, when combined with other controls, there was a positive impact in reducing exposure. Therefore, it is essential to determine a feasible ventilation rate and then consider additional control technologies to reduce DPM concentrations below the recommended limit further if needed.

The machine engine health and emissions control relies on a maintenance program of machines. Maintenance also ensures that mechanical issues are identified and addressed timeously to prevent excessive wear and tear of machines. Emissions-assisted maintenance of diesel engines is based on two beliefs: (1) an improperly maintained diesel engine can emit undesirable concentrations of exhaust emissions compared to a well-maintained diesel engine, and (2) onsite emission tests may be employed to determine if and where there is a need for engine maintenance (Bugarski et al. 2006). The OEM provides a maintenance program that the maintenance team at a mine must follow to ensure machines are always within standards. This is an administrative control, and its success is driven by compliance with the OEM requirements. Maintenance implementation showed a significant reduction of 31% for machines that underwent maintenance only. In a study by Hines in 2019, significant improvements were achieved in reducing tailpipe emissions (reduction at source) by implementing an emission-based maintenance (EBM) program. This has decreased Carbon Monoxide (CO) by more than 80% and DPM by more than 47% on personal exposure, showing the EBM's direct impact on reducing exposure of DPM to employees working underground. The study successfully reduced tailpipe emissions by introducing the EBM program at the mines. Further, fuel usage was also reduced by 7-20%, showing that when machines are well maintained, there are improvements in efficiencies and even utilisation and availability of machines for production (11). These findings validate our study that when EBM is done correctly, tailpipe emissions can be reduced. Wear and tear can potentially increase larger particles emitted to the environment; with EBM, these can be reduced and indicate that engine components require replacement.

The success of maintenance control depends on the competency of maintenance teams and the overall program that aligns with OEMs. Training the maintenance team to diagnose and fix breakdowns is critical as a preventative tool. Hines (2019) reported that the success of the EBM was linked to the training of maintenance teams to diagnose engine performance and respond timeously (11). Furthermore, team members measured the emission levels to check the

effectiveness of their maintenance intervention after the maintenance services. During the present study, it was identified that operators could easily skip planned maintenance since the maintenance systems were not stringent enough, leading to the maintenance teams not following the OEM maintenance schedules. The training of operators plays a vital role in identifying critical maintenance-related failures and determining the effectiveness of any intervention applied during the study. In this study, it became evident that when DPFs were fitted, critical checks were supposed to be put in place, such as ensuring that back pressures are within limits, ensuring that the filters are washed to remove the accumulated soot during significant maintenance, and ensuring that any deviations are timely to their supervisors. Supervision and over-inspection by maintenance supervisors and engineers are of critical importance for the success of the overall maintenance program.

There is a great need to regulate DPM limits in South African mines. Currently, few mines have adopted international best practices regarding ventilation dilution rate design parameters for DPM, Occupational exposure limit (OEL) for EC and TC, and implementation of engine after-treatment technologies despite slow progress. Therefore, it is required to prioritize regulating and implementing integrated strategies.

Over and above reducing DEE at the source and personal exposure monitoring of DPM in underground mines, effective workplace exposure management requires critical input parameters during the planning and design phase of the mining operations. This allows dilution and effective removal of pollutants once liberated in an underground environment. Ventilation parameters, for example, are used to determine the total ventilation infrastructure requirements, dilute airborne contaminants, and regulate heat underground (26). Through general ventilation, the reduction in diesel emission concentration in the mine atmosphere can be achieved using clean air directed to the working area (Zheng et al. 2015). Increasing airflow can be achieved by using higher horsepower fans, adding more fans in parallel, and adding new ventilation shafts or airways (15). The design parameters dictate the airflow required to ventilate a workplace effectively and the number of machines needed to load, haul, and Muck in a specific workplace. A well-designed and properly implemented ventilation system provides beneficial physiological and psychological side effects that enhance employee safety, comfort, health, and morale. Determining the quantity of air required to circulate to meet all health and safety standards underground is essential in planning a ventilation system during the design phase. Once the air volume requirement has been calculated, the correct shaft size, number of airways, and fans can be determined (26,90).

Figures 5.1 -5.4 below show the current LHDs and Dump trucks operating at Mine B. It also shows the diesel exhaust systems (dump truck) and the new replacement with the diesel particulate filters. Figure 5.1A shows the old exhaust system, while the figure shows the positioning of the two new DPF systems (for machines with a rated power of more than 250kW). Figures 5.2 and 5.3 show the LHD, the DPF is fitted underneath as pointed by the yellow arrows, and 5.3 shows the sampling port area. It must be noted that these machines are available on Tier III and Tier IV emission technologies. However, due to cost and technological constraints in SAMI, Tier II is mainly preferred.

Figure 5.4 shows a new tier III LHD, which is being introduced in the latest mine as a replacement strategy for more efficient machines based on the current study's findings.

Lastly, Figures 5.5 and 5.6 show the service check system installed on the dashboards of the LHDs and Dump trucks. This system continuously monitors the machines' back pressure and temperature during operation.

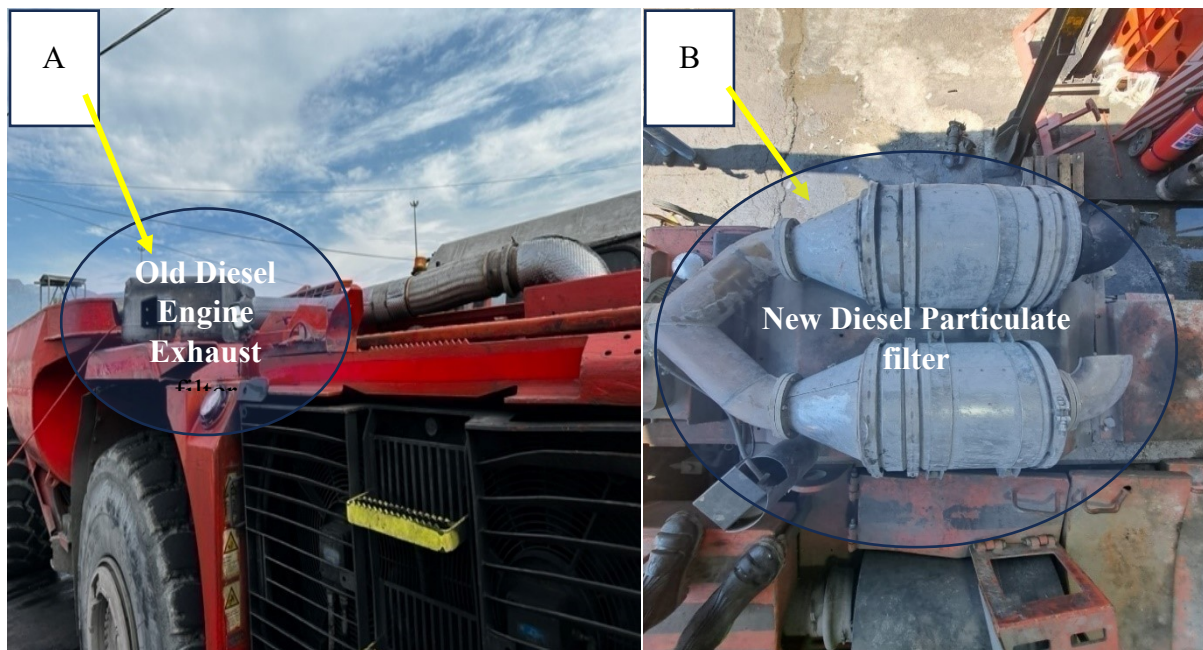


Figure 5.1: Tier II Dump truck with old exhaust system (A) and Dump truck retrofitted with 2 DPFs (B)



Figure 5.2: Tier II LHD was installed with DPF, as shown in the arrow.



Figure 5.3: Tier II LHD was installed with DPF, showing the sampling point.



Figure 5.4: Tier III LHD (low emissions) purchased for implementation in the sister mine

Further, a phased-in approach to replace the tier II engines with tier III engines must be considered as the ones being rolled out at the new mining site as part of learnings from the current study (See Figure 5.4). As part of what was learned from the current study, the organisation has started implementing new control strategies, which include better technology, by introducing tier III engines at the new mine. This program will ensure that tier IIIs and tier IV engines are procured for the mine, as well as the introduction of electrical equipment from 2027, when the technology is accessible for SAMI.

Referencing the findings, running the primary and secondary ventilation systems (10 half-levels) of $435\text{m}^3/\text{s}$ at a pressure of 3136Pa costs 9 771 967,30 USD at base-case. In contrast, the total cost of retrofitting the DPF to 73 machines (32 LHDs and 41 Dump trucks) was 874,376 USD. To achieve a 30% improvement in the ventilation system, the primary and secondary ventilation system absorbed power must be increased by 54.5% and 52.4%, respectively. This is equivalent to a total of 21 468 971,27 USD, an increase of more than 50% of total ventilation running base-case cost per annum; this excludes any capital cost for additional fans or spares in case the fans are damaged. These findings suggest controlling the DEE at source is a better investment choice than ventilation alone.

Maintaining diesel particulate filters (DPF) is essential to efficiently running your engine. Without regular maintenance, the filter can become clogged with soot, reducing engine performance and leading to costly repairs (66,71). After-treatment engine technology has been carefully assessed in this study, and careful consideration is required before the mine can

successfully roll out the program. Once DPF is installed, a system for a post-DPF installation maintenance program is required. If the change is not made systematically and does not consider all the risks from the DPFs, an inherent fire risk can be introduced in an underground environment. Active regeneration technology suffers from uneven heating, melting of filters at high local temperatures, and high energy losses (66). Another factor resulting from heat is the possible machine surface heat, which creates a challenge when machines break down; cooling of the surfaces is required before maintenance can be considered, which may result in production delays. Effective means to insulate the surface of the engine and exhaust area are necessary to reduce the risk. Therefore, it is crucial to ensure that the engineering maintenance team is fully trained to understand the technical requirements of the DPFs. Also, the operators and the Ventilation Engineering department must be conversant to ensure they know all the monitoring and checks of the DPFs.

When a walk-about inspection was done six months after the installation of DPFs, the back pressure monitors for some machines were damaged, and some were reporting back pressure red lights without any escalation to the maintenance supervisors by operators. Upon investigation, operators could not correctly articulate knowledge of the critical checkpoint requirements on their machines. Also, the roadway conditions and water accumulation caused damage to some of the back pressure and temperature sensors. Post-maintenance of DPF and continuous coaching of the teams are essential to ensuring that necessary controls are adequate. Failure of the team to own their system could result in engine failure in the long run, affecting DPM's entire critical control management system. Jacobs and his colleagues (MHSC) recommended conducting an in-depth gap assessment for skills development regarding maintenance skills and operating the machines in the study they conducted in 2018 (6). This area remains a gap, and a plan to close the gaps is recommended (118). The two pictures below show the findings of a failed essential control, where the operators could not identify maintenance failure.



