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Effects of sintered metal diesel particulate filter system on diesel aerosols and nitric oxides in mine air

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ABSTRACT: This study was conducted to establish the effects of a diesel particulate filter (DPF) system with sintered metal substrate on the concentrations and size distributions of nano and ultrafine aerosols and concentrations of nitric oxides in underground mine air. The study focused on the formation and transformation of nucleation mode particles in mine air under prevailing test conditions. Experimental work was conducted in the NIOSH Diesel Laboratory at the Lake Lynn Laboratory experimental mine, a facility developed to allow evaluation of control technologies directly in underground conditions. The DPF system was examined for four repeatable steady-state engine modes using a naturally aspirated mechanically controlled Isuzu C240 diesel engine fueled with ultralow sulfur fuel. The engine coupled to an eddy-current dynamometer was operated in the underground drift with tightly controlled ventilation. Measurements upwind and downwind of the exhaust system discharge were used to quantify the effects of the DPF system on the mine air. A baseline was established using a standard muffler. The study showed that sintered metal DPF systems reduced the total mass of aerosols in the mine air by more than ten-fold when compared to a muffler. The nucleation mode aerosols ($_{50}d_{em}$<40 nm) in mine air were found to be strongly influenced by engine operating mode. The concentration of nucleation mode aerosols was found to be significantly higher for high-load modes than for low-load modes. The muffler and DPF system resulted in comparable total nitrogen oxides (NO_x) concentrations. However, the nitrogen dioxide (NO_2) fraction of the total NO_x was found to be substantially higher for both systems for low-load modes than for high-load modes.

1 Introduction

Extensive utilization of diesel-powered equipment made the reduction of underground miners' exposure to particulate matter and gases a major challenge for underground mining industry in the U.S. and worldwide. Ever since in January 2001, when the U.S. Mine Safety and Health Administration (MSHA) promulgated regulations, 30 CFR 57.5060, limiting exposures of underground metal and nonmetal miners to diesel particulate matter (DPM), the U.S. underground mining community has been working on identifying technically and economically feasible controls. Improvements in mine ventilation and the curtailment of DPM and toxic gaseous emissions from existing and new diesel powered equipment are commonly perceived as two promising solutions. Diesel oxidation catalytic converters (DOCs), diesel particulate filters (DPFs) systems, and high-temperature disposable filter elements (HT DFEs) are some of the exhaust aftertreatment technologies available to the industry to control gaseous and DPM emissions. Currently the majority of underground mining vehicles are equipped with muffler and/or diesel oxidation catalysts (DOCs) that are primarily designed to control carbon monoxide and hydrocarbon emissions. DPF systems, which are currently recognized as the most effective technology for removing DPM from exhaust of diesel-powered equipment (Suvapro 2005), are gradually becoming more utilized for new and retrofit underground mining applications.

The findings of previous laboratory and field studies (Vaaraslahti 2005, Bugarski 2006a, 2006 b) indicate that the use of various diesel exhausts after treatment technologies can dramatically change the physical, chemical, and toxicological properties of DPM and so potentially change adverse health effects associated with DPM exposure. DPM exposures are currently regulated solely on the basis of the total and elemental carbon mass per unit volume of air (mass concentration), and no reference is made to either size or the number concentration of the DPM particles. Mass-based exposure assessments are not always fully predictive of disease risk and some studies have indicated the importance of complementing mass based exposure monitoring with measurements of size, number, and surface area of aerosols in attempts to assess adverse health impact of nano and ultrafine aerosols (Donaldson et al., 2000, 2003; Tran et al., 2000; Englert, 2004, Oberdörster et al., 2000, 2004).

The effects of DPF systems with ceramic (cordierite or silicon carbide) filtration elements on concentrations and size distribution of diesel aerosols in mine air were previously studied by Bugarski and coworkers (2006a and 2006b). Corresponding effects of DPF systems using sintered metal filter elements are not found in the literature. Therefore, this study was conducted to establish the effects of a sintered metal (SM) DPF system on the concentrations and size distributions of nano and ultrafine aerosols and concentrations of nitric oxides in the underground mine air, and, in particular, on the formation and transformation of nucleation mode particles in mine air under prevailing test conditions.

2 Experimental Methodology

2.1 DPF System

The DPF system evaluated in this study was supplied by Mann+Hummel GMBH, Speyer, Germany. The Model SMF-AR system consists of a sintered metal particulate filter (SMF) and a fully automated closed system regeneration unit (AR) (Mann+Hummel 2007). The SMF-AR system utilizes both electric heating elements and fuel-borne catalyst additive to achieve automatic regeneration during normal engine operation. A simplified version of the system with surface area of 2.75 m^2 was installed in the exhaust of Isuzu C240 for this evaluation. The system was installed without an automatic on-board fuel additive dosing system and without an electronic control unit (ECU) with associated sensors (temperature, backpressure, and air mass). For this evaluation the additive was premixed with the fuel manually. The installation is shown in Figure 1. An engine emissions baseline was established with generic muffler installed in place of the DPF system.

