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Title: Effects of retrofit diesel particulate filters on diesel particulate emissions: a small-scale

intervention study

RESEARCH REPORT

by

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Declaration

I, Ludwick Tshogofatso Lebaka (student number: 1588764), declare that the research project entitled “Effects of retrofit diesel particulate filters on diesel particulate emissions: a small-scale intervention study” is my research work undertaken under the supervision of Prof Derk Brouwer. The work is being submitted in partial fulfillment for the degree of Master of Medicine in the field of Exposure Science at the School of Public Health, University of the Witwatersrand, Johannesburg. This work has not been presented for examination at any other university. The author designed the study, carried out all field data collection, data analysis, and writing the research report. All the sources cited in this study have been acknowledged through comprehensive references. The senate plagiarism policy is signed and attached as an **Appendix A: Plagiarism Declaration Form**.

Dedication

I dedicate this work to my late grandparents. You believed in me when no one did and through your words of encouragement, I pushed against all odds. I am because you were. The value of hard work, perseverance, and commitment you instilled in me did not go to waste. To my selfless supportive family and friends, I thank you.

Abstract

Diesel Particulate Matter (DPM) is a significant health hazard in the workplace, particularly in underground mining (UG) settings where diesel-powered machines are utilized for production purposes. Achieving a considerable decrease of DPM exposure in the workplace relies widely on the ability of the industry to apply tried and tested diesel emissions control technologies, in particular the use of diesel particulate filters (DPF) systems. This research report explores the effectiveness of installing and using retrofit DPFs in reducing tailpipe DPM emissions of an existing fleet of diesel-powered machines used in an UG platinum mine in Limpopo, South Africa. In-depth engine exhaust emissions were carried out on 10 trackless mobile machineries (TMMs) fitted with *Wall-flow* Active regenerating DPFs. Each evaluation was carried out in a stationery mode in the UG workshop whilst the vehicle engine was idling and revving. The data obtained were used to illustrate the effects of DPF systems on exhaust emissions, regeneration, particle size distributions, and the effects on personal DPM (Elemental Carbon-EC) exposures. Significant reductions as a result of the DPF system on mass (mean 84%) and particle number concentration (mean 97%) were achieved. In terms of particle size distribution, both pre and post DPF measurements were similar in shape owing to majority of particles were saturated around the 0.1 μm region. However, the number concentration differed significantly. Personal exposure to EC were also significantly ($P < 0.0001$) reduced with a before and after intervention 90th percentile of 338 and 16.7 $\mu\text{g}/\text{m}^3$ respectively. The outcomes of this study were able to demonstrate the benefits of using aftertreatment devices to control diesel exhaust emissions at the source in order to influence concentrations along pathway and at the receptor.

Acknowledgments

Throughout the journey of this research study, I have received a great amount of support and assistance. I am therefore indebted to several individuals who have made this study possible. My supervisor Professor Derk Brouwer, whose expertise were invaluable from the protocol development stage till to the end. Your insightful feedback pushed me to sharpen my thinking and brought my work to a relatively higher level. I want to take this opportunity to thank you for your time, efforts, guidance, and dedication to seeing this project succeed. I wouldn't have done this without you, may God bless you.

To Amu Mudau, thank you very much. From lending me your equipment, availing yourself whenever I needed your assistance and generally supporting me through the process. All your efforts didn't go unnoticed – thank you.

To my colleagues Angelique Trollip, Mothusi Buthelezi, Cynthia Phetlhe, Martin Lebea, and Pule Sephai, none of this was going to be possible without your assistance, thank you and may God bless you.

To my current employer, thank you for the time off and financial support.

Abbreviations

AM	Arithmetic Mean
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DE	Diesel Exhaust
DEE	Diesel Exhaust Emissions
DEEP	Diesel Emissions Evaluations Program
DPFs	Diesel Particulate Filters
DPM	Diesel Particulate Matter
EC	Elemental Carbon
GM	Geometric Mean
GSD	Geometric Standard Deviation
IARC	International Agency for Research on Cancer
kW	Kilowatt
LHD	Load, Haul, Dump
MHSA	Mine Health and Safety Administration
NIOSH	National Institute for Occupational Safety and Health
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide

NOx	Oxides of Nitrogen
OC	Organic Carbon
OEL	Occupational Exposure Limit
OEM	Original Equipment Manufacturer
PM	Particulate Matter
ppm	parts per million
SAMI	South African Mining Industry
SD	Standard Deviation
SANAS	South African National Accreditation System
TMM	Trackless Mobile Machinery
UG	Underground

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CHAPTER 1: INTRODUCTION

1.1 Background

Diesel-powered equipment used underground (UG) are powerful, robust, long-lasting, and consume less fuel compared to other fuel-powered equipment. Another added advantage is that mechanized mining equipment provides a safer working environment, however, diesel exhaust emissions (DEE) are of concern to the health of employees. Exposures of UG metal/nonmetal miners to Diesel Particulate Matter (DPM) as part of the DEE, are significantly higher than those of any other occupation. (1) Studies conducted by the mine health and safety administration (MHSA) between 2002 and 2005 showed that miners were exposed to DPM concentrations as high as 3300 $\mu\text{g}/\text{mg}^3$. (2)(3) Exposure in the South African mining industry (SAMI) is of a particular concern because at times DPM air concentrations are much higher than environmental levels, even exceeding concentrations as high as 2000 $\mu\text{g}/\text{m}^3$, which is a thousand times higher than a typical environmental level.(4) High emission levels may be attributed to the age of engine, diesel particulate filters (DPFs) used, fuel type, frequency of maintenance, whereas resulting levels of exposure will also be determined by the number of machines in the area and ventilation requirements.(3)

DPM consists of fine particles of less than 2.5 μm in diameter, including a subgroup with a large number of ultrafine particles with a diameter of less than 0.1 μm .(5) Long-term exposure to combustion-related fine particulate pollution is perceived as an important risk factor for cardiopulmonary and lung cancer mortality.(6) In 2012, the International Agency for Research on Cancer (IARC) classified diesel exhaust as being carcinogenic to humans (class I) by inhalation.(7)

SAMI has since been working on identifying technically and economically feasible strategies and phase-in plans to reduce exposures to diesel particulate matter emitted by diesel-powered equipment underground. The current obstacle however is that there is/are no legislation regulating exposure to DEE.

The Mine Health and Safety Council and the Mining Occupational Health Advisory Committee have come

up with “phased-in” approaches with the aim at reducing exposure levels. To date there is no compliance regulated measures in place. However, in the absence of exposure limits nationally, reference can be made to international standards as means of best practice. Also, employers are still obligated to protect the health and safety of employees as legislated under section 11 of the Mine Health and Safety Act 29 of 1996. This section states that risk assessments must be conducted, and the employer must ensure that measures are put in place to protect employees from overexposure from airborne pollutants.

Currently within the South African mining industry, the use of low sulphur fuel, normal/specific maintenance, ventilation (dilution) and administrative controls are some of the measures widely used to control DPM exposure but may not be limited to the aforementioned. Typically, exposure to DPM for UG mine employees may be reduced or controlled with use of the following fundamental methods. The first method would be to reduce the DPM emissions at the source (engine maintenance, the use of reformulated fuels and exhaust filtration), that is by controlling combustion products before they are released from the tailpipe.⁽⁸⁾ The second method would be to ensure sufficient volumes of dilution air are available where people travel and work or within ventilation districts [section of a mine with an independent intake and return airway]. The third method would be to limit the number of diesel powered equipment allowed within a given volume of ventilation air for effective dilution.⁽¹⁾⁽⁸⁾ Ventilation by means of dilution in this case will only be able to reduce exhaust emissions after they have been released into the mine air.

The purpose of this study was focused on the first approach, i.e. control at the source using aftertreatment technologies (i.e. Installation of retrofit DPFs). It is important to note that the study population (Tier 3 diesel-powered equipment) was fitted with catalytic converters, with no form of particulate filtration.

