Effectiveness of retrofitted diesel particulate filters on diesel particulate emissions: a small-scale intervention study

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ABSTRACT

Background: Exposure to diesel particulate matter (DPM) is a significant health hazard in the workplace, particularly in underground mining settings where diesel-powered machines are utilised. Decreasing DPM exposure relies widely on the ability of the industry to implement diesel emission control technologies; in particular, the use of diesel particulate filter (DPF) systems.

Objective: We explored the effectiveness of retrofitted DPFs in reducing tailpipe DPM emissions from a fleet of diesel-powered machines, and exposures to workers, in an underground platinum mine in Limpopo province, South Africa.

Methods: Using a size-selective particle monitor (Dekati ELPI®+), pre- and post-DPF system engine exhaust emissions from 10 trackless mobile machines (TMMs), fitted with wall-flow actively regenerating sintered metal DPFs, were measured. Using the device's built-in software, each measurement was analysed for particle number concentration, mass concentration, and particle size distribution. Personal DPM samples from 172 workers were analysed using Expostats to assess the effects of TMM DPF retrofitting on ambient elemental carbon (EC) exposures.

Results: DPF systems were effective in reducing DPM emissions. Total particle number and mass concentrations were reduced by an average of 96.8% and 83.7%, respectively. Mean personal exposure to elemental carbon was also significantly reduced after the installation of DPF systems, by 87.2%.

Conclusion: The use of DPFs was effective in reducing tailpipe DPM emissions and personal EC exposures. This technology will greatly benefit the South African mining industry (SAMI) by improving compliance with emission standards and preventing adverse health effects as a result of over-exposure of DPM to employees.

INTRODUCTION

Diesel-powered machines used in underground mining are powerful, robust, long-lasting, and consume less fuel than petrol/gasoline-powered machines. However, diesel exhaust emissions – the term used for what is released from a diesel-powered engine during combustion – contain a mixture of complex gases and particulate mattter[1] and are thus of concern regarding workers' health. The gases include, but are not limited to, carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), hydrocarbons, and nitrogen and its various oxides, e.g. nitrogen monoxide (NO) and nitrogen dioxide (NO_2).[2,3] The particulate fraction results primarily from incomplete combustion of the hydrocarbons in the fuel and lubricating oil.[4] It comprises a solid elemental carbon (EC) core and semi-volatile and volatile hydrocarbons (organic carbon (OC)). The EC and OC fractions are reported to comprise 33–90%, and 7–49% of the particulate mass, respectively.[2,5]

Diesel particulate matter (DPM) consists mainly of fine particles < 2.5 µm in diameter, including a large subgroup of ultrafine particles with diameter < 0.1 µm.[6,7] Long-term exposure to combustion-related fine particulate air pollution is an important risk factor for cardiopulmonary and lung cancer mortality.[8] In 2012, the International Agency for Research on Cancer (IARC) classified diesel exhaust as a human carcinogen (Group 1), by inhalation.[9]

Exposures to DPM, as part of diesel exhaust emissions, are significantly higher for underground miners than for workers in any other occupation.[3] Studies conducted by the US Mine Safety and Health Administration (MSHA) from 2002 to 2005 showed that miners were exposed to DPM concentrations as high as 3 300 µg/mg.[3,10] In the South African mining industry (SAMI), DPM air concentrations were reported, in a Mine Health and Safety study published in 2002, to exceed 2 000 µg/m^3.[11]

Exposure to DPM underground may be eliminated, reduced, or controlled along the exposure pathway, using several interventions. The first approach is to replace diesel-powered machines with battery-powered machines. Ways to control combustion products from diesel-powered machines, before they are released from the tailpipe, include the substitution of high-emitting traditional (tier I–III) engines with low-emitting advanced engines (tier IV), engine maintenance, the use of reformulated fuels, and exhaust filtration.[12] Another approach is to ensure that sufficient air volumes are available for particulate dilution where people travel and work, and within ventilation districts (sections of the mine with independent intake and return airways). Yet another approach is to limit the number of diesel-powered machines within a given volume of ventilation air for effective dilution, and to implement a 'no idling' policy.[3,12] These interventions may require a multifaceted approach and optimisation to suit a mine's needs.