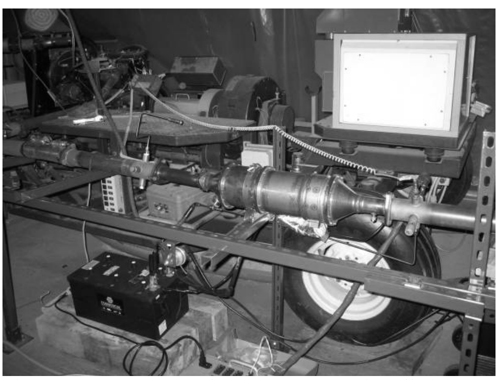

Figure 1. Mann+Hummel SMF-AR system installation

The first DPF test started after the system had been in operation for approximately four hours. By end of testing the DPF had accumulated approximately 21 operating hours over the different modes.

2.2 Fuel

The single-batch ultralow sulfur (ULS) diesel fuel was used as a primary fuel in this study. The results of the analysis performed on that fuel by Core Laboratories, Houston, TX are given in Table 1.

Table 1. Fuel properties

Test		Method	Result	Units
BTU, Net		ASTM D-240	43468	kJ/kg
Cetane Number		ASTM D-613	61.8	-
Density		ASTM D-4052	0.8038	g/ml
Flash Point, PMCC		ASTM D-93A	62.2	°C
Hydrocarbon Type	Aromatics	ASTM D-1319	7.2	LV%
	Olefins	ASTM D-1319	1.1	LV%
	Saturates	ASTM D-1319	91.7	LV%
Oxygen Content			3.45	Wt. %
Sulfur Content		ASTM D-5453	11	mg/kg

During the baseline evaluation, the ULS fuel was supplied to the engine from a 200-liter main fuel tank. The SM DPF system was evaluated using the same fuel to which the fuel-borne catalyst from Innospec Limited, Cheshire, United Kingdom (Satacen 3) had been premixed to 0.677 milliliters per liter of diesel fuel before it was added to 45-liter fuel tank on-board of the engine/dynamometer system. Precautions were taken to avoid cross contamination of the fuels from baseline and DPF system tests.

2.3 Evaluation Procedure

Since the aerosol size and concentrations of semivolatile materials emitted by diesel engines in the underground mines are strongly influenced by a number of processes and ambient conditions, the best way to characterize them is to sample directly in an underground environment and conditions. The Diesel Laboratory developed at the NIOSH Lake Lynn Laboratory (LLL) permitted experimental work in underground environment with laboratory precision and accuracy (Bugarski et al. 2007). The NIOSH Diesel Laboratory has integrated a transportable dynamometer into D-drift of the NIOSH Lake Lynn Laboratory (LLL) experimental mine shown in Figure 2 (Tribsch and Sapko 1990). This drift is approximately 530 m (1750 ft) long, 6 m (20 ft) wide, and 2 m (7 ft) high.

A schematic of layout of the laboratory is shown in Figure 3. The major components are engine/dynamometer system, a ventilation measurement and control system, and three sampling and measurement stations.

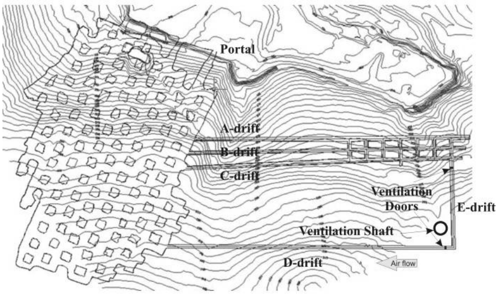

Figure 2. NIOSH Lake Lynn Laboratory Experimental Mine

2.4 Engine/Dynamometer System

The water-cooled eddy-current dynamometer rated at 150 kW (201 bhp) was used to load and control a naturally aspirated mechanically controlled Isuzu C240 engine. The specifications for the engine and dynamometer are given in Table 2.