1.2 Literature Review

1.2.1 Diesel Exhaust Emissions

Diesel Exhaust (DE) is normally the term used for what is exhausted from a diesel-powered engine after combustion. (9) DE contains a mixture of complex gases as well as particulates, and these gases include but not limited to CO₂, CO, Sulphur dioxide, Nitrogen, and their various oxides i.e. NO, NO₂ and NO_x. (10)(1) The other component is the particulates (DPM), which mainly result from incomplete combustion of the hydrocarbons in the fuel and lube oil. (11) The particle fraction comprises of insoluble elemental carbon (EC) core and an adsorbed surface coating of relatively soluble organic carbon (OC). The EC and OC is reported to vary between 33-90% and 7-49% of the particulate mass respectively. (10)(12)

1.2.2 Diesel Particulate Filter Systems

DPF systems are endorsed as an effective technology for removing particulate matter from the exhaust of diesel-powered equipment.(13) DPF systems can capture the solid fraction of diesel exhaust, including EC, at high efficiencies, allowing the exhaust gases to pass through the system. A complete DPF system consists of the filter and a process to regenerate the filter. The non-solid fraction of diesel exhaust, including the soluble organic fraction and sulphates, are captured at much lower efficiencies or not at all. (14) However, the efficiency of a DPF in the removal of non-solids from the exhaust stream can be enhanced by adding a catalytic converter. Installations of a DPF system also require instrumentation for monitoring the exhaust gas back pressure due to build-up of soot/ash.(3)

In their studies, Bugarski et al(2) demonstrated that DPF systems with cordierite and silicon carbide wall flow monolith filter elements are capable of reducing concentrations of DPM and elemental carbon (EC) in UG mine air by more than 70% and 90%, respectively. DPF systems have also shown to have effects on exhaust emission mass and particle number concentrations.(15) In a recent industry wide collaborative

project (9) within SAMI context, DPF systems were proven to reduce diesel particulate tailpipe emissions between 60 and 90%.

1.2.3 Diesel Particulate Filter Systems – Regeneration

DPFs physically filter or trap the particulate matter (PM) generated from the engine. The filter is designed in such a way that it allows the gaseous component to pass through yet remaining impervious to collect the PM. As the filter becomes saturated with soot, a layer of soot is generated on the surface of the filter channel walls. The soot layer provides a highly efficient surface filtration for the following operation. However, excessive build-up must be averted as it may / will have an impact on fuel consumption, the engine and filter complications as a result of increased back pressure.(11)

Therefore, to avert build-up of soot, the DPFs provide a means for regeneration in order to restore the filter back to its soot collection capacity. This process of removal can be achieved either continuously (passive regeneration) during normal operation of the engine or periodically (active regeneration), after a pre-determined level / limit (about 45%) of soot loading on the filter has been accumulated. (11)(14) Both the abovementioned means of regeneration do not require input from the vehicle operator. The process occurs automatically.

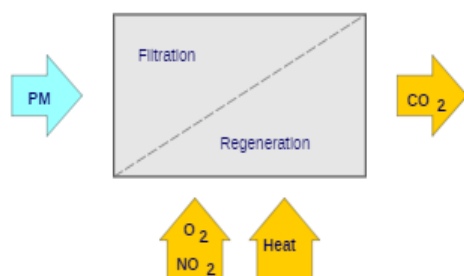


Figure 1: The concept of particulate filter regeneration(14)

1.2.4 Diesel Particulate Filters – Active Regeneration

Active regenerating DPFs uses a catalyst/fuel additive added in the fuel tank during operation and/or the electrical heaters integrated in the DPF unit. The fuel additive in addition to the electrical heaters, allow the DPF to actively incinerate, or regenerate the trapped soot/DPM under at almost any engine operating point, irrespective of the exhaust gas temperature. If the required exhaust gas temperatures ($\pm 400^{\circ}\text{C}$) are not reached to activate auto regeneration, the unit's thermoelectric (i.e. electrical heaters) regeneration function gets introduced.

1.3 Problem Statement

Improving the safety of UG employees by reducing their exposure to hazards has been a major driver behind the increasing prevalence of mining mechanization.(9) This initiative has in recent years proven to be a problem worldwide. The problem is attributed to the challenge of diesel exhaust emissions from the diesel-powered machines being used. As alluded in the introduction, there is lack of legislation in the South African context necessary to regulate emissions and exposure to UG miners. These diesel machines can be eliminated by deploying electrical equipment but since the machines are still in use due to their robustness, high reliability and low fuel consumptions, industry health and safety professionals are tasked with a mammoth task to come up with interventions to reduce workplace airborne levels of diesel exhaust emissions and thus subsequently protecting employee health. Industries must therefore look into investing in proactive interventions to reduce DPM emissions. One primary significant intervention of reducing airborne levels of diesel exhaust of UG employees is to reduce the amount of emissions from the engine.(8) Post implementation of intervention(s), one may probe effectiveness. Therefore, this study aims to evaluate that.

1.4 Research Question

Will the retrofitting of diesel particulate filters on diesel-powered trackless mobile machinery reduce diesel particulate emissions?

1.5 Hypothesis

The post installation effects of retrofit DPFs will significantly reduce DPM emissions.

1.6 Aim

To determine whether the installation of retrofit DPFs will significantly reduce DPM tailpipe emissions of diesel-powered trackless mobile machinery (TMM).

1.7 Objectives

To achieve the aim of the study, the following specific objective has been set:

- To measure DPM tailpipe emissions of trackless mobile machinery before and after routine maintenance to determine the variability of the DPM emission.
- To measure DPM tailpipe emissions of trackless mobile machinery after installation of retrofit DPFs.
- To determine the effectiveness of the retrofit DPFs in reducing tailpipe emissions.

CHAPTER 2: METHODOLOGY

2.1 Study Area and description

The study was conducted at an UG platinum mine in Limpopo utilizing trackless mobile machinery (Load, Haul and Dump Trucks (LHD), Drill rigs and Roof bolters). The tailpipe measurements took place at the UG workshop where maintenance of the machines is taking place.

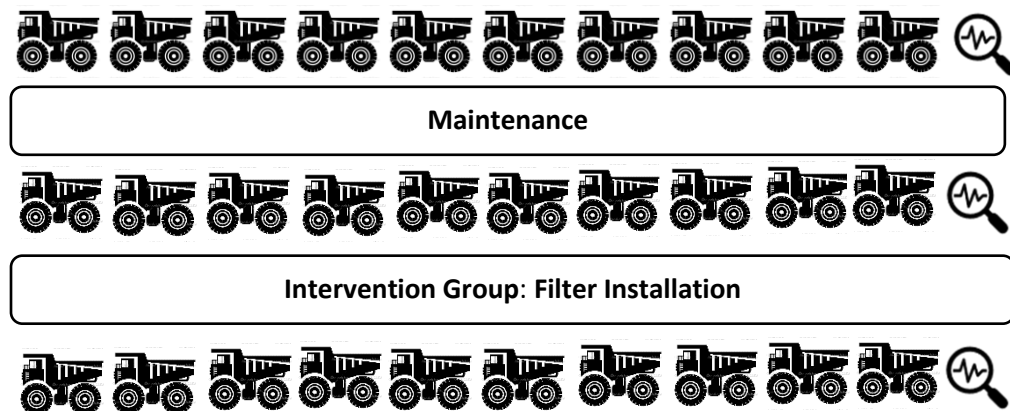
2.2 Study Design

This quantitative study is a quasi-experimental study design with an intervention component. The intervention approach focused on evaluating the direct impacts of the filtration system to lower the engine emissions. The DPM emission was characterized by the cumulative (5min) particle concentration over the 14 size bins of the particle monitor.

2.3 Sample size

- The selection of the machinery was based on the available fleet and equipment for fitment of DPFs. As part of the protocol development stage, 9 (nine) machines were selected for assessment of which 3(three) formed the control group. However, this could not be done. A risk assessment based on high emissions emitting machineries was conducted by the mine and a decision was made to retrofit all machinery. This process led to the 10 (ten) that was assessed.

The measurements and analysis followed the below sequence:



- In the protocol development stage, G*power (<https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower>) was used to calculate the required sample size given an assumed effect size of the dependent variable, i.e. the DPM emission expressed as total particle number concentration. For a minimum of 6 repeated samples and a power of 0.8, it was calculated that one would detect an effect of > 1.1 which is considered a significant effect.(16) The G*Power calculations are presented in ANNEXURE C.

2.4 Inclusion/Exclusion criteria

The study was conducted at the UG platinum mine workshop where the researcher is employed, which is situated in Limpopo. Only diesel operated equipment operating in this mine, i.e. TMMs (LHDs, Drill rigs and roof bolters), were evaluated.