Diesel particulate filter (DPF) systems are endorsed as an effective technology for removing particulate matter from the exhausts of diesel-powered equipment.[13] These systems are highly efficient in capturing the solid fraction of diesel exhaust, including EC, allowing the exhaust gases to pass through the system. A complete DPF system consists of the filter and a process to regenerate the filter (restore it to its soot collection capacity). This can be achieved either continuously (passive regeneration) during normal operation of the engine, or periodically (active regeneration) after a pre-determined amount of soot has accumulated on the filter. Neither of these regeneration processes requires input from the vehicle operator; the process occurs automatically. The non-solid fraction of diesel exhaust, including the soluble organic fraction and sulphates, are captured at much lower efficiencies than is the solid fraction, 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 to monitor the exhaust gas back pressure due to the build-up of soot.[3]

Bugarski et al. (2006) demonstrated that DPF systems with cordierite and silicon carbide wall-flow monolith filter elements can reduce DPM and EC concentrations in underground mine air by more than 70% and 90%, respectively.[15] In an industry-wide collaborative project within the SAMI, DPF systems were shown to reduce diesel particulate tailpipe emissions by 60–90%.[1]

In this study, we assessed the effectiveness of retrofitting diesel-powered mobile machinery with DPFs in an underground platinum mine in reducing DPM tailpipe emissions and, consequently, worker exposure.

METHODS

The study was conducted at an underground platinum mine in Limpopo province, South Africa, on 10 tier II trackless mobile machines (TMMs): six load, haul, and dump trucks (LHDs), two drill rigs, and two roof bolters, with highest allowed power input of 140 Kilowatt (kW) for the LHDs and 74 kW for the others. The tailpipe measurements were taken at the underground workshop where maintenance of the machines takes place.

The study design was quasi-experimental with an intervention component. All TMMs were retrofitted with wall-flow actively regenerating sintered metal DPFs as the intervention. The direct impacts of the filtration system, i.e. reduction of the engine tailpipe DPM emissions, was measured. The TMMs were not fitted with any form of particulate filtration prior to the study. Therefore, when retrofitting them with DPFs, no existing devices were removed.

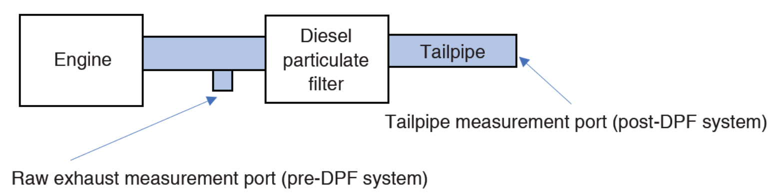
The TMMs' DPM emissions were characterised as the cumulative (five-minute) real-time particle number concentrations, separated according to their aerodynamic size over the 14 size bins (impactor stages or fractions) of the low-pressure particle impactor (Dekati ELPI®+), with no repetition of measurements and no chemical analysis of the composition of the particles. The impactor was assembled at the underground workshop, and was switched on 30 minutes before measurements were taken, to stabilise the electrometers. A leakage test was conducted to prevent changes in the sample airflow, operation pressures, and particle cut-off diameters in the impactor stages. As the last (smallest-size fractions) stages of the ELPI®+ impactor operate under low pressures, failure to conduct a leakage test causes errors in the measurement of the aerosol size distribution and concentrations. The pressure of the impactor was set at 40 mbar. Compressed air, at a pressure of 3 mbar, was connected to the unit (air conditioning system and double diluters) to achieve appropriate dilution. The zeroing of the electrometer was conducted with zero-air pump switched 'on' and the charger (used to give an electrical charge to incoming particles) switched 'off' for two minutes. Thereafter, the zero-air pump was switched 'off', the main vacuum pump was switched 'on', and the flow rate of the vacuum pump was set at 10 l/min. The impactor inlet was then connected to the desired measurement port in the TMM (Figure 1).

Each TMM engine was warmed up for 10–15 minutes prior to taking the measurements. Measurements for each TMM were conducted on low idle and snap acceleration (high transient revolutions per minute (rpm)) duty cycle modes. The two modes' emissions were combined, and evaluated pre-DPF system (raw exhaust) and post-DPF system (tailpipe), as shown in Figure 1.

The TMM fleet was retrofitted with the DPFs from 17 August to 8 October 2020. The TMMs were then operated for an average of 256 days (201–331 days) before DPM emissions were measured.