Service check screen installed on the machine dashboard

The red button indicates high back pressure on the DPF and was not reported to maintenance Manager.

Figure 5.5: The figure shows the service check dashboard of the machines to monitor the Engine back pressure status.



Service check screen installed on the machine dashboard

The service check is not working on the operational machine and was not reported to maintenance Manager.

Figure 5.6: The figure shows the service check dashboard on the machines to monitor the Engine back pressure status.

Other critical controls may include automated engine cut-off once the back pressure and temperature exceed the limit. The timing and loading sequence can be executed such that the

dump trucks only start loading when the first LHD completes loading. Only then can the mucking of the second LHD begin to load on the dump truck. In addition, the idling of the other LHDs and dump trucks in the section must be restricted to ensure that the DPM levels remain below $0.1\text{mg}/\text{m}^3$. This requires an interdisciplinary approach as it influences production targets, and the mine management must fully align and support the team.

The load and haul processes dynamics could exceed the ventilation requirements when the number of machines is idling at the intake of development headings; continuous monitoring of workplace conditions is key. The CFD simulation program/ tool has the potential to be linked to the ventilation and real-time DPM monitoring sensors, which could then be linked to a digital mining system, such as through SCADA (107). The goal would be to link real-time environmental sensors associated with DPM concentrations, feeding the dispersion model to predict workplace diesel emissions and activate the required controls. Further investigation is needed to determine suitable real-time/direct monitoring equipment that measures DPM concentrations or appropriate proxies. There is a need to evaluate different methods to proactively monitor DPM to identify and respond immediately if the recommended DPM threshold is exceeded in underground working areas. When designing predictive monitoring strategies, it is essential to understand the type of information required and the outcome linked at every control point.

The diagram below depicts the recommended flow analysis model:

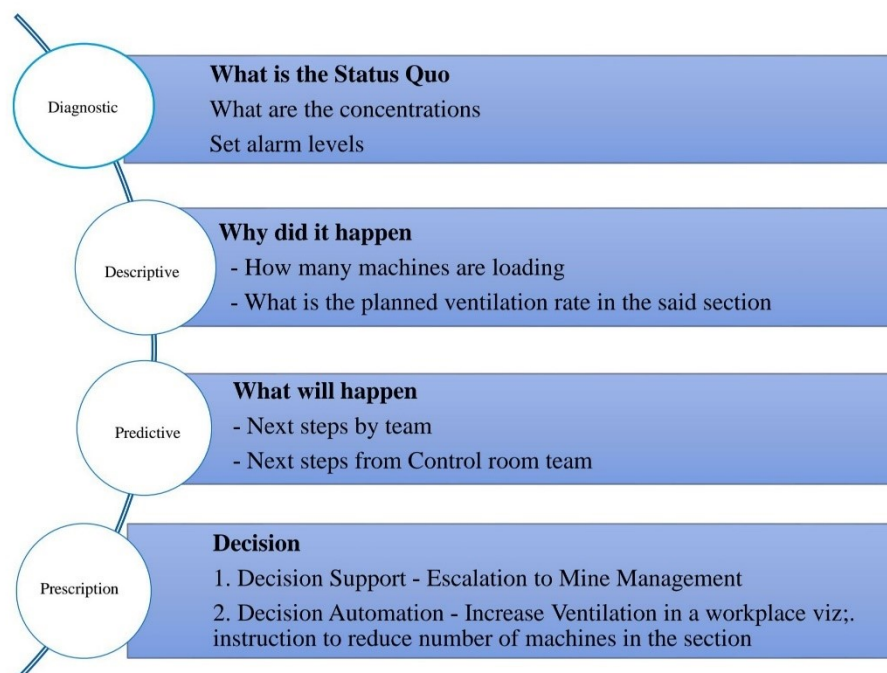


Figure 5.7: *Flow analysis model to assist in defining the DPM system architecture to interface the SCADA and to manage exposures.*

5.3 Strengths and Limitations of the Study

This study characterises diesel engine exhaust by measuring point source pollution of diesel-powered machines in underground mines, testing and evaluating different control strategies in real operative underground mines on an entire production fleet ($N = 41$). Characterisation is assessed based on parameters such as engine age and running hours. The study design was structured to evaluate the exposure pathway from the point source by determining particle number, mass, and volume concentrations and the propagation of DEE to the environment, followed by stepwise interventions. The intervention steps, comprising emission-based maintenance, retrofitting machines with diesel particulate filters, and ventilation, were assessed to evaluate their impact on controlling DEE, emphasising DPM in the environment. Despite some limitations presented below, a proper baseline using real-life production situations on diesel-powered machines was achieved, and a process to properly formulate control strategies was evaluated. This provides an excellent basis for integrated risk-based management pollution control strategies in SAMI. Amongst other limitations, the following were identified.

First, the sample size was small for analysing categorical data, e.g., there was a significant variation in rated power between the three categories, limiting the comparison of emissions by rated power. Although engine hours were paired correctly, there was variation in the engine size, reducing the confidence interval for inferential statistical analysis. Since the calculated R^2 for the multiple regression model, only simple regression was performed. Conducting a similar study in a larger sample and proper pairing is recommended to achieve a predictive multiple regression model.

Second, the dynamic simulation for DPM dispersion was based on tailpipe particle mass concentration; the ELPI+ software converts particle number concentration to particle mass concentration by assuming the default aerosol effective density of $1 \text{ mg}/\mu\text{l}$; this density may not be correct for soot; and mass concentration and could have had a potential bias due to few larger and heavier particles (108). A literature review by Rissler et al. (2013) indicated that while the material density of the primary particles constituting the soot core is $\sim 2 \text{ g}/\text{cm}^3$, the

effective density of the agglomerated soot particles is lower, and it significantly decreases with size to less than a factor of ten of the material density. They also indicated that the effective density could be altered by primary particle size and particle mass coating; further, density can be influenced by the operating mode or conditions of machines, air-fuel-ratios, and agglomeration (108). All these essential factors were not accounted for in this study; it is strongly recommended that additional studies be done to address the limitation of density at different operational modes, agglomeration, and different size particles.

Third, in the modelling, the source strength estimates for the particle fraction were converted to Elemental Carbon, assuming that EC forms 50% of the DPM. This percentage is based on previous literature reviews but could be affected by factors such as exhaust leakage and equipment errors during sampling. Future studies can consider chemical analysis of tailpipe input EC to increase the accuracy of the ventilation models.

Fourth, single tailpipe measurements were taken during the sampling from the machines, whereas triplicates would have provided a more reliable conclusive result. This decision for single measurements was based on the complexity of the sampling environment. Underground locations at the development headings or haulages are confined by design, and machine interaction poses some risk. The limitation of this setup is that it could not allow space to properly set up the Dekati ELPI+ with all its connections underground. The maintenance bay did not have a cover shade for the surface measurements, meaning measurements could not be taken during sunny or rainy days, leaving more samples only to be taken during the night shift. Further to note is that ELPI+ connects to the laptop during the measuring process, and both devices are heat-sensitive. This was a limitation because the sample measurements could only be taken at night when there was no direct sunlight or when it was not raining. Further to note is that during the tests, productivity and availability of the allocated fleet were expected to be maintained. Therefore, each machine was strictly allocated 15 minutes for complete measurements of exhaust gasses and particle concentrations. Although the ANOVA for tailpipe gas emissions did not indicate significant differences for triplicate, it is unclear whether this result is also valid for the particle concentrations; the method employed could have been improved by ensuring triplicate measurements as a standard rule.

Fifth, to assess the effectiveness of ventilation as a control to dilute DPM emissions, a single dimension computer fluid dynamic (Hardy-cross) analysis was used to model diesel particulate dispersion behaviour. Even though this Hardy-cross dynamic simulations method has been successfully used in planning to predict heat load, dust load, and airflow, the diesel particulate module is a new application. Currently, there is no published data on previous work deploying

this module, and there is a need to further validate the results with experimental measurements and CFD (2D or 3D) simulations. The recommendation is further to validate the input/output parameters with experimental data; this is an essential aspect in the future planning and monitoring of DPM in the mining industry. It must be noted that the results from dispersion modelling were validated by the reduced number of DPM (EC) from personal exposure sampling.

Lastly, when evaluating diesel exhaust gas emissions, CO₂ is one of the most critical gasses to be measured to understand combustion efficiency better. When fuel is injected after the start of combustion, fuel pyrolysis or rapid oxidation occurs when mixed with air, resulting in complete combustion. Conditions that may slow the rate of pyrolysis and oxidation will lead to exhaust gas containing more significant concentrations of unburned hydrocarbon (64). Hence, the combustion efficiency (CO/CO₂ ratio) must be measured before and after maintenance to diagnose and address emission concerns. This study's CO/CO₂ ratio was not calculated due to the limited available Testo gas analyser. Further, the flow velocity in the sampling line should be the same as in the flow, a condition referred to as isokinetic sampling (118). This was not done in this study with the gas flow meter for repeatability and reliable data. Additional studies are recommended to consider measuring CO₂ to determine combustion efficiency and help the maintenance team properly diagnose the machines for EBM and correct all the faults accordingly.

5.4 Scholarly Contribution of the PhD Study

This study is one of the first significant studies in SAMI to characterise the DEE on a larger scale in a real operational setting. Most studies were done in a simulated environment, where environmental conditions were also simulated. This study offered new knowledge regarding the characterization of DEE for the two Platinum mine fleets, e.g., particle number concentration, particle size distribution, and concentrations of emitted gases.

Baseline measurements were done for all primary machines, intervention strategies were done, and post-measurements were evaluated. Three control strategies were compared to measure the success of each one of them. Overall, it was demonstrated that maintenance, retrofitting of diesel-powered machines, and ventilation dilution have positively impacted reducing DEE at source and in the underground environment. Retrofitting machines with DPF showed the highest success rate; however, other control methods significantly reduced the DEE.

Nevertheless, this study has further demonstrated that an integrative approach is critical when implementing the DPM strategy.

The outcome of this study has also highlighted the need to progressively consider implementing higher-technological Tier machines and fast-tracking the investigations of energy-efficient machines. This study has provided additional information on the impact of DPM exposure and encouraged the mine to start rolling out Tier III engines. Other mines can adopt this approach. A great potential has been demonstrated that using Ventilation dynamic software packages for simulation of DPM emission dispersion is possible in the mining industry. Ventilation engineers can adopt and apply this to enhance their planning processes supported by the highly specialized 2D and 3D CFD packages. Other critical contribution areas that can assist engineers include the following:

- 1) Testing the effectiveness of control strategies by managing point source measurements
- 2) The tailpipe diesel emission measurement results could be used directly in the numerical modelling simulations.
- 3) The impact of integrated interventions at various levels of the Hierarchy of Controls, such as Engineering controls (Retrofitting machines with DPF and diesel oxidation catalysts) and administrative controls, such as maintenance and ventilation evaluation, could be simulated timeously during the ventilation planning phase. Ensuring that a proactive approach to eliminating and reducing emissions before they reach the workplace.