2.5 Data collection methods and tools

2.5.1 DEKATI ELPI®+

Exhaust emissions expressed as total particle number concentration was quantified using a Dekati ELPI®+ (Electric Low-Pressure Impactor) real-time measuring instrument. No further chemical analysis of the particles were conducted to determine their chemical composition. 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 instrument is suitable for measuring tailpipe emissions, also considering high temperatures of particles when leaving the exhaust system. The ELPI detects particles over 14 size

bins in the range of 0.006-10 μ m and is equipped with a cyclone to control possible interference by larger particles.

The instrument consists of the following components:

- Impactor - ELPI[®]+ impactor is used for particle size fractionation.
- Charger - Corona charger placed on top of the impactor charges the particles before they enter the impactor
- Electrometers
- Zero air pump/flush pump
- Dekati double diluters for diluting samples
- Vacuum pump
- Pressure and temperature sensors
- Temperature controllers

Below is the working principle of the dekati ELPI[®]+

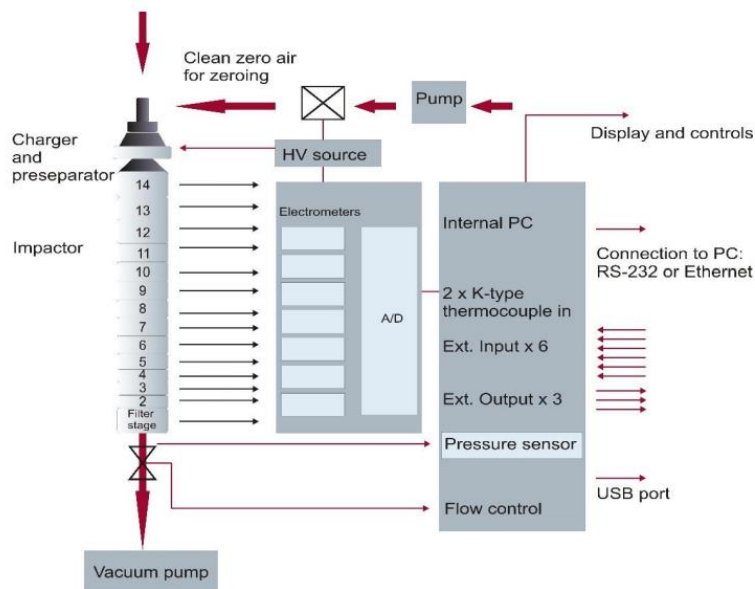


Figure 2: Operating principle of the ELPI[®]+ (17)

Instrument Use, Calibration and Sample Preparation

- Instrument was assembled at the underground workshop, where measurements took place.
- The device was switched on 30 minutes prior to a measurement to stabilize the electrometers.
- Leakage test was conducted to avert changes in the sample airflow, impactor operation pressures and particle cut-off diameters in the impactor stages. This is because the last stages of the ELPI®+ operate in low pressure, therefore failure to conduct it will cause errors in determining the aerosol size distribution and concentration.
- The impactor low pressure to was adjusted and set at 40mbar.
- Compressed air was connected to the unit (air conditioning system) and pressure set a 3 mbar. This was to ensure the residence time of particles in the instrument is minimal to allow accurate detection by the electrometers.
- Electrometer zeroing with zero air pump on and charger turned off was conducted. This process takes about 2 minutes and stops automatically. After this process, the electrometers are now calibrated, and the device is ready for making a measurement. The ELPI®+ control display will then show “system OK” message when the device is ready.
- The zeroing pump is switched off and the main vacuum pump is switched on. The flow rate of the vacuum pump is set at 10lpm.
- The ELPI®+ inlet is then connected to the desired sampling line/port.
- Air-zeroing/Flushing of the instrument after each measurement before commencing with the next vehicle/machinery was conducted.
- Each TMM was warmed up for a sufficient period before taking measurements.
- Each TMM was measured during idling and revving (on a transient cycle), and both modes were evaluated before the DPF system and after (Tailpipe).

2.5.2 Fuel Analysis

- Sulphur content has a significant impact on diesel exhaust emissions. Recent studies conducted have revealed that the use of low sulphur fuels promote cleaner exhaust emissions with 10% particulate matter emission reductions observed when switching from a diesel containing 500 ppm to 50 or 10 ppm. (9)

Therefore, in order to ensure validity, accuracy of our results and, to confirm that the diesel type used at the mine is the same Sulphur parts per million (ppm) content throughout the data collection period, fuel/diesel samples were taken both on the surface and UG storage tanks with 60ml containers prior to commencing with measurements. Samples were then sent to an approved SANAS accredited laboratory for analysis (Annexure E: Laboratory Fuel Analysis Report).

2.5.3 Objectives

Objective 1

- The pre and post maintenance emission measurements could not be done. However, the following were recorded and are discussed in the report to determine the maintenance-affected variability of the 'raw exhaust/ prefilter' engine DPM emissions:
 - Type of TMM and kW rating
 - Machine hours at the time of measurement.
 - Operational hours from last maintenance (Major Service 1000hrs).
 - Both the above recorded hours were used to determine the number of hours post the TMM maintenance.
 - Pre-filter (raw exhaust) particulate concentrations were used to determine variability of engine DPM emissions.

Objective 2

- All measurements were collected before (raw engine exhaust DPM) and after (filtered DPM) the diesel particulate filter.
- The selected TMMs (10) were planned to undergo tailpipe measurements at the workshop before and after routine maintenance is conducted (i.e. objective 1). This includes that two repeated samples were taken for each TMM during revving (on a transient cycle) and idling mode. Each test mode was supposed to be conducted for a minimum period of 10 minutes (adopted from the Mine Health and Safety Council – Methodologies for the measurement of DEE and DPM).(18) All measurements were also supposed to be collected at the exhaust discharge point of the tailpipe. However, this proved to be difficult as the instrument flashed “high concentrations” on the screen when taking pre-filter / raw exhaust DPM emissions. Therefore, avoiding clogging up the device, measurements were limited to 5 minutes each for both modes.

Objective 3

- Distributions of the data were determined
- Inference tests were used to determine and assess the effect of the intervention.

2.5 Data Analysis

Data generated and logged by the Dekati instrument was downloaded into an excel spreadsheet for analysis. The following statistical data analysis methods were carried out using MS Excel Analysis ToolPak:

- A multiple regression analysis was run to predict and evaluate the correlation between total particle concentration (dependent variable) and the independent variables; age the of the machine in hours, the number of hours since the last maintenance was carried out and the Power Rating as a categorical (binary) variable, respectively.

- (Paired) T-test (comparison of 'raw' and 'tailpipe' emission for each TMM was conducted to determine the efficacy of the DPF system in reducing tailpipe emissions (i.e., particle number and mass concentrations).
- A Students T test for independent samples was deployed to determine the significance of pre and post DPF system retrofitting on personal DPM exposure levels.
- In addition, Expostats (<https://expostats.ca/site/outils.html#Tool3>) was used to analyze pre and post retrofitting personal exposure data.

CHAPTER 3: RESULTS

3.1 Determination of the maintenance-affected variability of the 'raw exhaust/ prefilter' engine DPM emissions.

Since the introduction of diesel-powered machinery in the UG mining industry, a need for a good and specific maintenance protocol has been widely acknowledged. However, this recognition has always been met with hesitance to adopt or implement on the machinery used. This may/has mainly been attributed to lack of legislation within the SAMI to regulate diesel exhaust emissions. Nevertheless, the maintenance of diesel-powered machinery is and has proven to be an essential step in the reduction of DPM emissions, i.e. to reduce all combustion products before they are released from the tailpipe to the working environment. In this chapter we evaluate the effect of maintenance on the raw exhaust DPM emissions.

The population assessed/measured is under a specific maintenance protocol as stipulated below.