To confirm that the sulphur concentration in the diesel, in parts per million (ppm), was consistent throughout the data collection period, samples were taken from both the surface and underground diesel storage tanks, using 60 ml containers, prior to commencing the emission measurements. Sulphur content has a significant impact on diesel exhaust emissions. A study in the SAMI showed that the use of low-sulphur fuels promotes cleaner exhaust emissions, with 10% particulate matter emission reductions observed when switching from diesel containing 500 ppm sulphur to that containing either 50 or 10 ppm.[1] The samples were sent to an accredited South African National Accreditation System (SANAS) laboratory for analysis, using the ASTM method D4294. The results confirmed 10 ppm sulphur content of the diesel from both the surface and underground storage tanks. The effects of diesel sulphur content on engine exhaust emissions were, however, not evaluated in this study.

We also assessed whether DPFs had an effect on the levels of EC to which workers were exposed, by analysing personal exposure samples from 172 workers (54 pre-intervention: August 2019 to August 2020; and 118 post-intervention: August to December 2020), randomly collected by the mining company for different job occupations. The occupations comprised of LHD operators, roof bolter operators, drill rig operators, diesel mechanics, rock drill operators, and general and engineering workers. By December 2020, more than 70% of the fleet was fitted with DPFs. The personal samples were analysed for EC by a SANAS-approved



DPF: diesel particulate filter

Figure 1. TMM measurement positions

laboratory, using the National Institute for Occupational Safety and Health (NIOSH) Method 5040.[16]

Ethics clearance was obtained from the University of the Witwatersrand's Human Research Ethics Committee (clearance certificate no. M2010128).

Data analysis

The data were captured and analysed using Microsoft Excel. Expostats – a Bayesian form of inferential statistics – was used to analyse the personal EC exposure data. The particle number concentration generated by the impactor was based on particle numbers, normalised for bin width (dN/dlogDp, where dN = particle concentration and Dp = particle diameter) and processed by the device software to generate particle size distributions. The mass concentration was calculated from the particle number concentration, assuming the default effective density for aerosols of 1 mg/µl. The 'raw exhaust' and 'tailpipe' emissions (pre- and post-DPF system) from each TMM were compared, using the paired t-test. The effectiveness of the DPF system in reducing tailpipe emissions was calculated as:

$$Effectiveness = \frac{\text{Pre-DPF system emission} - \text{Post-DPF system emission}}{\text{Pre-DPF system emission}} \times 100$$

As there is no legislation within the SAMI governing personal DPM exposure, we used the Australian conservative limit value (surrogate occupational exposure limit (OEL)) of 100 µg/m^3 for EC as the concentration against which we could test compliance.[17] Expostats tool 1 was used for compliance testing and Expostats tool 3 for comparison of the pre- and post-DPF intervention personal exposure data.[18]

RESULTS

Particle number concentrations

There was a statistically significant mean difference of 96.8% (± 4 standard deviation (SD)) in particle number concentrations measured pre- and post- the DPF system ($p < 0.003$), for the 10 TMMs. The effectiveness ranged from 87.0–99.9% (Figure 2).

Particle size distribution

Both the raw exhaust and tailpipe particles emitted (pre- and post-DPF system, respectively) were in the accumulation mode (> 0.05 µm), with the majority of the particles approximately 0.1 µm in diameter. No statistically significant differences were observed in the mean particle size distribution (Figure 3), based on the geometric mean (GM). The pre-DPF GM was 0.08 µm (± 1.50), while the post-DPF GM was 0.09 µm (± 1.66). However, the particle number concentrations in the 0.01 and 0.75 µm size bins, where the majority of the particles were concentrated, were substantially different pre- and post-DPF intervention.