The study has demonstrated that the current ventilation dilution rates are inadequate in controlling DPM to the recommended limit value for EC of $0.1\text{mg}/\text{m}^3$. Strong consideration must be given to reviewing the dilution rate of $0.06\text{ m}^3/\text{s}/\text{kW}$. Also, the corrected dilution rate must not be examined in isolation but must incorporate other control strategies to meet the requirements.

5.5 Policy Impact

The overall findings from this study show that an integrated approach to reducing DEE at source had the highest positive impact on reducing worker exposure. A slight impact was achieved when either maintenance or ventilation interventions were implemented individually. However, in an instant where a series of interventions (maintenance, retrofitting machines with

DPF, and dilution with ventilation) were implemented, there was the highest reduction in the tailpipe DEE and a decrease of DPM in the work environment.

These findings draw attention to the South African Mining Platinum sector, where there has been a growing need for mechanization processes. These findings are critical in assisting the SAMI in regulating DPM and assisting in a step-by-step approach for mining employers to implement measures to ensure that employees are protected from any over-exposure from DEE. Further, studies of this nature will also assist different mines in developing risk-based approaches in implementing occupational hygiene programs and critical control management systems to prevent and manage over-exposure to DEE in underground development headings; it will also help them to make informed decisions when choosing control strategies.

The findings suggest a need to evaluate mine maintenance strategies and a massive focus on technology implementation, such as the DPF. Findings also indicate that ventilation dilution rates need to be revised to ensure adequate ventilation in underground working places; the current rate of $0.06\text{m}^3/\text{s}/\text{kW}$ is inadequate to dilute DPM in underground workings, even at increased altered ventilation quantities. In this study, it became evident that when increased ventilation was considered alone using this ventilation dilution rate, the DPM remained above the recommended value of $0.1\text{mg}/\text{m}^3$ when no engineering interventions (EBM and retrofitting machines with DPF) were implemented; this validates the urgent need to review the current ventilation rate used in SAMI. Therefore, policymakers must consider stricter regulations to improve engine technology, such as introducing higher-tier engines like tier III and tier IV. Further, it will be very critical that SAMI shift towards clean energy by introducing electrical and battery-operated machines, which require attention. This elimination strategy is necessary to eliminate the risk of developing possible cancers in long-term exposure to DEE.

5.6 Recommendations

5.6.1 Recommendations for South African Mining Industry

Maintenance and retrofitting of TMM with DPF have shown an average filtration reduction efficacy of 96% in reducing the tailpipe particle concentration and over 70% for the tailpipe gasses. Ventilation or maintenance of machines alone could not reduce the levels of DPM to below the recommended threshold value of $0.1\text{mg}/\text{m}^3$ of EC. Additional scenarios were added to the dynamic simulations where the two (2) LHDs and the dump truck were replaced by electrical ones, showing a higher reduction of simulated DPM concentrations. However, the

levels of DPM were still higher than the recommended threshold value of $0.1\text{mg}/\text{m}^3$. Further, this study has demonstrated that increasing ventilation only, without reducing the DEE at the source, does not yield positive results. An increase in ventilation as an exposure control will also increase the operational cost of running the ventilation systems. These results demonstrate that an approach that focuses on eliminating or reducing diesel emissions from the source should be prioritized to prevent employees' exposure to diesel emissions.

In South Africa, the mining industry has adopted ventilation design parameters of $0.06\text{m}^3/\text{s}/\text{kW}$ of installed diesel power equipment. However, these parameters are not regulated and are not enforceable. This dilution rate can only be adequate if machines have lower rated kW power and the load, muck, and haul processes align with the ventilation requirements. The current air volumes of the development heading design, designed to accommodate a 75kW fan size and column diameter of 1015m ($25\text{m}^3/\text{s}$), are inadequate and must be revised to enable possible dilution.

- Without electric or battery-powered machines, a multifaceted approach must be implemented to curtail the levels of DEE underground. Further, ventilation engineers must be involved during pre-feasibility and feasibility studies, use computational numeric dynamic systems to plan promptly and advise mine management of the required infrastructure. Overall, this study's findings show that the current dilution rate of $0.06\text{m}^3/\text{s}/\text{kW}$ is inadequate for diluting DPM concentration to lower/safer limits.

Referring to these findings, the following recommendations influencing policy are proposed:

- Consider implementing a recommended workplace limit value for EC TWA(8h) concentration at $0.1\mu\text{g}/\text{m}^3$, which aligns with international standards and research results.
- Consider regulating the ventilation design dilution rate based on available controls at the mine. A dilution rate value of $0.06\text{m}^3/\text{s}/\text{kW}$ is recommended when complying with the diesel particulate matter management program, such as using higher-tier engines (Tier 3 and 4 engines), DPF, catalytic converters, and diesel with a low sulphur content (10-50 ppm). It is further recommended that a ventilation dilution rate of $0.12\text{m}^3/\text{s}/\text{kW}$ be adopted and regulated in cases where ventilation dilution is the only control.
- Consider mandatory implementation of strategic controls, focusing on reducing diesel emissions at the point source in South African Platinum mines, such as installing compulsory engine after-treatment technologies.

- SAMI to consider a phased approach to replace machines with energy-efficient machines to ensure that part replacement has the potential to reduce the DPM to below the stipulated recommended threshold value for EC.
- Previous research has shown that regulatory frameworks pertinent to diesel engines have resulted in the rapid development of after-treatment technologies, fuel technologies, and the reassessment of the OELs internationally. A similar approach and urgency are required in South Africa. This needs to be accelerated, especially considering the rapid growth in mechanisation in SAMI.
- Regulation of the engine Tier standards for underground machinery must be considered, especially when drafting a phased approach to replacing old-generation machinery.
- A continuous improvement in emission management could be achieved by measuring the gas ratios during maintenance and assisting the maintenance team in checking these gases before and after maintenance. The ventilation and occupational hygiene teams can also confirm this quarterly to determine if the maintenance is adequate and the prolonged efficacy of the DPFs, especially after cleaning. A good maintenance plan for the TMMs, including cleaning filters per the OEM specifications and adhering to the schedule and servicing of engines, will ensure the continued efficacy of the installed DPF.
- SAMI should consider integrating multidisciplinary teams to select and approve the design criteria for procuring diesel-powered fleets at the mines. This is to ensure that health aspects from pre-risk assessments are integrated into the Engineering aspects before the machines arrive on site.
-

5.6.2 *Recommendations for Future Research*

Additional research is needed to address the limitations of this study. Research should include proper diagnostic methods when machines go for maintenance. Although tailpipe gas measurements were done in this study, undiluted or raw gas sampling is also a common technique because of the relative simplicity of the sampling system. However, it isn't easy to obtain reproducible and reliable results because of the high concentration of moisture, particulates, and high temperatures (118). There is a need for additional studies to address this gap variation and to have ideal documented methods that the maintenance team can use.

The ELPI+ has provided a reasonable basis for the tailpipe characterisation of diesel particles. The instrument is robust and yields reliable results. However, the instrument is not ideal for

day-to-day use because of its cost. There is a great need to evaluate other portable equipment that can measure gases and particles to diagnose EBM. This will ensure proper diagnostic tools that will effectively assist in managing EBM by operators. Furthermore, the portable gas measuring equipment must also be evaluated appropriately and ensure that flow velocity in the sampling line is the same as in the flow, a condition referred to as isokinetic sampling. Otherwise, aerodynamic effects may lead to a depletion or an enrichment of coarse particles in the sampling line (118). In this study, the mass flow variation was not accounted for and should be thoroughly addressed.

This study was done in underground mines where operational activities were ongoing. Only two transient modes were assessed in this study: idle mode and high transient mode. The diesel emissions are affected by load, and emissions increase at light rather than during high transient load. Factors that may increase the generation of unburned hydrocarbons at idle/light load may include the fuel not reaching the walls of the combustion bowl and burns in the space between the nozzle tip and the combustion bowl perimeter, resulting in spatial combustion. The spray core's fuel concentration is sometimes relatively small (64,65). These aspects must be well understood and built into the maintenance program and the numerical modelling process. Additional studies to incorporate additional studies are recommended, such as Opacity meters, also known as smoke meters, which measure diesel smoke opacity (particles suspended in the exhaust) in the tailpipe. These instruments do not accurately measure DPM concentrations. Still, they are a quick and easy-to-use tool to evaluate the condition of an engine or gross malfunctions of DPM control technologies such as ceramic or other high-efficiency filtration units (119).

The numerical modelling for DPM is relatively new on the VentSim or Vuma software. Although the modelling results correlated well with the tailpipe and environmental, personal monitoring results, validating the results with experimental measurements is necessary. This step is critical in understanding the possible real-time methods linked to the digital mining systems to report DPM concentrations in real-time.

The recommended DPM exposure limit should be implemented, tested, and implemented in line with integrated controls. An evaluation of the effectiveness of the implementation in underground mines can follow these. Also, a natural time method covering a wide range of aerodynamic size particles must be tested as a proxy for the NIOSH 5040 method. Once this is tested, it can be linked to workplace real-time monitoring techniques for continual improvement and to ensure that employees are protected from exposure to DPM.

CHAPTER 6 – CONCLUSION AND SIGNIFICANCE

This chapter concludes the main findings of the research study based on the different objectives and literature review presented in chapter two. The chapter further provides the study's significance and final remarks for future projects.

6 Conclusion and Significance

The thesis has reviewed the literature indicating that exposure to DPM/DEE may result in adverse health effects, and therefore, interventions are vital. The present study demonstrated that maintaining diesel-powered machines and retrofitting machines with diesel particle filters reduced tailpipe emissions and exposures to underground employees. The study further pointed out that emitted particle number concentration (PNC) was concentrated around the smaller aerodynamic diameters, which is linked to health effects. Therefore, efforts to reduce the generation of DEE at source are required. There must be a baseline risk assessment process to quantify diesel particulate matter and employee exposure levels to establish whether a hazard exists and, if so, to assess and prioritize sources of employee exposure and risk, thus enabling the implementation of appropriate control measures. These controls and processes should improve engine efficiency and prevent DPM generation. EBM and DPF technology are currently effective in controlling particulate emissions, although there are still many challenges to overcome when implementing EBM and DPF solutions. For example, this study identified that during the regeneration process, the high ash load increases the temperature of the DPF and the exhaust surfaces, which may eventually cause melting and initiate fire in the engines. Furthermore, the management of breakdown downtime can be increased due to heating the surfaces around the exhaust, so a cooling period is required before the machine can be attended to for the breakdown. Further research on DPF regeneration requirements and insulation of some exhaust system parts is necessary to improve the overall engineering control strategy. Continuous monitoring of back pressure and temperature must be done; further, the continuous data linked to the electric control unit (ECU) must be integrated into a real-time system that will allow automated response, such as cutting off the engine when the critical control safe parameters are exceeded. This information will also help in early diagnosis of machine health performance timeously and built on the EBM.