- At an interval of 250 operating hours the engine is serviced. The following is done:
 - ✓ Engine oil replaced.
 - ✓ Oil filters replaced
 - ✓ Diesel fuel filters replaced
 - ✓ Engine air filters replaced
- At an interval of 500 operating hours the engine is serviced as the above and the v-belts are replaced.
- At an interval of 1000 operating hours, the engine is serviced. The following additional activities take place (performed by the Original Equipment Manufacturer (OEM))
 - ✓ The fuel injectors are replaced
 - ✓ The valve clearance is set
 - ✓ DPF filters are cleaned

In the absence of baseline measurements (pre and post maintenance), the protocol was amended to determine maintenance affected variability of the raw exhaust / pre-filter engine DPM emissions. Total particulate concentrations of the pre-exhaust (idling and revving) were quantified using the DEKATI instrument. The characteristics of the trackless mobile machinery (TMM) included in the study are presented in Table 1 below:

Table 1: Characteristics of the trackless mobile machinery (TMM)

TMM#	Power Rating (kW)	Age (Hours)	No. of hours since last maintenance	Date of DPF system Installation	Date of measurement
1	140	2641	86	17-08-20	07-05-21
2	140	2115	89	19-08-20	18-04-21
3	140	2294	182	17-07-20	03-02-21
4	140	3211	113	17-07-20	12-05-21
5	140	2951	322	17-07-20	13-06-21
6	140	2011	217	17-07-20	18-04-21
7	74	870	21	08-10-20	13-06-21
8	74	506	213	08-10-20	03-06-21
9	74	506	307	08-10-20	13-06-21
10	74	1123	315	08-10-20	12-05-21

A form of an inferential statistics was used to evaluate the correlation within our set of data. A multiple regression analysis was run to predict the correlation of particle concentration as a proxy for DEE, by, the age of the machine in hours, the number of hours since the last maintenance was carried out and the Power Rating (Categoric). The model (Table 2) statistically significantly predicted the DEE $F(3, 7) = 50.1$, $p < 0.0001$, $R^2 = 0.955$. The Adjusted R-Square output indicates that 79.9% of the variation in total particle concentration is explained by the predictors, and 20.1% (100%-79.9%) of the variation is caused by factors other than those mentioned above. The Power rating demonstrated to be the only predictor ($p < 0.06$) that (almost) significantly affected the total particle concentration as compared to the other two variables. Therefore, only a higher kW rating of a TMM equated to higher emissions as explained by the coefficient. However, emissions in this study were not affected by hours after maintenance.

Table 2: Regression results (Dependent vs predictors)

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Kw Rating (cat	4.71822218	1.21414739	3.886037	0.006006	1.847219817	7.589224542	1.847219817	7.589224542
Hours at Last I	-0.0009038	0.005198405	-0.17385	0.866903	-0.01319603	0.011388522	-0.013196027	0.011388522
Age	0.00328147	0.004871334	0.673628	0.522161	-0.00823741	0.01480034	-0.008237409	0.01480034

3.2 Comparison of Pre and Post filter engine DPM emissions

DPF systems are considered as one of the effective technologies in reducing diesel particulate emissions of diesel-powered machines utilized in UG settings. The efficiency of the DPFs, as per the manufacturer's specification, is claimed to be 99%. This paragraph evaluates whether the installation of retrofit DPFs significantly reduced DPM tailpipe emissions of the already existing fleet of diesel-powered TMMs. The Pre (Raw exhaust) and post (Tailpipe) filter measurements of each TMM (n=10) were taken, and total particulate concentrations were quantified. Paired T-test using total particulate concentration log-values (dN/dlogDp) were used to determine whether differences between the pre and post DPF results were significant or not.

The results (pre and post DPF) show a statistical significant difference (p value is <0.003). According to the efficacies calculated, the DPF system achieved an average filtration efficiency around its design claims of around 97% (AM) and a SD of 4 for total particle concentration. The filtration efficiencies ranged from 87 – 99.9% (Figure 2).

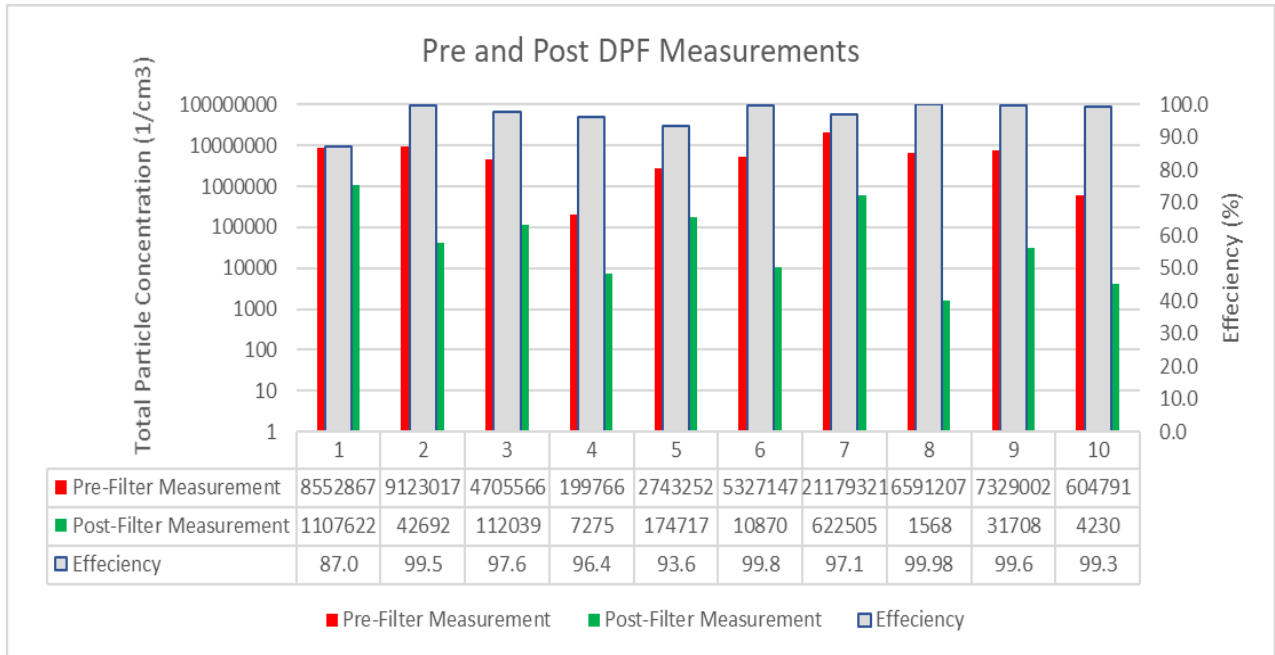


Figure 3: Pre and Post DPF total particle concentration

3.2.1 Particle Size Distribution

The results of the Particle size distribution measurements were performed with the same instrument (DEKATI) real time monitor and are summarized in Figure 3 below. The illustrated are normalized particle number concentrations of the various size bins, with the left and right panel depicting size distributions for pre and post DPF system respectively. For both pre-post DPF system measurements, it can be observed that particles emitted are both in the nucleation (<0.05µm) and accumulation modes (>0.05µm) with majority of the particles (mode) are concentrated around the 0.1 µm region (aerodynamic size). This is further explained by the GM, GSD and percentage reductions per size bin calculated; the pre DPF GM is 0.08µm, GSD of 1.5, and the post DPF GM is 0.09µm with a GSD of 1.7. Significant reductions ranged from 87-98% and were observed between 0.01 and 0.75 µm size bins, which is where majority of the particles are concentrated. Filtration efficiencies per size bin were similar in all the TMMs.