Particle mass concentrations

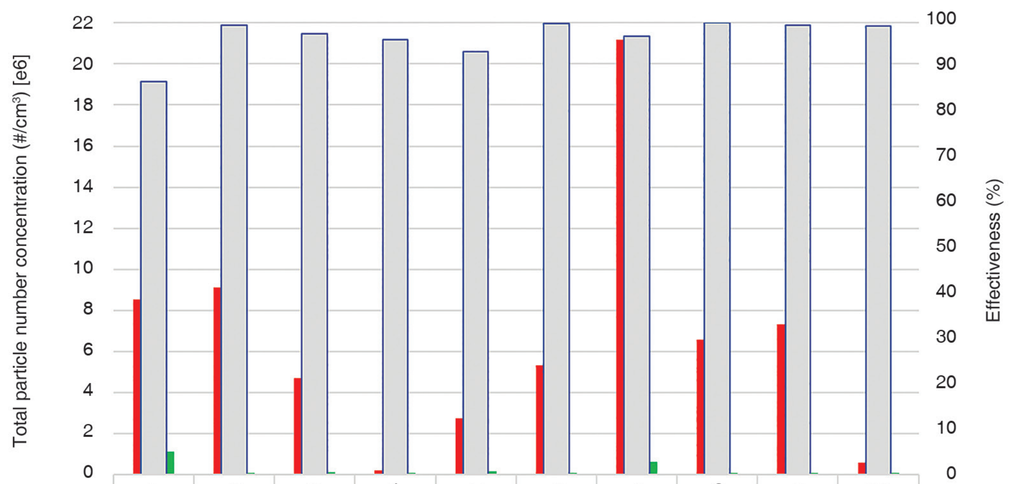
For both pre- and post-DPF system measurements, most particles were in the sub-micron size range (Figure 3). As mass concentration is governed by larger particles, it was expected that the reduction in mass concentration would be lower as a result of the low particle number concentrations observed in the size bins > 1 µm. The pre- and post-DPF system GM mass concentrations were significantly different, at 0.60 mg/m^3 and 0.03 mg/m^3, respectively ($p = 0.016$).

The DPF system achieved a mean filtration effectiveness of 83.7% (95% credible interval (CI) 69.1, 98.9), with a relatively large SD of 24%, which was attributed to the low pre-DPF mass concentrations observed in TMM 1, 4, 8, and 10 (Figure 4). Although mass concentrations were statistically significantly reduced, on average, the effectiveness was poorer than that based on the mean total particle number concentration (96.8%).

Personal DPM exposure

The results of the DPM personal exposure data analysis (expressed as EC concentrations) are presented in Table 1 and Figure 5. There was a significant difference between the arithmetic mean EC concentrations before and after the installation of the DPFs to the TMM fleet (190 µg/m^3 and 8.9 µg/m^3, respectively, $p < 0.001$).

The GM of the personal EC exposure (concentration) after the DPF installation (5.5 µg/m^3) was significantly lower than that before the installation (43.0 µg/m^3), with an effectiveness of 87.2%. The upper



	1	2	3	4	5	6	7	8	9	10
Pre-filter	8.553	9.123	4.706	0.200	2.743	5.327	21.179	6.591	7.329	0.605
Post-filter	1.108	0.043	0.112	0.007	0.175	0.011	0.623	0.002	0.032	0.004
Effectiveness	87.0	99.5	97.6	96.4	93.6	99.8	97.1	100.0	99.6	99.3

Pre-filter Post-filter Effectiveness

Figure 2. Pre- and post-DPF system total particle number concentrations and effectiveness of the 10 TMMs

limit of the 95% CI of the EC concentrations was lower after, than before, the intervention, viz. 6.4 μg/m^3 and 63.0 μg/m^3, respectively. Table 1 shows that a larger proportion of personal exposures to EC exceeded the surrogate OEL of 100 μg/m^3 pre-installation of the DPFs (exceedance of 31%) than post-installation (exceedance of 0.15%).

The box plots of the distributions of the EC concentrations before and after DPF installation, as depicted in Figure 5, also indicate that the DPF system was effective in reducing EC concentrations below the surrogate OEL.

DISCUSSION

The installation of the DPF systems in the 10 TMMs was effective in that it resulted in significant mean reductions of 83.7% and 96.8% of particle mass and particle number concentrations, respectively. The particle number concentration mean was close to the original equipment manufacturer's (OEM's) claim of an effectiveness of around 99%.

These findings are similar to those from a study conducted within the SAMI and published in 2016, using similar retrofitted DPFs, in which the authors concluded that DPFs reduce particulate matter concentrations by more than 98%.[1] The effectiveness of the DPF system in reducing mass concentrations was, however, lower than its effectiveness in reducing particle number concentrations. This may have been due to the low pre-DPF system mass concentrations observed in TMM 1, 4, 5, and 10, which diluted the mean effectiveness. The reductions in the mass concentrations for these TMMs were poor, possibly because there was 'less mass to reduce' compared to the other TMMs. In their study, Giechaskiel et al. (2014) concluded that the mass measurements of total (not only solid) particle number concentrations are unsuitable for monitoring the performance of DPF systems. This is due to the methodology used for collection/measurements (i.e. real-time measurement of particle number concentrations and the uncertainty regarding the conversion of these results into mass concentration).[19]