Personal DPM and CO sampling after the installation of DPFs in all machines demonstrated a reduction of personal exposures compared to pre-installation results. Personal exposure monitoring results can vary significantly based on employees' work activities and

environmental conditions on the sampling day. A wide variety of possible factors could contribute to personal exposure results, such as a reduced number of machines in working places, alterations of the load and haul cycle due to ore availability, and or employees moving between areas where there are fewer load haul activities, however in this study there was consistency between personal DPM and CO reduction which are attributed to DPF installation. The findings confirm that reducing DEE at source is highly effective and should remain a priority for exposure control and risk management. Further considerations to collect enough data for both personal and area monitoring using the NIOSH 5040 method are strongly recommended. It must be noted that when sufficient monitoring data is available, monitoring results can provide information on workplace DPM exposure levels in general and specific tasks when it is known what tasks a worker was performing and the location of these tasks. It is recommended that employers establish a proper occupational hygiene program that will ensure more data points are completed to evaluate exposure conditions and fully understand the personal and area exposure profiles.

In this study, dynamic simulations were conducted based on emission scenarios to evaluate the effects of ventilation in the dispersion of DPM within the underground environment. The study showed that the current load and haul tramming planning cycle (total number of machines planned per section) were not in line with the ventilation requirements, resulting in higher underground pollution levels due to inadequate air volumes to dilute the emissions. Further, the study showed that when machines underwent maintenance and were fitted with DPF, the ambient conditions and DPM concentration could be reduced to below the recommended action limit of 0.1mg/m^3 . However, this could not be achieved when the machines were subjected to maintenance only.

This study also showed that singular controls, such as maintenance only or ventilation dilution only, could not curtail the DEE levels at the source and ambient environment. A multifaceted approach is therefore required to address the issue of DEE exposure in underground mines. At this point not all mines can transition speedily to implementing after-treatment solutions or engine-replacement strategies with clean technology machines due to financial constraints. However, mines are still encouraged to implement strategies that will allow them to avoid or at least reduce exposure to DEE to their employees'

The South African mining industry must be deliberate when implementing risk assessment and management strategies to assist the mines in transitioning. Based on the HoC, the mines can assess the best approach to eliminate, substitute, and reduce exposure using the interventions

investigated in this study and administrative controls such as maintenance, improved shift rosters, and PPE. This should be done with cost evaluation benefits to ensure that cost-effective controls are implemented; for example, this study has shown that dilution ventilation control only to reduce exposure was more expensive than the once-off installation of DPFs and continuous maintenance. Furthermore, the dynamic simulations showed that when diesel-powered machines were partially replaced with electrical-powered machines, the workplace conditions improved. Implementing energy-efficient machines will improve employees' health and assist the mining industry in achieving its commitment to climate change and ESG decarbonization. Further, this study showed an opportunity for mining companies to use the single-dimension dynamic simulation tool to plan, model, and predict workplace exposure timeously.

The success of overall DPM management progress in SAMI will be made possible if adequately linked to training. DPM exposure and management are new areas of knowledge, especially emerging technologies. Therefore, all stakeholders must be engaged and taken along the journey of overall risk management for DPM. Training of employers, Engineers, Occupational health and hygiene teams, maintenance teams, Ventilation engineers, and the integration process with OEM is of utmost importance to transition properly during the implementation process. Continuous training and maintenance systems post-installation of after-treatment engine technologies are critical.

In conclusion, this study has shown that it is possible to implement a risk management strategy for identifying, controlling, and reducing the risk of exposure to DPM using current technologies. The research outcome will assist South African mechanized mining companies in assessing their risks, evaluating control strategies, and measuring the effectiveness of controls using different monitoring tools. It will also benefit SAMI in setting the basis for mining companies to understand and set up DPM dispersion modeling and the use of correct ventilation parameters for DPM during the early ventilation resourcing and planning phase. Computer-based methods are used to develop monitoring systems, calibrate ventilation models, improve maintenance systems, or select technological options to reduce exposure. The study will also add value to policy development, implementing risk-based risk assessment, assessing the effectiveness of controls, and monitoring implemented controls. The study also provides knowledge to mining engineers, VOHE specialists, and the industry at large to assist them in facilitating cost-effective business cases for implementing robust DPM control strategies.

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8 Appendices

8.1 Appendix 1: Study Ethics



R14/49 Mrs Amukelani Portia Modau

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL) CLEARANCE CERTIFICATE NO. M190308

NAME: Mrs Amukelani Portia Modau
(Principal Investigator)
DEPARTMENT: Public Health
 Modikwa Platinum Mine

PROJECT TITLE: Evaluation of Air Pollution exposure levels from Diesel Exhaust Emission in Underground south African Mines: Implementing a risk based monitoring system to manage over exposure

DATE CONSIDERED: 29/03/2019

DECISION: Approved unconditionally

CONDITIONS:

SUPERVISOR: Prof Derk Brouwer and Prof Cas Bardenhost

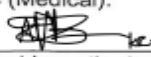
APPROVED BY: 
 Dr CB Penny, Chairperson, HREC (Medical)

DATE OF APPROVAL: 30/07/2019

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the Third Floor, Faculty of Health Sciences, Phillip Tobias Building, 29 Princess of Wales Terrace, Parktown, 2193, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report.** The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **March** and will therefore be due in the month of **March** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).


 Principal Investigator Signature

Date 09/08/2023

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

8.2 Appendix 2: Study Clearance

Date: 22 April 2018

To: General Manager

RE: Permission to conduct a research study: *Evaluation of Air Pollution exposure levels from Diesel Exhaust Emissions in underground South African Mines: Implementing a risk-based monitoring system to manage over exposure*

Dear Sir/Madam

I am writing to the company to request a permission to conduct a PHD research in your Mine. I am currently enrolled for a PHD study at the Witwatersrand (Wits) University and currently in a processes to get a clearance from the Ethics Research Committee of the school. The study is entitled as follows; *Evaluation of Air Pollution exposure levels from Diesel Exhaust Emissions in underground South African Mines: Implementing a risk-based monitoring system to manage over exposure*

Available research information indicates that there are human health hazards associated with exposure to Diesel Exhaust Emissions (DEE). During 2012 the IARC has classified Diesel exhaust (DE) as being carcinogenic to humans (class I) by inhalation. On a day to day operational use of diesel powered trackless mobile equipment DE is liberated to an underground environment, once emitted from the tailpipe it causes environmental pollution where employees work. In the absence of Occupational Exposure Limit (OEL) for DE by the Department of Labour (DoL), no mandatory monitoring reports to the Department of Mineral Resources (DMR) are required on the employee exposure to Diesel Particulate Matter. However as the employer is legally bound to assess the risk and have systems to eliminate or reduce the exposure to the employees, there is a need for South Africa to understand the exposure levels and come up with stringent policies to regulate the exposure levels and also to enforce compliance thereof.

The main objective of the research project is to evaluate the possibility of integrating a monitoring module in a digital mining and communication system as an early warning detection and risk management tool for diesel exhaust in underground mines.

The research will include the following activities; measuring the tailpipe of the Trackless Mobile Machineries (TMM) before and after maintenance, measuring of diesel exhaust emissions underground development sections by means of real-time sampling equipment's, and gravimetric sampling pumps, and gasses in a stationery location. All collected data will be used as part of routine on-mine monitoring program to inform the continuous risk assessment and to assist in implementing risk based maintenance management for your TMM fleet.

The name of the Mine will not be used in any publication of the study, only the mining design will be used.

I hope you will grant me the permission to use your company's resources to conduct the study.

Your approval to conduct the study will be highly appreciated. I am available to answer any questions relating to the study from the following email address: Amukelaniportia.modau@angloamerican.com and/or amu.manyike@gmail.com.

If you agree, kindly sign below with the mines letterhead acknowledging your consent and permission to conduct the research study.



15 May 2018

Mr. Vusi Khumalo

General Manager Modikwa Mine

8.3 Appendix 3: Calibration Certificate Dekati ELPI+

ELPI+™ DATA SHEET
DEKATI Impactor # **10259**

Cut points, downstream pressures and residence times:

Stage	D50% (µm)	Pressure (kPa)	Residence Times
1	0.0060	4.00	0.0010
2	0.0155	4.18	0.0024
3	0.0307	9.91	0.0056
4	0.0548	22.50	0.0127
5	0.0947	39.21	0.0222
6	0.154	68.37	0.0391
7	0.256	89.38	0.0505
8	0.381	97.22	0.0552
9	0.601	99.65	0.0585
10	0.945	100.48	0.0622
11	1.63	101.01	0.0571
12	2.46	101.18	0.0578
13	3.64	101.25	0.0736
14	5.35	101.30	0.1029
15	9.85	101.32	0.00
inlet		101.33	

Diffusion loss parameters

a	b	c
9.80E-08	-2.7300	0.05085
9.80E-08	-2.7300	0.05085
9.80E-08	-2.7300	0.05085
3.63E-08	-3.0600	0.03083
1.58E-06	-2.2600	0.02342
4.83E-06	-2.0600	0.02183
1.02E-05	-1.9000	0.02097
6.22E-05	-1.4900	0.01158
4.03E-05	-1.5600	0.00804
7.31E-05	-1.4000	0.00671
1.01E-04	-1.3100	0.00475
8.22E-05	-1.3500	0.00288
1.09E-04	-1.3100	0.00129
9.07E-05	-1.3600	0.00186

$$\text{Loss} = a \cdot D_p^b + c$$

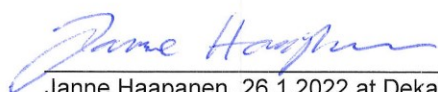
Inlet Pressure: 1013.3 mbar
 Outlet pressure: 40 mbar
 Flow rate: 10.01 lpm

Calibration information

Date: 15.5.2018
 Temperature: 20.5 °C
 Calibrated by: Timo Alanen

Charger Efficiency PnEQ

Limit1	Limit2	
1.035	4.2820	
Mult1	Mult2	Mult3
1.83	1.8114	3.3868
Exp1	Exp2	Exp3
1.225	1.515	1.085



Janne Haapana, 26.1.2022 at Dekati, Finland

Calibration based on: Järvinen, A., Aitomaa, M., Rostedt, A., Keskinen, J. & Yli-Ojanperä, J. 2014. Calibration of the new electrical low pressure impactor (ELPI+). Journal of Aerosol Science, Volume 69, pp. 150-159.