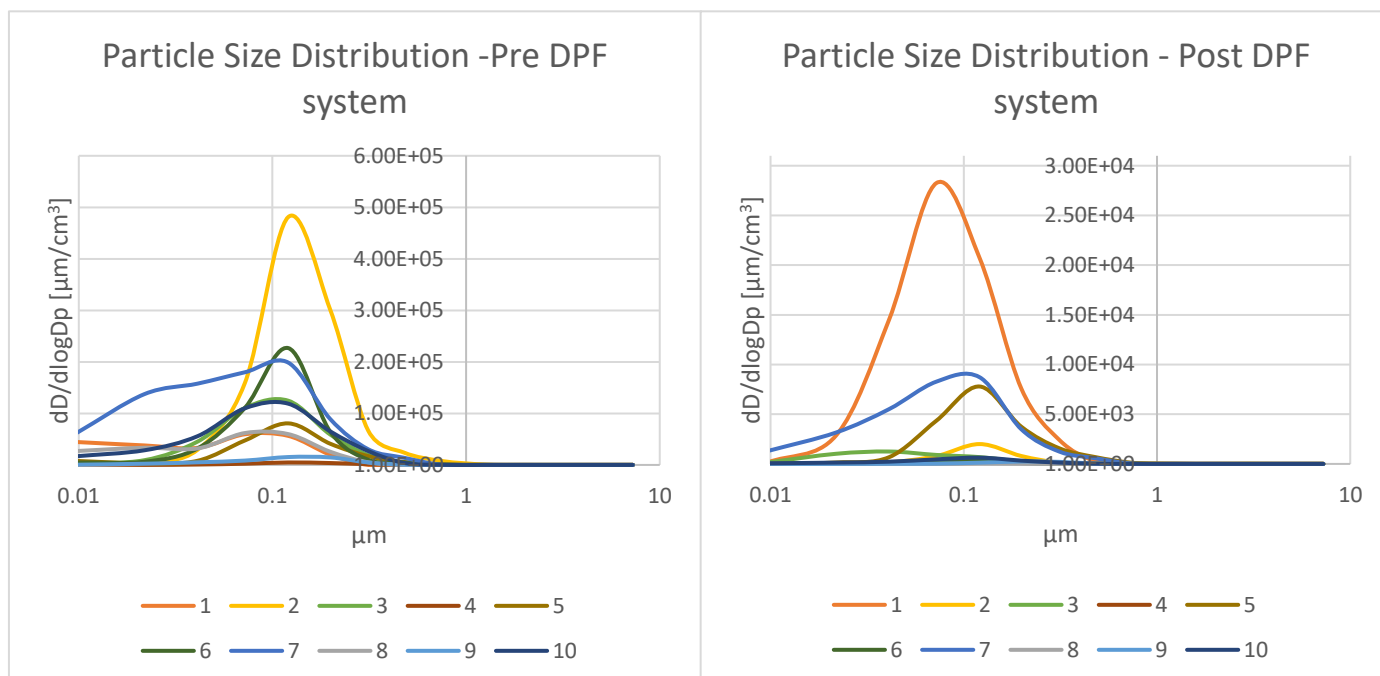


Figure 4: Particle Size Distributions (PSD). The left panel shows the PSD of the ‘raw’/ pre-filter exhaust for the 10 TMMs, whereas the right panel shows the PSD of the post-filter exhaust.

3.2.2 Mass concentration

Here it is interesting to see, whether the total Mass concentration is often dominated by larger particles. In Figure 3 above, it is observed that both pre and post measurements show the largest number of particles in the sub-micron range (nanoparticles). Therefore, to better quantify and explain the effect of particles on mass concentration, a Paired T-test was deployed to determine the statistical significance of pre-post DPF system mass concentration. The pre and post DPF system GM of the mass concentration of the mass concentration were 0.6 mg/m³ and 0.03 mg/m³ respectively, which indicates a significant difference (p value < 0.02). The DPF system achieved an average filtration efficiency of around 84% (AM), 95% CI [69.1, 98.9] and a relatively large SD of 24%), which is attributed by the low efficiencies observed in TMM 1 and 4 (Figure 4). Both TMMs showed already a relatively low pre-DPF mass concentration compared to the other TMMs. Though the mass concentration efficiencies show a statistically significant

reduction, there is however a 13% efficacy difference from the results observed based on the total particle concentration efficacies.

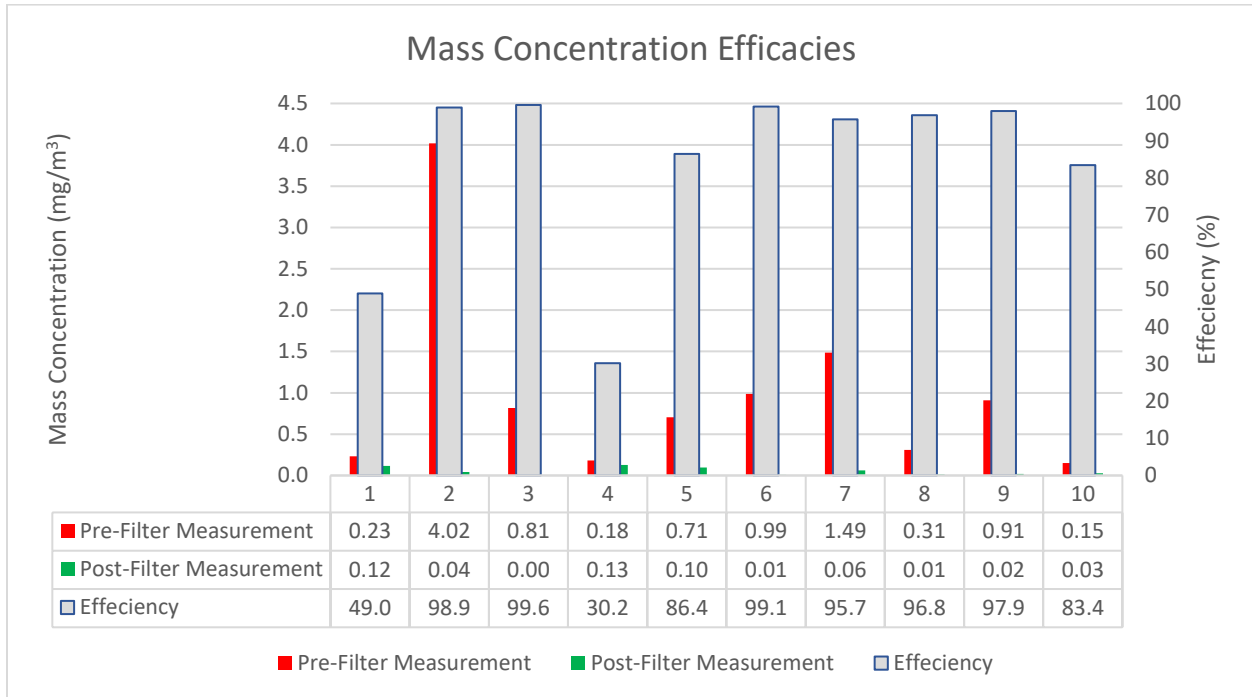


Figure 5: Mass Concentration efficacies

3.3 Performance and effectiveness of the DPF regeneration process during Cold and Hot start

According to the manufacturer’s specifications, the installed or retrofitted active regenerating DPFs uses electrical heaters integrated into the DPF unit as a backup to when the required ($\pm 400^{\circ}\text{C}$) exhaust gas temperatures are not reached to activate auto regeneration. Under normal operating conditions, the fuel additive along with the electrical heaters, allow the DPF to actively burn off the trapped soot at almost any engine operating point. To this effect, we measured the raw exhaust and tailpipe DPM emissions of **one** TMM 4 when the engine was cold and hot. Both temperature modes were evaluated against each other to determine the effectiveness of the DPF to actively incinerate the soot trapped in the DPF chamber. The results showed that the efficiency of the DPF in reducing the total number of particles generated is reduced when the engine is cold (71.5%) compared to when it is hot (96.4%).

3.4 Personal DPM Exposure

Exposure to DPM is a significant health hazard for employees working in a section UG utilizing diesel-powered trackless mobile machinery. Various DPM reduction strategies have been widely recommended and used globally and within the SAMI to control exposure. They include maintenance, reformulated fuels, aftertreatment technologies, ventilation, and administrative controls. In this chapter we evaluate whether aftertreatment technologies (DPFs) did have an effect (directly or indirectly) on the levels of personal elemental carbon (EC) samples taken within the same mine where the intervention occurred.

Occupational exposure limit for EC is 100 ug/m^3 , this was adapted from the Australian standard as there is no legislation within the SAMI governing DPM exposure. A secondary analysis of data with a total $n=172$ of personal samples which were carried out over a period of a year as per the NIOSH (National Institute for Occupational Safety and Health) 5040 method and analysis of elemental carbon (EC) was conducted by a SANAS accredited laboratory. The occupations sampled were TMM operators (LHD, Roof bolters & Drill Rig), diesel mechanics, general workers, and rock drill operators amongst others. The samples used were taken from, 2019 August – 2020 August [Before] until December 2020 [After]. The period “after” was when more than 70% of the fleet were fitted with DPFs. A Student’s t-test for independent samples was used for statistical analysis of the data, see Figure 5 below. The 90th percentile was also calculated for the before and after personal samples. This calculation is a requirement by the Department of Mineral Resources and Energy for the SAMI to determine exposure risk of a homogenous exposure group and compliance testing.