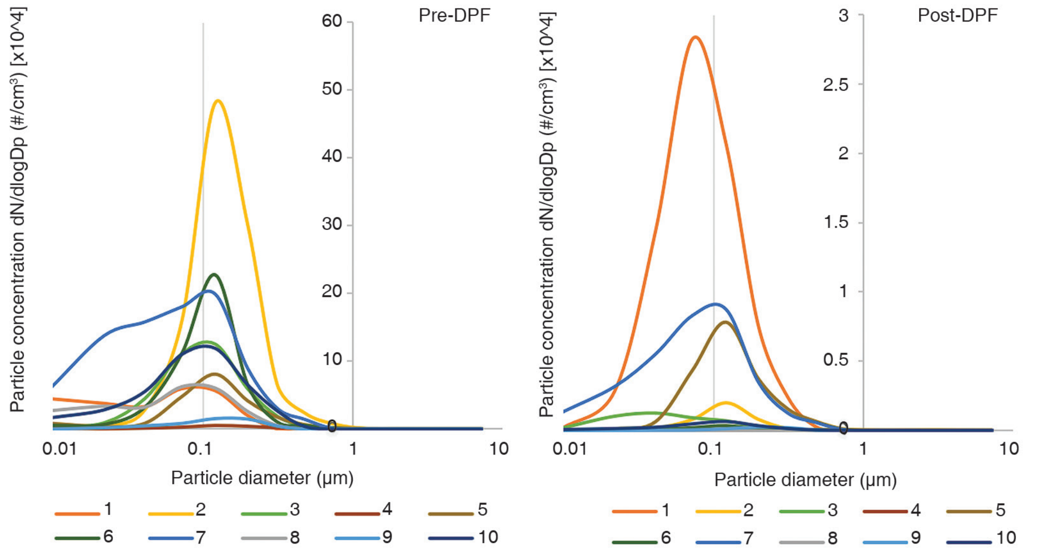
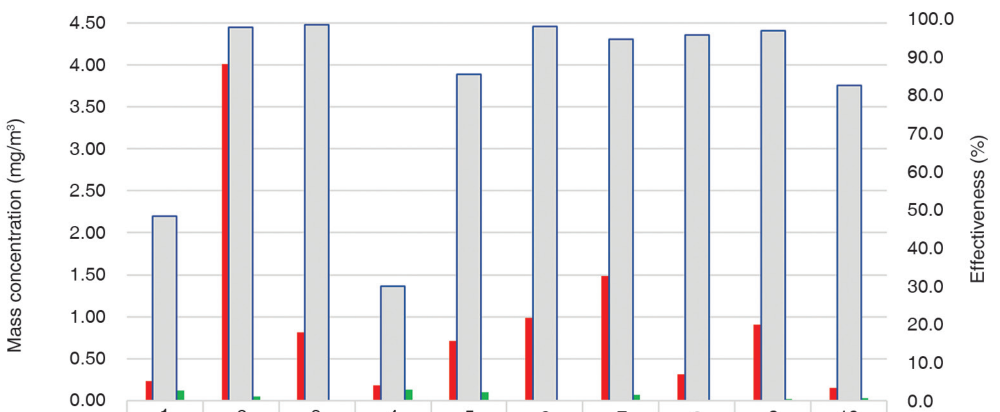


Figure 3. Particle size distributions for the 10 TMMs



	1	2	3	4	5	6	7	8	9	10
Pre-filter	0.23	4.02	0.81	0.18	0.71	0.99	1.49	0.31	0.91	0.15
Post-filter	0.12	0.04	0.00	0.13	0.10	0.01	0.06	0.01	0.02	0.03
Effectiveness	49.0	98.9	99.6	30.2	86.4	99.1	95.7	96.8	97.9	83.4

Figure 4. Pre- and post-DPF system total mass concentrations and effectiveness of the 10 TMMs

In terms of the size distribution, the majority of particles were around 0.1 µm in diameter in both the pre- and post-DPF system. Bugarski et al. (2009) and McGinn et al. (2002) demonstrated bimodal size distributions for engines retrofitted with DPFs, with a relatively large number of particles in the < 0.05 µm nucleation and ≥ 0.05 µm accumulation modes.[20,21] This is different from the unimodal size distribution we observed, viz. particles only in the > 0.05 µm accumulation mode. The reasons that we observed a unimodal distribution may be partly attributed to the different methodology applied. In previous studies, the measurement periods were longer, and different duty cycles and engine speeds in rpm were evaluated.