8.4 Appendix 4: Calibration Certificate Testo 350

Kalibrier-Protokoll

Certificate of conformity • Protocole d'étalonnage
Certificato di taratura • Informe de calibración



Gerät / Module type / Type de modèle / Prodotto / Modelo:

T350

Seriennummer / Serial No. / No. de série / No. Serie strumento / n° de serie:

63944821

Temperaturmessung Temperature measurement Mesure de température Misura della temperatura Medición de temperatura	Sollwert Reference Référence Valore campione Referencia	Istwert Actual value Valeur effective Valore misurato Valor medido	zulässige Abweichung Permissible deviation Différence admissible Scostamento ammesso Desviación permitida
--	---	--	---

Verbrennungslufttemp./ Ambient air temp. Température d'air de combustion Temperatura aria comburente Temperatura ambiente	100.0 °C	100.0 °C	+ - 0.5 °C
--	----------	----------	------------

Abgastemperatur / Flue gas temperature Température des fumées Temperatura fumi Temperatura gases	100.0 °C	100.0 °C	+ - 0.5 °C
---	----------	----------	------------

Zug-/Druckmessung Draught/pressure measurement Mesure de tirage/de pression Misura della pressione/ tiraggio Medición de trío/ presión	8.00 hPa	8.00 hPa	+ - 0.12 hPa
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Gasmeßwerte / Gas values / Valeurs de gaz mesurées / Parametri di misura dei gas / Gases patrón

Reg. Nr. Reg. No. Reg. No. Num. reg. n° certi	Gas	Sollwert Reference Référence Valore campione Referencia	Istwert Actual value Valeur effective Valore misurato Valor medido	zulässige Abweichung Permissible deviation Différence admissible Scostamento ammesso Desviación permitida
303D880604	NO2	100.3 ppm	101.3 ppm	+ - 5.0 ppm
301D039774	NO	149 ppm	149 ppm	+ - 8 ppm
30260050	CO2	17.00 %	17.04 %	+ - 0.40 %
20230729	CO2	38.5 %	38.6 %	+ - 0.7 %
301D039769	O2	4.99 %	5.02 %	+ - 0.20 %
302D671463	O2	2.50 %	2.52 %	+ - 0.20 %
301D039774	O2	0.00 %	0.00 %	+ - 0.20 %
301D039769	CO	401 ppm	400 ppm	+ - 20 ppm
302D671463	CO	691 ppm	688 ppm	+ - 35 ppm
301D039774	CO	99 ppm	102 ppm	+ - 10 ppm

Prüfer/Inspector/Vérificateur/Verificatore/Verificador: 7092

8.5 Appendix 5: Dump truck Toro 50 Tier II Engine



TORO 50

TECHNICAL SPECIFICATION
T0050-3

2/2

Weights

Operating weight	32 500 kg (71 650 lb)
Total loaded weight	82 500 kg (181 880 lb)

Capacities

Payload capacity	50 000 kg (110 232 lb)
Box std.	20.0 m ³ (26 yd ³)

Dump box movements

Discharging time	16,5 sec
Dumping angle	62°

Driving speeds forward and reverse

1st gear	6.1 km/h (3.8 mph)
2nd gear	8.0 km/h (5.0 mph)
3rd gear	11.0 km/h (6.8 mph)
4th gear	14.5 km/h (9.0 mph)
5th gear	19.2 km/h (11.9 mph)
6th gear	25.5 km/h (15.8 mph)
7th gear	35.0 km/h (21.7 mph)
Reversing with 1st and 3rd gear	

Engine

Diesel engine	Detroit S-60 DDEC IV
Output	390 kW (525 hp)
Number of cylinders	in line 6
Displacement	14 000 cm ³
Cooling system	Water cooled
Combustion principle	Direct injected, turbo + inter cooler, 4- stroke
Air filtering	Donaldson
Exhaust system	HTI covered exhaust manifold & Turbo Double wall exhaust pipe, Catalytic purifier and muffler
Fuel tank capacity	700 l (185 gal.)

Drive line

Converter	Dana SOH, CL 8672
Gearbox	Dana SOH, 8821
Axles	Front, Dana SOH, 21D, oscillation ± 13°. Rear, Dana SOH, 21D

Tyres

Size and type	26.5R25, Bridgestone
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Operators compartment

Safety canopy	with electric gear shift control
Height	2720 mm (107")
Optional air-conditioned ROPS/FOPS safety cabin	

Lubrication system

Centralized manual lubrication
Optional automatic central lubrication

Manual languages

Spare part manual	
Operation instructions	main European languages
Maintenance instructions	main European languages
Engine spare part information	English
Machine spare part information	English
Workshop manual	
Operation instructions	main European languages
Maintenance instructions	main European languages
Engine workshop manual	Original
Power train components manual	Original
Optional equipment instructions	English

Optional box sizes

- Dump box capacity 19,0 m³ (25 yd³), width 3260/3540 mm, flat top.
- Dump box capacity 20,0 m³ (26 yd³), width 3260/3540 mm, flat top.
- Dump box capacity 20,0 m³ (26 yd³), width 2960/3240 mm, flat top.
- Dump box capacity 22,0 m³ (29 yd³), width 2760/2980 mm.
- Dump box capacity 24,0 m³ (31 yd³), width 3260/3540 mm.
- Dump box capacity 25,5 m³ (33 yd³), width 3260/3540 mm.
- Dump box capacity 28 m³ (37 yd³), width 3260/3540 mm.
- Ejector box, capacity 16.5 m³ (22 yd³).

SANDVIK TAMROCK reserves the right to change this specification without further notice



SANDVIK TAMROCK Corp., P.O. Box 434
FIN-20101 Turku, Finland
Tel. +358 20544131
Fax. +358 20544130
www.toro.sandvik.com

8.6 Appendix 6: Dump truck TH541 Tier II Model

TECHNICAL SPECIFICATION SANDVIK TH545i

The TH545i is a high performance 45 tonne articulated underground dump truck for use in 4.5 x 4.5 meter haulage ways. The truck's performance is based on proven design, high engine power and high payload related to own weight.

This robust and intelligent truck delivers benefits in safety, productivity and profitability. Safety, health and comfort are enhanced with enclosed and vibration isolated cabin. Optional EU Stage IV / Tier 4f low emission engine will further help reducing the fuel consumption and emissions without sacrificing the high productivity.

The TH545i truck features a wide range of intelligence integrated technology, such as Sandvik Intelligent Control system, My Sandvik Digital Services and Automation compatibility as standard, supplemented with Onboard Weighing System option for tracking the payload. With the latest addition of the AutoMine® Trucking Onboard option, the TH545i enables autonomous haulage for both transfer level and decline ramp application.

CAPACITIES

Maximum payload capacity	45 000 kg
(SAE heaped 2:1)	
Standard dump box	22.0 m ³
Dump box range	18 - 26 m ³

SPEEDS (LEVEL/LOADED) WITH ENGINE VOLVO TAD1641VE-B

1st gear	5.4 km/h
2nd gear	7.2 km/h
3rd gear	9.7 km/h
4th gear	12.8 km/h
5th gear	16.9 km/h
6th gear	22.3 km/h
7th gear	30.1 km/h

DUMP BOX MOTION TIMES & MOVEMENTS

Discharging time	14 sec
Dumping angle	62 °

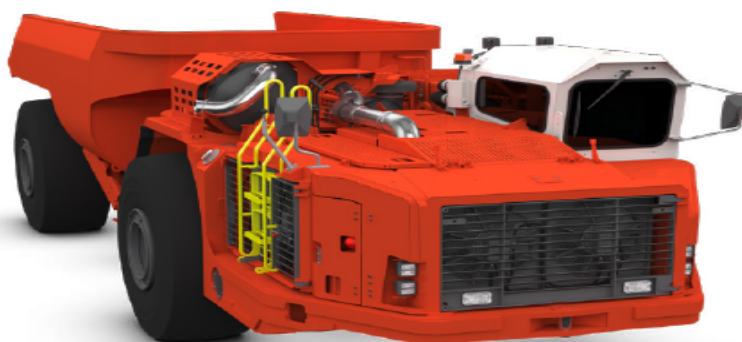
OPERATING WEIGHTS *

Total operating weight	36 000 kg
Front axle	26 500 kg
Rear axle	9 500 kg

LOADED WEIGHTS *

Total loaded weight	81 000 kg
Front axle	37 900 kg
Rear axle	43 100 kg

* Unit weight is dependent on the selected options



TS-TH545i-13/ENG/METRIC

OPERATIONAL CONDITIONS AND LIMITS

Environmental temperature	From -20°C to +50°C
Standard operating altitude	With engine Volvo TAD1641VE - B from -1500 m to +1000 m at 25 °C without rated power derate

REQUIREMENTS AND COMPLIANCE

Compliance with 2006/95/EC Low voltage directive
Compliance with 2004/108/EC Electromagnetic compatibility directive
Compliance with 2006/42/EC Machinery directive (Equipment for EU area, achieved with relevant options)
Design based on EN 1889-1. Machines for underground mines. Mobile machines working underground. Safety. Part 1: Rubber tyred vehicles.
Design based on MDG 15. Guideline for mobile and transportable equipment for use in mines. (Equipment for Australia, achieved with relevant options)
Electrical system based on IEC 60204-1. Safety of machinery – Electrical equipment of machines – Part 1: General requirements
*CONTAINS FLUORINATED GREENHOUSE GASES
Refrigerant R134a under pressure max 38 bar/550 PSI
Filled weight: 2,0 kg
CO ₂ e: 2,860 tons
GWP: 1430
Information based on the F Gas Regulation (EU) No 517/2016*

POWER TRAIN**ENGINE**

Diesel engine	Volvo TAD1641VE - B (Tier 2)
Engine brake	Yes
Output	450 kw (603 hp) @ 1800 rpm
Torque	2913 Nm @ 1200 rpm
Number of cylinders	In-line 6
Displacement	16.1 l
Cooling system	Liquid cooled
Combustion principle	4-stroke, direct injection, turbo, after cooler
Air filtration	Dry type
Electric system	24 V
Emissions	Tier 2, Euro Stage II
Ventilation rate	CANMET 34,800 CFM
(Ultra low sulphur diesel)	MSHA 30,000 CFM
Particulate index	MSHA Particulate Ventilation Index
(Ultra low sulphur diesel)	5,000 CFM
Exhaust system	Catalytic converter with muffler
Average fuel consumption at 50% load	49 l/h
Fuel tank refill capacity	620 l

TRANSMISSION

Fully automatic transmission with electric shifting system.
Seven gears forward and two reverse
Dana 8000 Series

CONVERTER

Dana C9000 Series with Lock up

AXLES

Front axle	Kessler D106 series, spring applied hydraulic operated brakes, equipped with standard differential, oscillation
Rear axle	Kessler D106 series spring applied hydraulic operated brakes, equipped with standard differential

TIRES

Tire size (Tires are application approved. Brand and type subject to availability)	29.5 R 25 E4 **
--	-----------------

HYDRAULICS**MAIN COMPONENTS**

Filling pump for hydraulic oil	
Door interlock for brake hydraulics	
Oil cooler for hydraulic and transmission oil capability up to 55°C ambient temperature	
Fittings	ORFS
Hydraulic oil tank capacity	225 l
Sight glass for oil level	2 pcs

STEERING HYDRAULICS

Fully hydraulic, center articulated, power steering with two double acting cylinders.