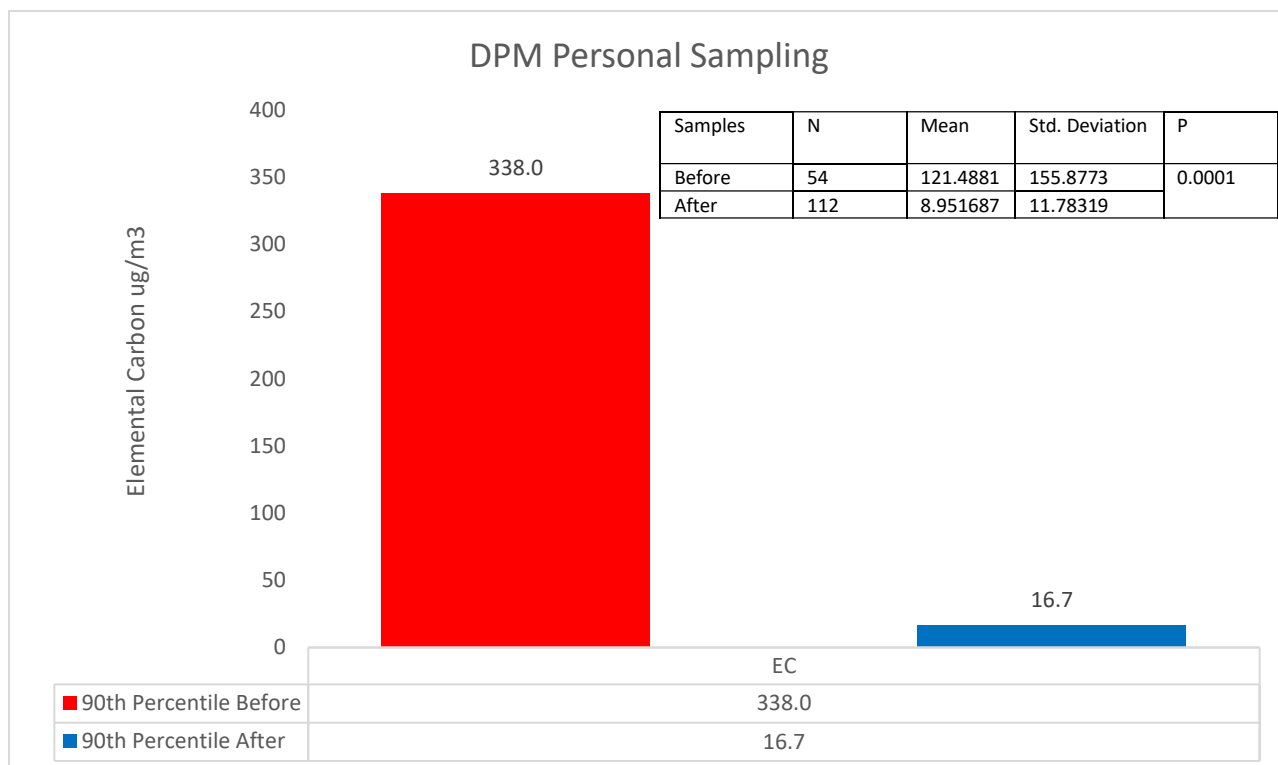


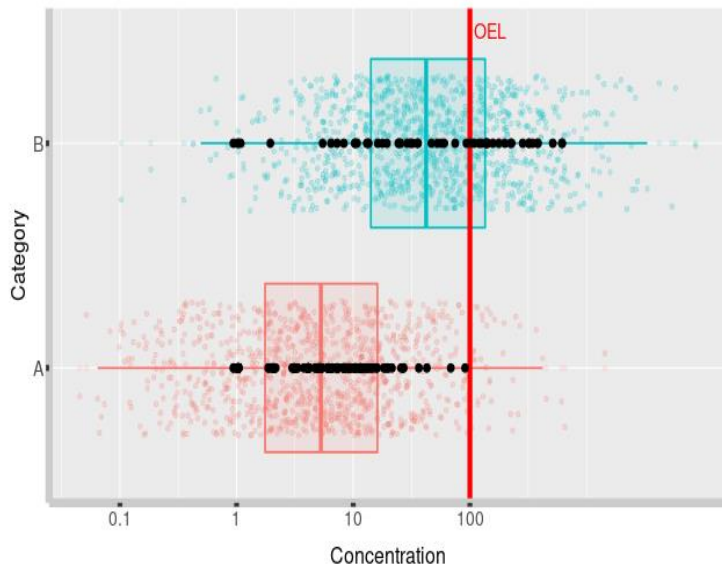
Figure 6: DPM Personal Sampling (90th percentiles of Before and After installation of DPF system)

The normal distribution plot indicated, however, that the data was not centrally distributed around the mean. Therefore, further data analysis was carried out using a form of an inferential statistics (Expostats Tool 3), a Bayesian prediction model) which is widely accepted by the occupational hygiene community as being the statistical analysis tool of choice for analyzing occupational hygiene data. The Box-plots of the concentrations are shown in Figure 6, whereas the results of the statistical analysis are presented in Table 3.

Table 3: Analysis comparing the different EC-personal air sampling results (*B-Before DPF Installation*A-After DPF Installation)

Parameter	B	A
GM (95% CI)	43 [29-63]	5.5 [4.8-6.4]
GSD (95% CI)	5.6 [4.4-7.6]	2.7 [2.4-3]
Exceedance fraction (%) (95% CI)	31% [23-40]	0.15% [0.045-0.44]
Percentile95 (95% CI)	720 [430-1400]	28 [22-35]
Percentile95_Upper Credible Level (UCL)	1200	33
Arithmetic mean (95% CI)	190 [110-380]	8.9 [7.5-11]

The GMs of 5.5 and 43, with GSDs of 2.7 and 5.6 respectively, show that the personal EC concentrations during the period after the DPF installation (A) were significantly less variable compared to the period before the installation (B). The period B also showed a larger portion of EC concentrations above the OEL (exceedance 31%) compared to prior the DPF installation (exceedance 0.15%). This analysis clearly illustrates the significant impact of DPFs in reducing personal exposure concentrations to DPM. The upper



credible limit of the 95-percentile (Percentile95_UCL) of the exposure values after the intervention period (category A) is far below the OEL, indicating that the exposure is adequately controlled and suggesting that the intervention was effective.

Figure 7: Box and Whisker Plot - Personal DPM Sampling (Before and After Intervention)

CHAPTER 4: DISCUSSION

4.1 Maintenance

A significant contributor to UG ambient conditions is the tailpipe emissions from diesel-powered equipment. In real-world situations, it is evident that exhaust DPM emissions from the engine will be significantly influenced by the kW rating of the TMM, and it is speculated that the maintenance protocol applied, as well as the age of the machine will also determine the emission. Comprehensive studies on the relationship between diesel engine maintenance and diesel exhaust emissions by McGinn under a research effort by the Diesel Emissions Evaluations Program (DEEP) were the significant contributors to the above matter. (3) In their findings, they notably observed dramatic reductions in exhaust particulate matter emissions in some of the cases where good maintenance was applied. In a study by Anyon (19), a 64% reduction in DPM levels were demonstrated as a result of applying effective maintenance.

Unfortunately, it was not possible in the present study to conduct pre and post maintenance measurements. Instead, a multiple regression analysis was conducted to determine whether maintenance affected variability of the raw exhaust DPM emissions. It was concluded that the proxy for maintenance, i.e., number of hours since the last maintenance had an insignificant ($p > 0.8$) effect on the emissions. The age of the TMM in hours also did not show a significant relationship. This may be attributed to the small sample size of the present study, as well as to the relatively small range of hours after the last maintenance (21-322, Table 1). In addition, it should be noted that the high-power category TMMs all had the highest ages, so an autocorrelation between TMMs' power and age may have biased the regression analysis outcome.

Even though in the present study the raw exhaust DPM emissions could not significantly be explained by the variables mentioned, the significance of maintenance and other factors were observed in other studies. Hines (20), demonstrated that emission based maintenance had significant reductions in DEE,

whereby an 18% (for a LHD) and 28.6% (for a PTV - personnel transportation vehicle) reductions in EC on the tailpipe from the baseline to final monitoring were observed. Nigel et al. (21) also determined that power class, fuel type, age and injection timing contributed to 30%, 60%, 1200% and an unknown respectively, to PM emissions.