Although the difference in particle mass concentrations pre- and post-DPF system was statistically significant, with an effectiveness of 83.7%, relatively large numbers of particles less than 1 µm were emitted from the tailpipe. This could be related to the high temperatures of the emitted exhaust gases and particles, which affects the effectiveness of DPF filters in capturing the organic fraction and sulphate particles.[14] Additional research is essential to analyse the chemical composition of the particles and to understand how they behave, e.g. particle size changes due to agglomeration when released from the tailpipe, as well as the potential health risks from exposure to underground employees.

The difference in personal EC exposure concentrations before and after installing the DPFs was statistically significant. It is important to note that reduction in exposure may be affected by other factors, e.g. reduced occupancy of TMMs in underground activities, good ventilation rates or air volumes, movement of the wearer of the personal sampler, air direction, maintenance history of TMMs, etc. Bugarski et al. (2009) demonstrated that DPF systems significantly reduced the concentrations of airborne DPM dust (70%) and EC (90%).[20] McGinn et al. (2002) also reported efficiencies in removing EC particles, of about 98%.[21] This is consistent with our findings.

Our study had some limitations. First, the effectiveness of the TMMs was calculated from only one set of 'raw exhaust' and 'tailpipe' measurements per TMM. Multiple measurements per TMM would validate our results. Second, the comparison of mass concentrations is not recommended for measuring effectiveness as results can be biased by a few larger and relatively heavier particles. In addition, the conversion of particle number concentration to mass concentration assumes the default effective density for aerosols of 1 mg/µl.

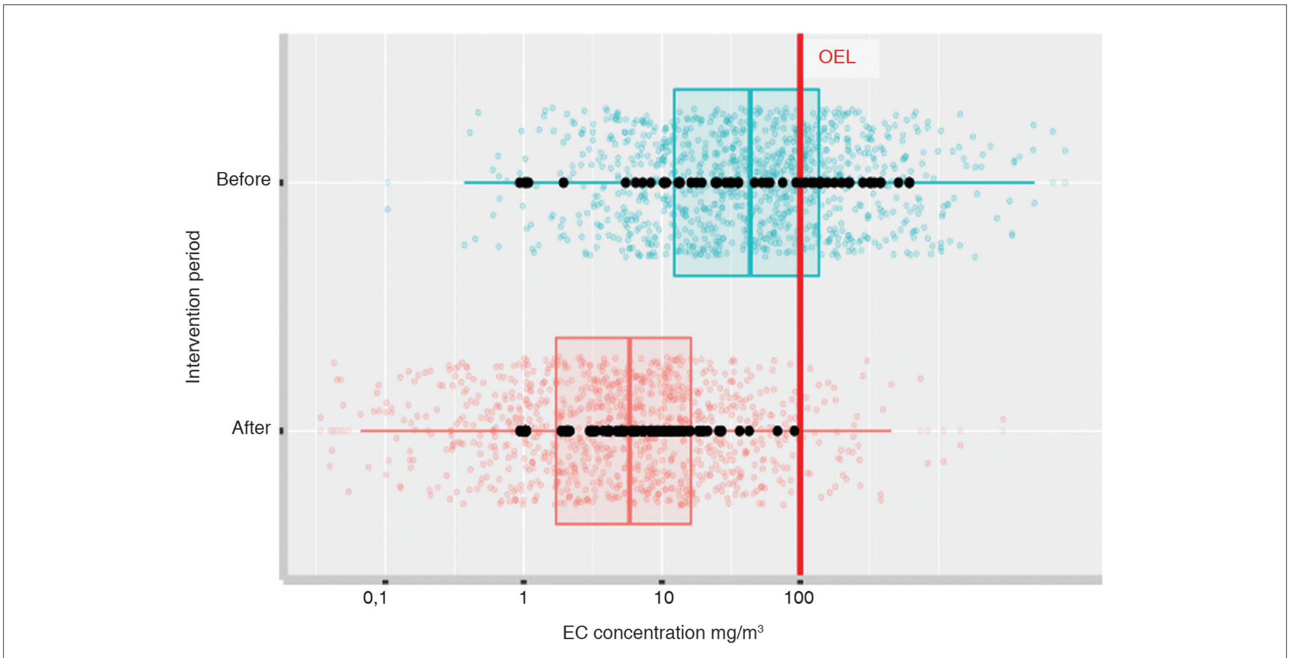
Furthermore, personal EC concentrations were used to evaluate the effectiveness of DPF systems in reducing exposures, rather than TC (combination of EC and OC). Although the mine's personal sampling programme for EC exposure was not designed to test the impact of retrofitting the TMMs, we used the data that were available, rather than collecting personal exposure measurements ourselves, due to limited resources.