Steering main valve	Pilot operated
Steering hydraulic cylinders	125 mm, 2 pcs
Steering pump	Variable displacement piston pump

DUMP BOX HYDRAULICS

Fully hydraulic system, equipped with variable displacement piston pump. Oil flows to box hydraulic system from the steering hydraulics. Oil flow from the brake circuit pump is divided to the brake system and oil cooler motor.

Hydraulic pump	Variable displacement piston pump
Control valve	Solenoid operated
Main valve	Solenoid operated
Cylinders	160 mm, 2 pcs

BRAKES

Service brakes are spring applied; hydraulically operated multi disc wet brakes on all wheels. Two independent circuits: one for the front and one for the rear axle. Service brakes also function as an emergency and parking brake. Brake system performance complies with requirements of EN ISO 3450, AS2958.1 and SABS 1589.

Neutral brake
Automatic brake activation system, ABA
Electrically driven emergency brake release pump
Foot operated brake pedal valve, fully modulated
Brake oil tank capacity 100l

8.7 Appendix 7: LHD LH514 Tier II Engine

TECHNICAL SPECIFICATION SANDVIK LH514

Sandvik LH514 is a high capacity underground loader for hard rock applications.

Sandvik LH514 combines smart geometry with powerful thrust, high breakout forces, responsive controls and high tramming speeds. The advanced but still robust loader provides fast bucket filling, high fill factors, fast cycle times and proven reliability for underground mining use.

Sandvik LH514 is equipped with Sandvik Intelligent Control System, the backbone of the loader. The control system monitors the equipment productivity and health, and enables multiple smart solutions, such as the optionally available Integrated Weighing System and AutoMine® loading readiness for fully automated use.

SHARK™ Ground Engaging Tools (G.E.T.) are available on a wide range of bucket sizes, optimized for loader productivity and extended bucket service life.

CAPACITIES

Tramming capacity	14 000 kg
Break out force, lift	28 042 kg
Break out force, tilt	23 453 kg
Standard bucket	5.4 m ³

SPEEDS FORWARD & REVERSE (LEVEL/LOADED) WITH VOLVO TAD1340VE ENGINE

1st gear	5.9 km/h
2nd gear	10.5 km/h
3rd gear	18.3 km/h
4th gear	32.7 km/h

BUCKET MOTION TIMES

Raising time	7.0 sec
Lowering time	4.0 sec
Dumping time	2.3 sec

OPERATING WEIGHTS

Total operating weight	38 100 kg
Front axle	16 700 kg
Rear axle	21 400 kg

LOADED WEIGHTS

Total loaded weight	52 100 kg
Front axle	38 625 kg
Rear axle	13 475 kg



Sandvik LH514

OPERATIONAL CONDITIONS AND LIMITS

Environmental temperature	From -20°C to +50°C
Standard operating altitude	With engine Volvo TAD1340VE from -1500 m to +3000 m at 25 °C without rated power derate

REQUIREMENTS AND COMPLIANCE

Compliance with 2006/95/EC Low voltage directive
Compliance with 2004/108/EC Electromagnetic compatibility directive
Compliance with 2006/42/EC Machinery directive (Equipment for EU area, achieved with relevant options)
Design based on EN 1889-1. Machines for underground mines. Mobile machines working underground. Safety. Part 1: Rubber tyred vehicles.
Design based on MDG 15. Guideline for mobile and transportable equipment for use in mines. (Equipment for Australia, achieved with relevant options)
Electrical system based on IEC 60204-1. Safety of machinery – Electrical equipment of machines – Part 1: General requirements
CONTAINS FLUORINATED GREENHOUSE GASES (closed cabin option) Refrigerant R134a under pressure max 38 bar/550 PSI: Filled weight: 2,000 kg CO2e: 2,860 tons GWP: 1430 Information based on the F Gas Regulation (EU) No 517/2016

POWER TRAIN**ENGINE**

Diesel engine	Volvo TAD1340VE
Output	256 kW @ 2100 rpm
Torque	1 770 Nm @ 1260 rpm
Engine brake	No
Number of cylinders	In-line 6
Displacement	12.78 l
Cooling system	Liquid cooled and piston pump driven cooler fan
Combustion principle	4-stroke, direct injection, turbo with intercooler
Air filtration	Two stage filtration, dry type
Electric system	24 V
Emissions	Tier 2, Euro Stage II
Ventilation rate	CANMET 9.96 m³/s, MSHA 15500 CFM
Particulate index	MSHA 10500 CFM
Exhaust system	Catalytic purifier and muffler, double wall exhaust pipe
Average fuel consumption at 40% load	33.0 l/h
Fuel tank refill capacity	540 l

CONVERTER

Dana C9602	No lock-up
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TRANSMISSION

Power shift transmission with modulation.	Dana 6422, automatic gear shift control, four gears forward and reverse.
---	--

AXLES

Front axle, spring applied hydraulic operated brakes. Fixed.	Kessler D106, limited slip differential.
Rear axle, spring applied hydraulic operated brakes. Oscillating ± 8°.	Kessler D106, limited slip differential.

TIRES

Tire size (Tires are application approved. Brand and type subject to availability.)	26.5x25 L5S 36 ply
---	--------------------

HYDRAULICS

Electric filling pump for hydraulic oil
Door interlock for brakes and boom, bucket, and steering hydraulics
Oil cooler for hydraulic and transmission oil capability up to 50°C ambient temperature
ORFS fittings
MSHA approved hoses
Hydraulic oil tank capacity 240 l
Sight glass for oil level, 2 pcs

STEERING HYDRAULICS

Full hydraulic, centre-point articulation, power steering with two double acting cylinders. Steering lock.	Steering controlled by electric joystick.
Steering main valve	Open circuit type
Steering hydraulic cylinders	125 mm, 2 pcs
Steering pump	Piston type, LS controlled
Steering and servo hydraulic pumps	Piston type

BUCKET HYDRAULICS

The oil flow from steering hydraulic pump is directed to bucket hydraulics when steering is not used.	Joystick bucket and boom control (electric), equipped with piston pump that delivers oil to the bucket hydraulic main valve.
Boom system	Z-link
Lift cylinders	160 mm, 2 pcs
Dump cylinder	200 mm, 1 pc
Main valve	Open circuit type
Pump for bucket hydraulics	Piston type, LS controlled

BRAKES

Service brakes are spring applied; hydraulically operated multidisc wet brakes on all wheels. Two independent circuits: one for the front and one for the rear axle. Service brakes also function as an emergency and parking brake. Brake system performance complies with requirements of EN ISO 3450, AS2958.1 and SABS 1589.
Neutral brake
Automatic brake activation system, ABA
Electrically driven emergency brake release pump
Brake oil tank capacity 75 l

Sandvik LH514

8.8 Appendix 8: LHD Toro LH410 Tier II Engine

TECHNICAL SPECIFICATION TORO™ LH410

Toro™ LH410 is an underground loader with 10 000 kg payload capacity. It is compact in size, but yet it features advanced technical solutions, common with Sandvik large i-series loaders.

The advanced Toro™ LH410 loader is equipped with Sandvik Intelligent Control System and 7" touch screen display as standard, monitoring equipment productivity and health, and enabling multiple smart solutions. The numerous available options include e.g. a state of the art Stage V Volvo engine, side-tipping and ejector buckets, Integrated Weighing System (IWS), traction control, operator speed assist, and full AutoMine® loading capability.

Toro™ LH410 delivers best in class performance in productivity with its high ramp speeds and fast bucket filling. To make truck loading easy, the loader offers superior lift height compared to any other loader of the same size class.

Toro™ LH410 is a matching pair for threepass loading with the TH430 dump truck.

CAPACITIES

Maximum tramming capacity	10 000 kg
Break out force, lift	20 390 kg
Break out force, tilt	19 340 kg
Standard bucket	4.0 m ³

SPEEDS FORWARD & REVERSE (LEVEL/LOADED) WITH VOLVO TAD11140VE ENGINE

1st gear	5.5 km/h
2nd gear	10.2 km/h
3rd gear	17.5 km/h
4th gear	31.7 km/h

BUCKET MOTION TIMES

Raising time	6.7 sec
Lowering time	4.3 sec
Dumping time	2.7 sec

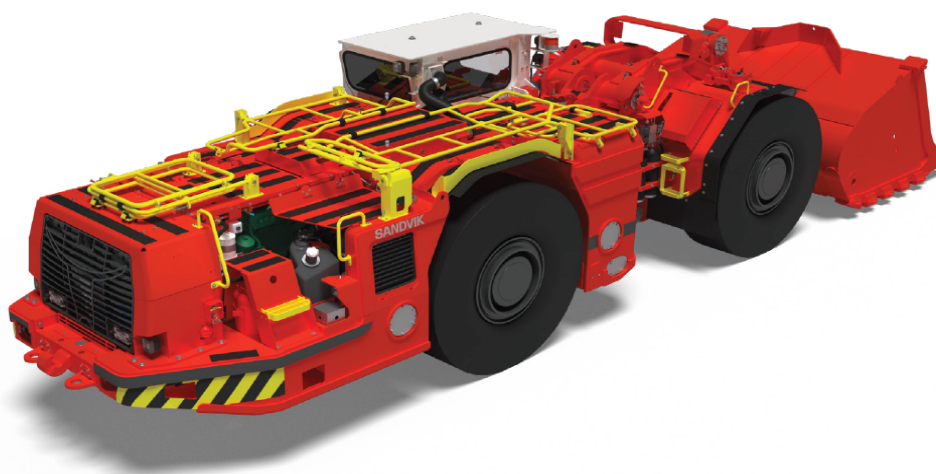
OPERATING WEIGHTS*

Total operating weight	28 500 kg
Front axle	12 850 kg
Rear axle	15 650 kg

LOADED WEIGHTS*

Total loaded weight	38 500 kg
Front axle	28 250 kg
Rear axle	10 250 kg

* Unit weight depends on selected options.



Toro™ LH410

OPERATIONAL CONDITIONS AND LIMITS

Environmental temperature	From -20°C to +50°C
Standard operating altitude	With engine Volvo TAD1140VE from -1500 m to +3000 m at 25°C without rated power derate

REQUIREMENTS AND COMPLIANCE

Compliance with 2006/95/EC Low voltage directive
Compliance with 2004/108/EC Electromagnetic compatibility directive
Compliance with 2006/42/EC Machinery directive (Equipment for EU area, achieved with relevant options)

Design based on EN 1889-1. Machines for underground mines. Mobile machines working underground. Safety. Part 1: Rubber tyred vehicles.