4.2 Particle and Mass Concentration of the emissions

The effects/filtration efficiencies of the DPF systems on both mass and particle concentration have shown to be significant with reductions of 84% for mass and 97% for particle concentrations were achieved. A study within the SAMI, using the same retrofitted DPFs in this current study also concluded that DPFs reduce above 98% of particulate matter concentrations. (9) However, lower average efficacy in mass concentrations are observed and were due to low efficacies achieved by two TMMs (1 and 4), see Figure 7 below. It is however unclear as to what attributed to the low efficacies. Both TMMs have the same power rating (140 kW) and were retrofitted around the same period as others, however, the pre-filter mass concentrations of both TMMs were already relatively low.

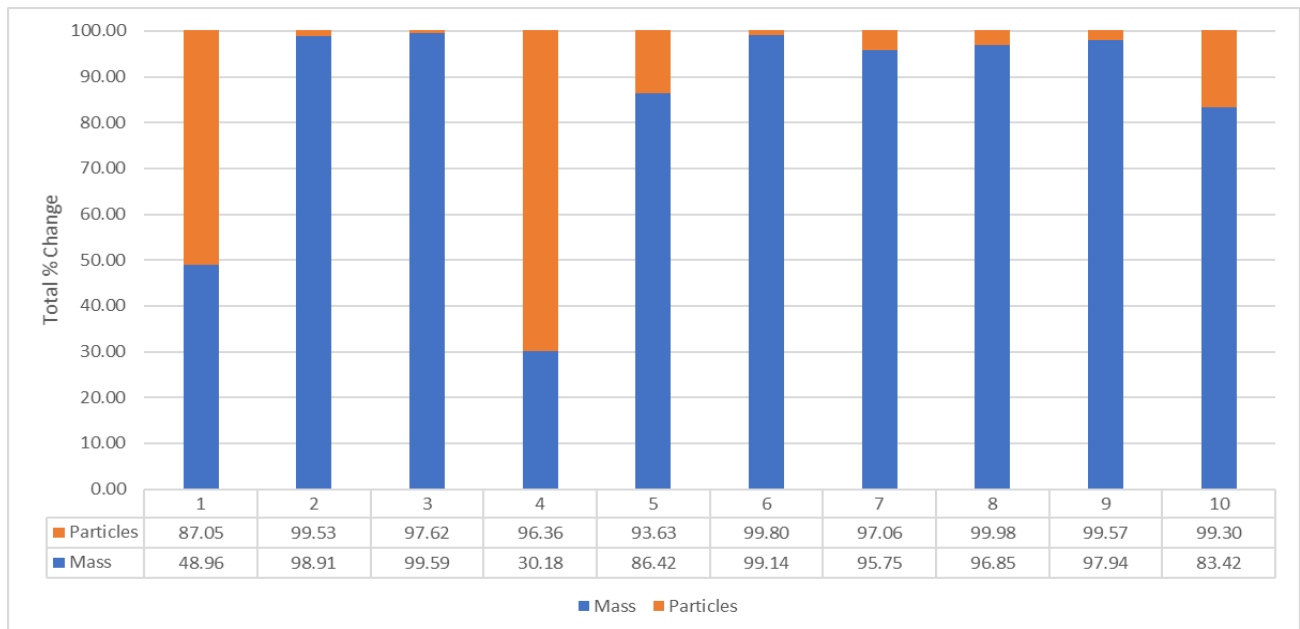


Figure 8: Mass vs particle number efficiencies per TMM

In terms of size distribution (Figure 3), both pre and post DPF measurements were similar in shape owing to majority of particles were saturated around the 0.1 μm region. The only difference was that a higher number of particles were measured pre-DPF system. In their studies, Bugarski et al (15) and McGinn et al (22), demonstrated bimodal size distributions retrofitted with DPFs with relatively high number particles $<0.05 \mu\text{m}$ which is different to what is observed in this current study ($>0.05 \mu\text{m}$ – only accumulation mode). The reasons for a single mode may be attributed but not limited to the methodology (i.e. longer measurement periods and evaluating different engine operating modes) applied in the previous studies.

Even though the efficacies are significant, the results still show a generation of high number particle concentrations of submicron post the DPF system. This is attributable to the high exhaust gas temperatures leaving the engine and tailpipe. Future work is, however, essential in understanding how these submicron particles behave e.g., particle size change due to agglomeration once released from the tailpipe, and their potential risk to the UG employees.

4.3 Personal Exposure

According to the results obtained, the difference in EC personal sampling levels before and after installing the diesel particulate filters is statistically significant ($P < 0.0001$). Significant reductions are observed from the period when no DPF systems were fitted on the diesel-powered machines to when retrofitting took place. Even though reduction of exposure may be affected by numerous factors, i.e. reduced occupancy of TMMs in the UG activities, sufficient ventilation rates or air volumes, movement of the wearer, air direction, maintenance history of the TMM etc., we can conclude that the retrofitting of the current fleet of TMMs did significantly influenced the levels of personal exposure to EC. Exposure levels were at one point, reaching EC levels in excess of $600 \mu\text{g}/\text{m}^3$ to now at lows of $1 \mu\text{g}/\text{m}^3$.

In their studies, Bugarski et al (15) demonstrated that DPF systems significantly reduce concentrations of airborne DPM (70%) and EC (90%). McGinn et al (22), also reported efficiencies in removing elemental carbon particles in the range of 98 to 99%.

Therefore, with the introduction of DPF systems across the SAMI, it would be possible to significantly reduce the diesel pollutant emissions on UG air pollution, strengthen compliance on emission standards and prevent health effects that may arise as a result of over exposure to DPMs.

4.4 Effectiveness over time

One of the critical factors to evaluate the effectiveness of the DPFs is the performance over time. The rule of thumb in relation to time, assumes that the DPFs will deteriorate, and efficiency will be reduced. In this study, the measurements were taken at an average of 256 days after the installation of DPFs for each TMM. According to the results of the pre and post DPF system as well as the personal measurements conducted, it can be concluded that the DPFs are performing relatively stable thus far.

CHAPTER 5: CONCLUSION

The primary focus of this research work was to determine whether the installation of retrofit DPFs would significantly reduce DPM tailpipe emissions of the diesel-powered trackless mobile machinery utilized at this mine. Literature as well as industry experience has shown that diesel particulate matter exposure in the UG mining environment is a significant occupational health hazard. Therefore, health and safety professionals need to institute adequate and effective controls to reduce emissions and personal exposure. From the results of this study, the below conclusions can be drawn:

- A maintenance protocol specific for an engine type or machinery is essential in reducing diesel particulate emissions and increasing the life span of the engine. However, the present study showed that a proxy for maintenance (i.e. hours since last maintenance) had a relatively insignificant correlation with raw exhaust DPM emission variations.
- Diesel particulate filters have proven to reduce total particle and mass concentration by an average of 97% and 84%, respectively.
- Personal exposure to EC was significantly reduced. Reduction can be attributed to but is not limited to the installation of diesel particulate filters on the diesel-powered machines
- According to the OEM, the DPF should be able to sufficiently regenerate at any engine temperature. However, according to the results obtained, the DPF is regenerating at higher efficiencies when the engine is relatively hot or the engine temperatures are high.

It can therefore be concluded that the aim of this study has been achieved.

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ANNEXURE A: Plagiarism declaration report



PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

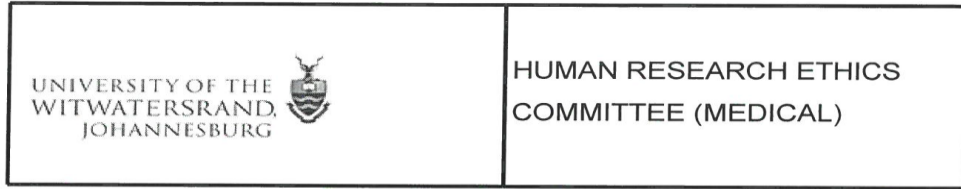
I Ludwick Tshegofatso Lebaka (Student number: 1588764) am a student registered for the degree of MSc in Medicine - Exposure Science in the academic year 2022.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature:  Date: 03 February 2022

ANNEXURE B: Ethics clearance certificate



Office of the Deputy Vice-Chancellor (Research and Postgraduate Affairs)

TO: Mr LT Lebaka
School of Public Health
Medical School
University

E-mail: ltlebaka@gmail.com

CC: Supervisor: Professor D Brower
Derk.Brower@wits.ac.za
and <HREC-Medical Research Office@wits.ac.za>

FROM: Mr Iain Burns
Human Research Ethics Committee (Medical)
Tel: 011 717 1252

E-mail: Iain.Burns@wits.ac.za

DATE: 20 November 2020

REF: R14/49

PROTOCOL NO: **M2010128** (This is your ethics application reference number. Please quote it in all enquiries, oral or written, relating to this study.)