Last, we did not measure OC or total carbon (TC) concentrations. It has been reported that EC and OC fractions vary from 33–90% and 7–49% of the particulate mass, respectively.[2,5] The concentration of

Table 1. EC personal air sampling results, before and after DPF retrofitting of TMMs

Parameter	Pre-intervention (n = 54)	Post-intervention (n = 118)
GM (95% CI), µg/m^3	43.0* (29.0–63.0)	5.6* (4.8–6.4)
GSD (95% CI), µg/m^3	5.6 (4.4–7.6)	2.6 (2.4–3)
Exceedance fraction (95% CI) (%)	31 (23–40)	0.15 (0.045–0.44)
Arithmetic mean (95% CI), µg/m^3	190* (110–390)	8.9* (7.6–11)
Effectiveness (based on GMs) (%)	87.2	

GM: geometric mean, GSD: geometric standard deviation, CI: credible interval
*p value < 0.001



EC: elemental carbon, OEL: occupational exposure limit

Figure 5. Box and whisker plot of personal DPM measurements, before and after DPF installation

OC is influenced by environmental factors, such as oil mist that results from poor hydraulic pipe management practices (e.g. oil leaks) in place. This is likely to increase the levels of OC detected in personal samples. It must be noted that, when measuring personal exposure, the OC concentrations may not be due entirely to emissions from TMMs. Therefore, taking direct tailpipe measurements and analysing OC may be more accurate and beneficial when quantifying TC concentrations.

One of the critical factors to consider when assessing the effectiveness of DPFs is their performance over time. It is assumed that the DPFs will deteriorate over time, and that particle filtration will be reduced. In our study, the measurements were taken, on average, 256 days after the installation of the DPFs. Good maintenance (i.e. cleaning of filters as per the OEM specifications, and adhering to the schedule and servicing of engines) will, however, ensure continued effectiveness.

Potential challenges that were identified during the study, regarding the introduction of DPF systems at the mine, should be considered by the SAMI when adopting this technology. 1) Retrofitting of DPF may require equipment modifications due to design differences between the DPF and TMM OEM design requirements. This may increase the installation costs and may also alter (reduce) the effectiveness of the DPF system. 2) Clogging of the DPF system by particles/non-combustible material may occur, causing increased resistance (engine back pressure), which may result in increased heat load or running temperatures, with a potential to damage the engine. It is therefore critical to ensure that the filters are 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. 3) The filters are expensive, which may make it difficult for small mining companies to implement the system, especially taking into account that DPM exposure levels are currently not regulated in South Africa (i.e. there is no OEL).

CONCLUSION

Exposure to DPM in underground mining is an occupational health hazard. We assessed the effectiveness of retrofitted DPFs in reducing DPM emissions of diesel-powered trackless mobile machinery in an underground mine. The DPFs reduced total particle number and mass concentrations, and substantially contributed to the reduction of personal exposure to EC. The introduction of DPF systems across the SAMI would greatly contribute to reducing diesel exhaust emissions, and improving compliance with emission standards, thereby preventing adverse health effects as a result of over-exposures.

KEY MESSAGES

1. DPF systems significantly reduce DPM tailpipe emissions.
2. DPF systems mitigate against excessive personal exposures to underground airborne DPM.

DECLARATION

The authors declare that this is their own work; all the sources used in this paper have been duly acknowledged and there are no conflicts of interest.

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All costs incurred in retrofitting the TMMs were covered by the mine at which the intervention took place. The authors wish to thank the reviewers for their valuable comments.

AUTHOR CONTRIBUTIONS

Conception and design of the study: LL, DB
Data acquisition: LL, AM-M
Data analysis: LL
Interpretation of the data: LL, AM-M, DB
Drafting of the paper: LL, DB
Critical revision of the paper: LL, AM-M, DB

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