Design based on MDG 15. Guideline for mobile and transportable equipment for use in mines. (Equipment for Australia, achieved with relevant options)

Electrical system based on IEC 60204-1. Safety of machinery – Electrical equipment of machines – Part 1: General requirements

CONTAINS FLUORINATED GREENHOUSE GASES
(closed cabin option)
Refrigerant R134a under pressure max 38 bar/550 PSI:
Filled weight: 2,0 kg
CO₂e: 2,860 tons
GWP: 1430
Information based on the F Gas Regulation (EU) No 517/2016

POWER TRAIN**ENGINE**

Diesel engine	Volvo TAD1140VE
Output	235 kW @ 2100 rpm
Torque	1568 Nm @ 1300 rpm
Number of cylinders	In-line 6
Displacement	10.84 l
Cooling system	Liquid cooled and piston pump driven cooler fan
Combustion principle	4-stroke, direct injection, turbo with intercooler
Air Filtration	Two stage filtration, dry type
Electric system	24 V
Emissions	Tier 2, Euro Stage II
Ventilation rate	CANMET 8.07 m³/s MSHA 16,000 CFM
MSHA	16,000 CFM
Particulate index	MSHA 5,500 CFM
Exhaust system	Catalytic purifier and muffler with Proventia thermal insulation system exhaust pipe
Average fuel consumption at 40% load	26 l/h
Fuel tank refill capacity	280 l

CONVERTER

Dana C5472	With lock-up
------------	--------------

TRANSMISSION

Power shift transmission with modulation	Dana transmission with automatic gear shift control, four gears forward and reverse
--	---

AXLES

Front axle, spring applied hydraulic operated brakes. Fixed.	Kessler D102, limited slip differential
Rear axle, spring applied hydraulic operated brakes. Oscillating ± 8°.	Kessler D102, limited slip differential

TIRES

Tire size (Tires are application approved. Brand and type subject to availability)	18,00x25 L5S 28 ply
--	---------------------

OPERATOR'S COMPARTMENT

CABIN (Cabin option replaces the standard canopy)

ROPS certification according to EN ISO 3471

FOPS certification according to EN ISO 3449

Sealed, noise suppressed and over pressurized cabin with air conditioning and heating

Sound absorbent material to reduce noise

Laminated glass windows

Cabin mounted on rubber mounts to the frame to reduce vibrations

Air conditioning unit located outside the cabin to reduce noise inside the cabin

Cyclone pre-filter for A/C device

Adjustable joysticks

No high pressure hoses in the operator's compartment

Inclinometers to indicate operating angle

Emergency exit

Floor washable with water to reduce dust

Three-point contact access system with replaceable and colour coded handles and steps

12 V output

Remote circuit breaker switch

CANOPY (Standard)

ROPS certification according to EN ISO 3471

FOPS certification according to EN ISO 3449

Adjustable joysticks

No high pressure hoses in the operator's compartment

Inclinometers to indicate operating angle

Emergency exit

Floor washable with water to reduce dust

Three-point contact access system with replaceable and colour coded handles and steps

12 V output

Remote circuit breaker switch

OPERATOR'S SEAT

Low frequency suspension

Height adjustment

Adjustment according to the operator's weight

Padded and adjustable arm rests

Two-point seat belt

Fore-aft isolation (with cabin option)

Adjustable lumbar support (with cabin option)

Selectable damping (with cabin option)

8.9 Appendix 9: LHD LH208L

TECHNICAL SPECIFICATION SANDVIK LH208L

The LH208L is a 7.7 tonne capacity underground loader designed to work in low-profile mining applications. The small envelope size and turning radius enable easy navigation in confined spaces. The loader's low-profile design enables operation in mine sections with headroom as low as 1.8 meters.

The LH208L is equipped with Deutz BF6M2012C diesel engine, Dana transmission and Kessler axles. Control system allows easy trouble shooting and provides alarms and warnings on the display.

ROPS and FOPS certified operator's compartment provides protection for the operator, and efficient LED lights improve visibility. Proximity Detection System Interface for a third-party PDS is available as an option.

CAPACITIES

Maximum tramming capacity	7 700 kg
Break out force, lift	12 100 kg
Break out force, tilt	12 400 kg
Standard bucket	3.3 m ³

SPEEDS FORWARD & REVERSE (LEVEL/LOADED) WITH DEUTZ BF6M2012C

1st gear	4.1 km/h
2nd gear	8.3 km/h

BUCKET MOTION TIMES

Raising time	4.0 sec
Lowering time	3.0 sec
Dumping time	3.7 sec

OPERATING WEIGHTS

Total operating weight	20 800 kg
Front axle	9 300 kg
Rear axle	11 500 kg

LOADED WEIGHTS

Total loaded weight	28 500 kg
Front axle	20 800 kg
Rear axle	7 700 kg



OPERATIONAL CONDITIONS AND LIMITS

Environmental temperature	From -20°C to +50°C
Standard operating altitude	Below 2 500 m

REQUIREMENTS AND COMPLIANCE

Compliance with 2006/95/EC Low voltage directive
Compliance with 2004/108/EC Electromagnetic compatibility directive
Design based on EN 1889-1, Machines for underground mines. Mobile machines working underground. Safety. Part 1: Rubber tyred vehicles.
Electrical system based on IEC 60204-1, Safety of machinery – Electrical equipment of machines – Part 1: General requirements

POWER TRAIN**ENGINE**

Diesel engine	Deutz BF6M2012C
Output	140 kW @ 2 500 rpm
Torque	671 Nm @ 1 500 rpm
Number of cylinders	In-line 6
Displacement	6.06 l
Cooling system	Liquid cooled
Combustion principle	4-stroke, turbo with intercooler
Air filtration	Two stage filtration, dry type
Electric system	24 V
Emissions	Tier 2, Euro Stage II
Exhaust system	Double wall exhaust pipe with catalytic purifier/muffler
Average fuel consumption at 40 % load	15 l/h
Fuel tank refill capacity	200 l

CONVERTER

Dana SOH C 273

TRANSMISSION

Power shift transmission with modulation.	Dana SOH R32421, electrical gear shift control, two gears forward and reverse
---	---

AXLES

Front axle	Kessler D91, Spring applied hydraulically released brakes, no-spin differential, fixed
Rear axle	Kessler D91, Spring applied hydraulically released brakes, No-spin differential, oscillating

TIRES

Tire size (Tires are application approved. Brand and type subject to availability.)	17.5 x 25 24 PLY L5S
---	----------------------

HYDRAULICS

Filling pump for hydraulic oil
Door interlock for brakes and boom, bucket, and steering hydraulics
Oil cooler for hydraulic and transmission oil
ORFS and SAE fittings and hoses
Hydraulic oil tank capacity 200 l
Sight glass for oil level, 2 pcs

STEERING HYDRAULICS

Hydraulically operated, center-point articulation, power steering with two double acting cylinders. Steering controlled by electro-hydraulic joystick. Interlock protection.

Steering main valve	Open center type
Steering hydraulic cylinders	100 mm, 2 pcs
Steering pump	Gear type
Steering and servo hydraulic pumps	No additional steering pump or separate servo hydraulic pump

BUCKET HYDRAULICS

Joystick bucket and boom control, equipped with gear pump that delivers oil to the bucket hydraulic main valve.

Boom system	Straight boom
Lift cylinders	180 mm, 2 pcs
Dump cylinder	160 mm, 1 pc
Main valve	Open center type
Pump for bucket hydraulics	Gear type

BRAKES

Service brakes are spring applied; hydraulically released multidisc wet brakes on all wheels. Two independent circuits: one for the front and one for the rear axle. Service brakes also function as an emergency and parking brake. Brake system performance complies with requirements of EN ISO 3450, AS2958.1 and SABS 1589.

Neutral brake
Automatic brake activation system, ABA
Electric 2.2 kW emergency brake release pump

OPERATOR'S COMPARTMENT**CANOPY**

ROPS certification according to EN ISO 3471
FOPS certification according to EN ISO 3449
Adjustable joysticks
No high pressure hoses in the operator's compartment
Inclinometers to indicate operating angle
Emergency exit
Floor washable with water to reduce dust
Three-point contact access system with replaceable and colour coded handles and steps
Remote circuit breaker switch

CONTROL SYSTEM, DASHBOARD AND DISPLAYS

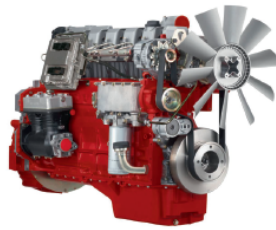
Critical warnings and alarms displayed as text and with light
Instrument panel with 5.7" display, adjustable contrast and brightness and illuminated switches

8.10 Appendix 10: LHD TCD 2013 Tier III Engine – New Mine implementation plan

TCD 2013

For mobile machinery 74.9 - 243 kW | 100 - 325.9 hp at 2100 - 2300 min⁻¹ | rpm
EU Stage IIIA / US EPA Tier 3

- Water-cooled 4 and 6-cylinder inline engines with turbocharging and charge air cooling
- The powerful DEUTZ Common-Rail (DCR®) injection system and the electronic engine control (EMR 3) with intelligent link to the drive management ensure optimum engine performance at low fuel consumption.
- The 4-cylinder is also available with a mechanical injection system.
- Best cold starting properties even under extreme conditions.



- Low noise emissions due to acoustically optimized components with very smooth running and high durability.

- The compact engine design and three PTO drive possibilities integrated into the gear drive reduce the installation costs and increase the number of applications.
- Wet cylinder liners, long oil change intervals and easy changing of the engine fluids reduce the running and service costs and increase the availability of the machinery.
- The robust engine design allows world-wide operation even with high sulphur fuels.

Technical data

Engine type		TCD 2013 L4 2V ⁵⁾	TCD 2013 L4 2V	TCD 2013 L6 2V	TCD 2013 L6 4V
No. of cylinders		4	4	6	6
Bore/stroke	mm in	108/130 4.3/5.1	108/130 4.3/5.1	108/130 4.3/5.1	108/130 4.3/5.1
Capacity	l cu in	4.8 292.9	4.8 292.9	7.2 439.4	7.2 439.4
Compression ratio		18.1:1	18.1:1	18.1:1	18.1:1
Nominal speeds	min ⁻¹ rpm	2100-2300	2000-2300	1800-2300	2200

Power output ¹⁾		TCD 2013 L4 2V ⁵⁾	TCD 2013 L4 2V	TCD 2013 L6 2V	TCD 2013 L6 4V
Power output as per ISO 14396	kW hp	104 140	129 173	200 268	243 325.9
at speed	min ⁻¹ rpm	2200	2300	2300	2100
Max. torque	Nm lb/ft	565 416.7	670 494.2	1050 ⁴⁾ 774.4	1310 966.2
at speed	min ⁻¹ rpm	1600	1600	1500	1450
Minimum idling speed	min ⁻¹ rpm	900	650	650	800
Specific fuel consumption ²⁾	g/kWh lb/hph	218 0.358	208 0.342	205 0.337	204 0.335
Weight as per DIN 70020 Part 7A ³⁾	kg lb	500 1102	500 1102	610 1345	660 1455

1) Capacity data without deduction of fan capacity

2) Best full load consumption refers to diesel with a density of 0.835 kg/dm³ at 15°C | 6.96 lb/US gallon at 60°F.