PROJECT TITLE: *Effects of retrofit diesel particulate filters on diesel particulate emissions: a small scale intervention study*

Please find attached the Clearance Certificate for the above project. I hope it goes well and that an article in a recognized publication comes out of it. This will reflect well on your professional standing and contribute to Government funding of the University.



MSWorks2000/Iain0007/Clearscan.wps



R14/49 Mr LT Lebaka

**HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
CLEARANCE CERTIFICATE NO. M2010128**

NAME: Mr LT Lebaka
(Principal Investigator)

DEPARTMENT: School of Public Health
Medical School
University

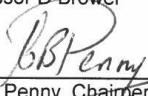
PROJECT TITLE: Effects of retrofit diesel particulate filters on diesel
particulate emissions: a small scale intervention study

DATE CONSIDERED: Ad hoc

DECISION: Approved unconditionally

CONDITIONS: Sub-study under M 190308

SUPERVISOR: Professor D Brewer

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

DATE OF APPROVAL: 20 November 2020

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

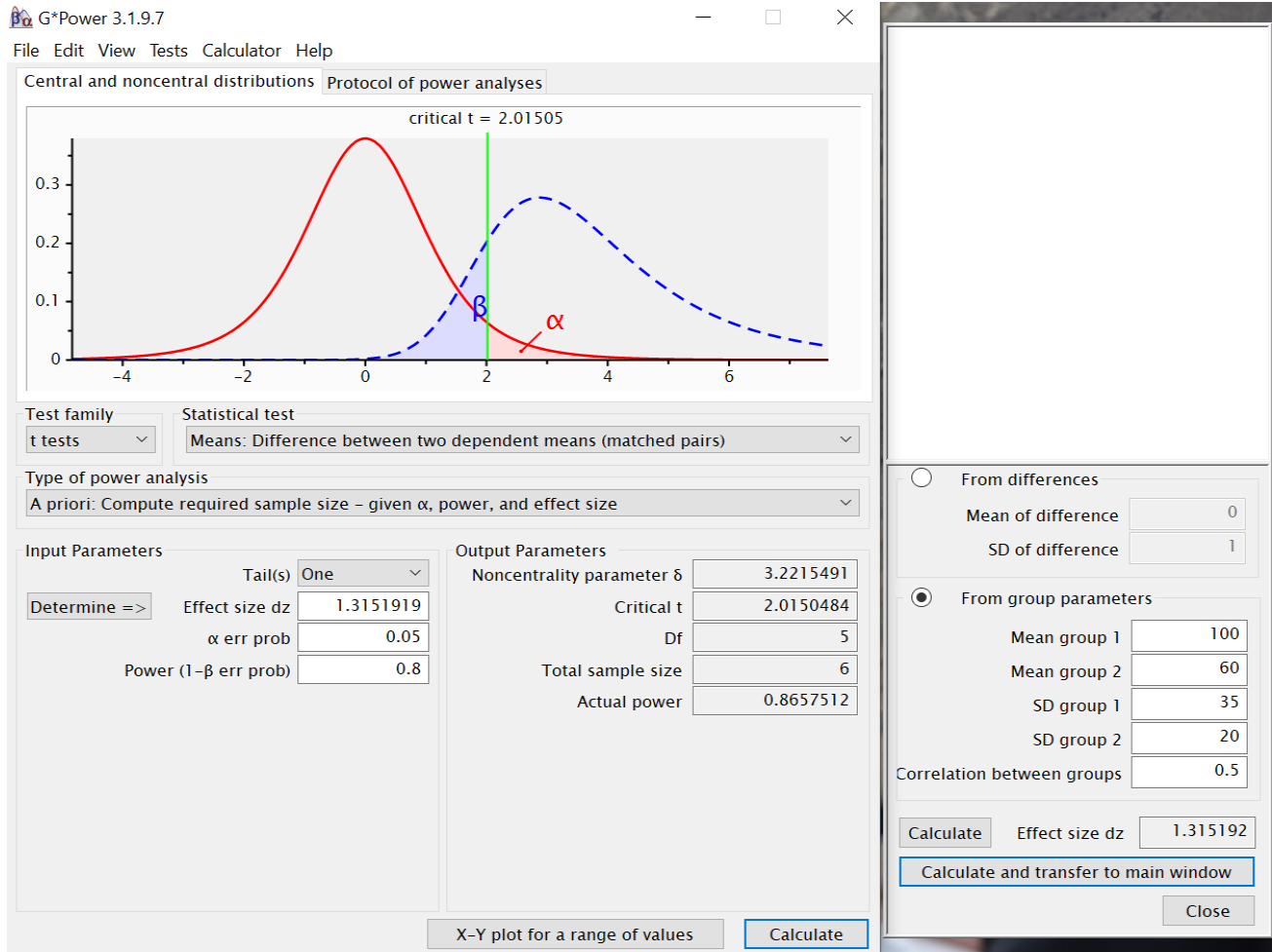
DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the 3rd Floor, Phillip Tobias Building, Parktown, University of the Witwatersrand, Johannesburg.
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 submit details to the Committee. **I agree to submit a yearly progress report.** When a funder requires annual re-certification, the application date will be one year after the date when the study was initially reviewed. In this case, the study was initially reviewed in **October** and will therefore reports and re-certification will be due early in the month of **October** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Principal Investigator Signature

Date

ANNEXURE C: Calculation of effect size based of sample size



The study population will consist of 9 TMMs, however the sample size to determine effect will be 6 for the intervention group and for 3 control group, this can be demonstrated by GPower figure above. It is assumed that the pre-intervention mean DPM emission would be 100 (Arbitrary Units (AU)), with a Standard Deviation (SD) of 35 and an assumed efficacy of 40% (a conservative estimate based on available literature). Therefore, the post-intervention mean will be 60 (AU) (i.e. 40% reduction due to the retrofit filter), with a SD of 20. If now the effect size is calculated and imputed in the sample size calculation, one will find that only 6 TMMs in the intervention group will be sufficient. However, the control group will provide the ‘actual’ SD of the pre-intervention DPM emission.

ANNEXURE D: Turnitin Report

LT Lebaka 1588764 Reseach Report.docx

ORIGINALITY REPORT

12% SIMILARITY INDEX	<i>10/10/2008</i> 10% INTERNET SOURCES	7% PUBLICATIONS	5% STUDENT PAPERS
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4	Submitted to Stow College Student Paper	1%
5	link.springer.com Internet Source	1%
6	C. Ellis. "Field Measurement of Diesel Particulate Matter Emissions", Annals of Occupational Hygiene, 01/23/2008 Publication	<1%

ANNEXURE E: Fuel analysis report

CERTIFICATE OF ANALYSIS

R20-17917



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Company : Rustenburg Platinum Mines Limited - Amandelbult Section
 Address : Private Bag X7275, Witbank, 1035
 Contact : Ludwick Lebaka
 Reference Number : 5505440253
 Date Received : 03 June 2020
 Date Completed : 26 June 2020
 Condition of sample(s) : All samples received at room temperature
 Lab Number(s) : B139989 - B139990

Analysis of 2 bulk sample(s) as received:

Test # : Sulphur Content
 Method : ASTM Method D4294

Determinant →	Sulphur
Sample Number ↓	Result ppm
Tumela Underground	18.1
Tumela Surface	19.5

Results in units specified

Results supplied by a subcontracting laboratory (SANAS Accredited Laboratory T0525)

Disclaimer:

This report relates to the specific items tested only and may not be reproduced in part or full without the written consent of Biograde.

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Willem Wepener
 Head of Laboratory