3) Without starter/dynamo, cooler and fluids but with flywheel and flywheel housing.

4) 1100 Nm | 811.3 lb-ft with switched internal EGR (exhaust gas return).

5) Mechanical injection system

The data on this data sheet are for information purposes only and are not binding values. The data in the quotation is definitive.

The engine company.

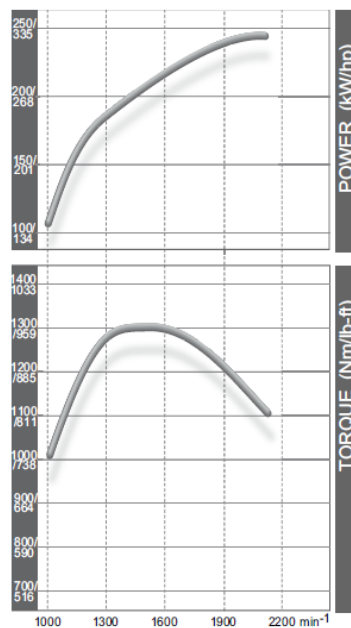
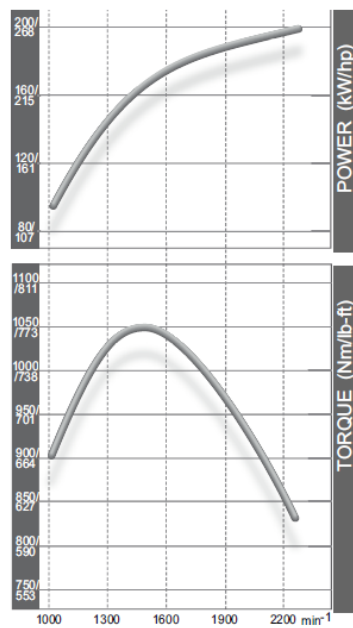
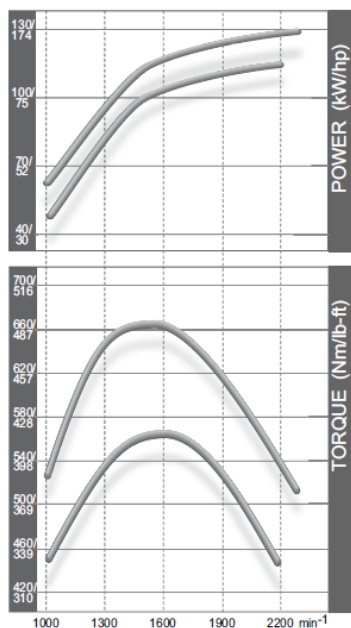


Torque curve

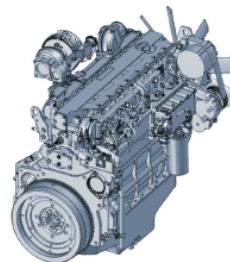
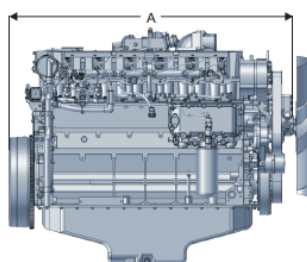
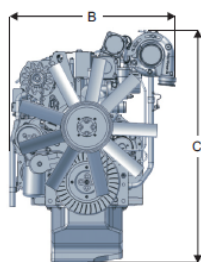
TCD 2013 L4 2V - 129 kW|173 hp
TCD 2013 L4 2V - 104 kW|140 hp

TCD 2013 L6 2V - 200 kW|268 hp

TCD 2013 L6 4V - 243 kW|325.9 hp
(2100 min⁻¹|rpm)



Dimensions



		A	B	C
TCD 2013 L4 2V	mm in	857 33.7*	638 25.1	870 34.2
TCD 2013 L6 2V	mm in	1154 45.4**	694 27.3	991 39.0
TCD 2013 L6 4V	mm in	1158 45.6**	703 27.7	974 38.3

* V-belt drive

** Poly-V belt drive

Note: The engine dimensions and weights vary depending on the scope of delivery.

Order No. 0031 2131 / 09 / 2011 / VC-CM

For more information please contact the DEUTZ AG Köln or the responsible sales partner.



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8.11 Appendix 11: Diesel Quality control sample for the fuel used in mine B (50 ppm)



FUEL SCREENING REPORT

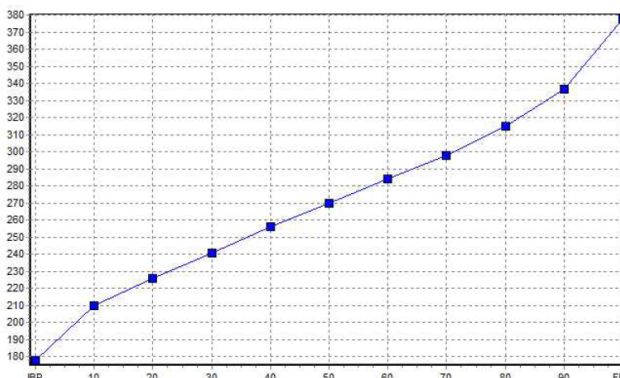


Customer	TOTALENERGIES		
Customer Address	P O Box 579, Saxonwold		
Site	Anglo		
Attention	Aluwani Ramaru		
Client	Anglo Modikwa		
Sample Number	1-SF007105	Unit ID	Meremsky - Nozzle
Container	1Litre Plstic Bottle	Sample volume	1LITRE
Date Sampled	15/08/2022	Date Received	22/08/2022
Product Type	Diesel 50ppm		

SAMPLE TEST RESULTS					
Sample test	Method	Test Date	Test Result	Test Units	Test Limits
Appearance	Visual	26/08/2022	Bright & Clear	Physical	Fail - Pass
Cetane Index	Calculation	27/08/2022	54		45 Min
Density @ 20	ASTM D4052	26/08/2022	0.8283	Kg/L	0.800 Min
Flash Point	ASTM D93	26/08/2022	65	C	55 Min
Free Water	Visual	26/08/2022	Nil	Physical	0 Max
ISO 4406	ISO 4406	26/08/2022	16/14/11	Class	
Total Contamination (IP440)	IP 440	27/08/2022	14	mg/Kg	24 Max
Viscosity @ 40	ASTM D445	27/08/2022	2.72	cSt	2.0 - 5.3
Visual - Colour	Visual	26/08/2022	Pale Yellow	Visual	
Water - KF	ASTM D6304	26/08/2022	46	ppm	350 Max

DISTILLATION (ASTM D86)

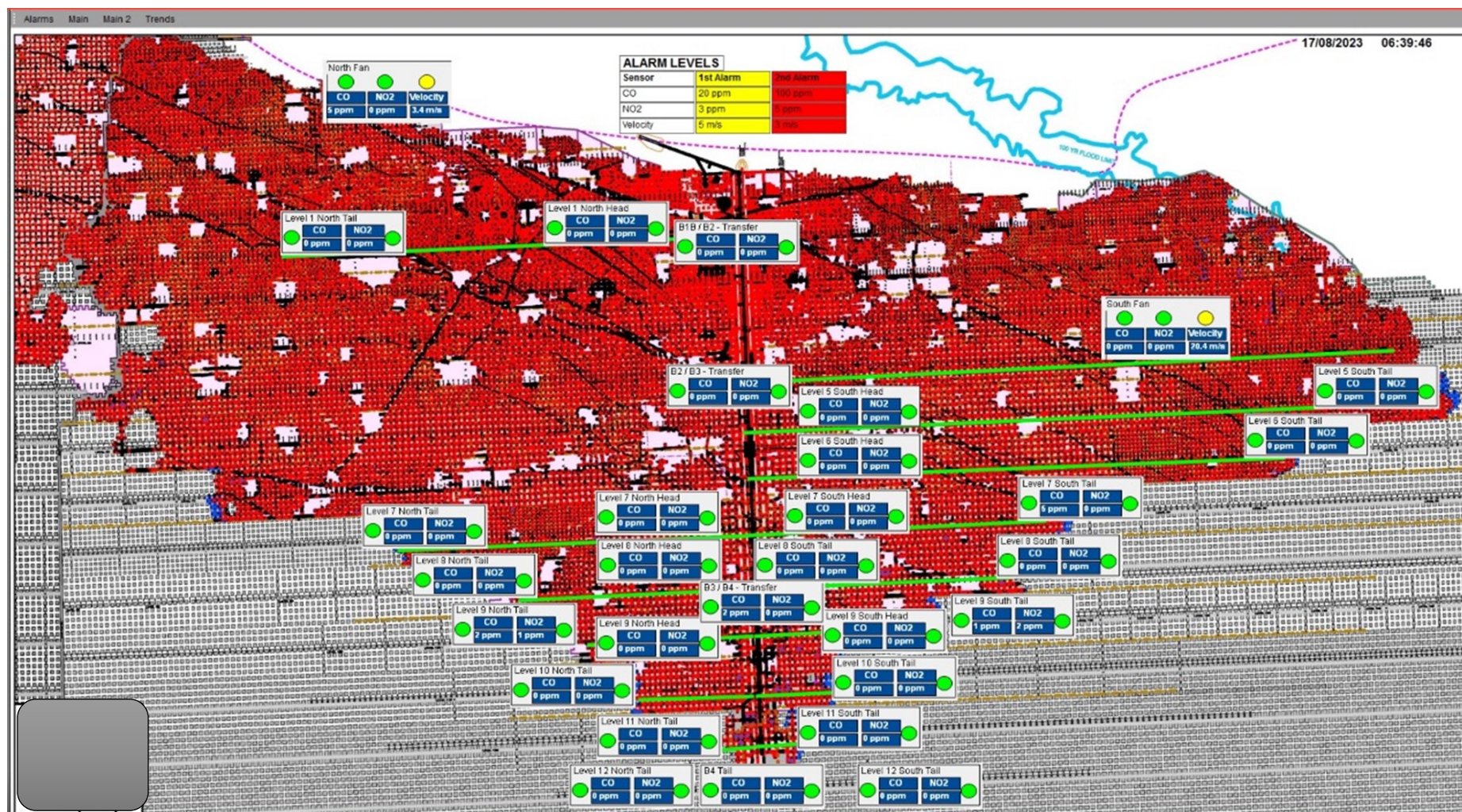
% Rec	Temp °C
IBP	178
10	210
20	226
30	241
40	256
50	270
60	284
70	298
80	315
90	337
FPB	378
% Recovery	99
% Residue	1



COMMENTS

Diesel sample analysed. Results comply with SANS 342:2016 specifications for tests conducted.

8.12 Appendix 11: SCADA Real Time Gas and Velocity Monitoring System



8.13 Appendix 13: Turnitin Report



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