Table 2. Engine specifications

Isuzu C240		Unit
Type	in-line 4	-
Cooling	Water	-
Injection	Indirect	-
Air intake system	naturally aspirated	-
Engine management	mechanical	
Displacement	2369 (145)	cm^3 (in^3)
Continuous rating	36.5 (49) @ 3000 rpm	kW (bhp)
Peak torque	146.4 (108) @ 2000 rpm	Nm (lb ft)

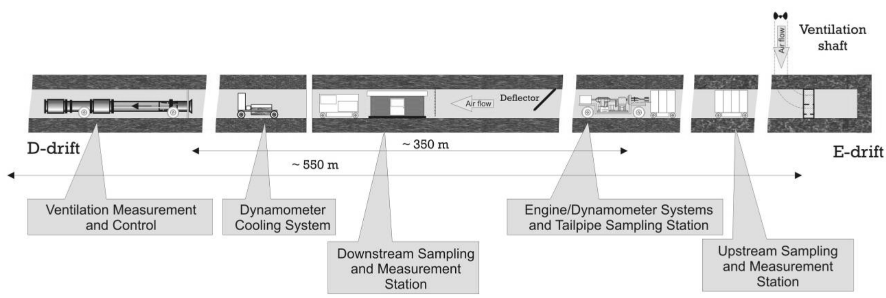

Figure 3. NIOSH Diesel Laboratory in D-drift of LLL

2.5 Ventilation Measurement and Control

Fresh air was supplied to the LLL underground facility via a ventilation shaft located in E-drift (Figure 1 and Figure 2). A Series 2000 Model 48-26-1770 XP Axivane fan (Joy Technologies Inc., New Philadelphia, OH) was used to push air into the mine from the surface. A portion of this air flows into the test zone via the E-drift that is situated immediately upwind and normal to the D-drift. A tightly sealed wall across D-drift was constructed near the downwind end of the drift. The flow was diverted though a subsonic venturi meter (Primary Flow Signal, Inc., Tulsa OK) followed by a Series 1000 Model 23017-3450 Axivane fan (Joy Technologies). This structure provides the means to measure and maintain a constant air flow through the drift. The flow rate measurements were compensated for variations in temperature, pressure, and humidity. Tightly sealed double doors in the wall provided the necessary safety and support access to D-drift and were kept closed during the active test periods.

In this study the objective was to supply constant flow of fresh air to the D-drift throughout the tests. The measurements showed the average flow rate over all tests of 5.85 ± 0.06 m^3/s (12395.45 ± 127.13 ft^3/min). Relatively low test-to-test variability in flow rate (1.04%) eliminated need for normalization of the data with respect to flow rate.

2.6 Measurement Methodology

Three sampling and measurement stations were established in the D-drift. The downstream and upstream stations are used to measure ambient concentrations of aerosols and gases, while the tailpipe station is used to measure concentrations of carbon dioxide (CO_2) and carbon monoxide (CO) in the tailpipe of the Isuzu C240 engine immediately upstream of the installed DPF to provide a additional assurance that engine modes were the same throughout all of the tests. The downstream ambient monitoring station is located about 60 m (197 ft) downwind of the dynamometer, and the upstream ambient monitoring station is located approximately 60 m (197 ft) upwind of the dynamometer. The concentration of aerosol, nitric oxide (NO), and nitrogen dioxide (NO_2) in the mine air were determined by measuring the pollutant concentrations and aerosol size distributions at the downwind measurement location. The corrections for the background concentrations of aerosols were made by subtracting the results of measurements performed at the upstream station from the corresponding results obtained at the downstream station. Due to low background concentrations of NO and NO_2 it was not necessary to apply same corrections on NO and NO_2 data.

A Tapered Element Oscillating Microbalance (TEOM) Series 1400a ambient particulate monitor was used at the downstream station, and another was used at the upstream station to measure total particulate matter mass with mean aerodynamic diameter ($_{50}d_{ae}$) under 0.82 µm. The flow rate of both TEOM instruments was set at 2.0 lpm. A 10-mm Dorr-Oliver cyclone followed by a diesel particulate matter cassette (SKC, Eighty Four, PA) with its collection filter removed were used to pre-classify aerosols entering the TEOM, allowing only particles with $_{50}d_{ae}$ smaller than 0.82 µm to reach the TEOM. The average concentration for a selected time period of a test was obtained from the difference in the TEOM filter masses logged at the start and end of the period.

A Scanning Mobility Particle Sizer (SMPS) (Wang and Flagan 1990) from TSI (St. Paul, MN) was used at the downstream station, and another was used at the upstream station to measure size distribution and number concentrations of aerosols in the ambient air at their respective locations. The SMPS at the downstream station was configured with an electrostatic classifier (EC) Model 3080L and a condensation particle counter (CPC) Model 3025A. The SMPS at the upstream station consisted of an EC Model 3080L and a CPC Model 3776. Both SMPSs were used to measure size distribution and number concentrations of particles in the range between 10 and 408 nm.

A Model DAS 3100 Electrical Low Pressure Impactor (ELPI) (Keskinen at al. 1992) from Dekati (Finland) was used at the downstream station to classify aerosols according to their aerodynamic diameter. Coarse particles with $_{50}d_{ae}$ larger than 1 µm were removed from the ELPI sampling stream by a URG-2000-30EHB cyclone (URG, Chapel Hill, NC). The ELPI was used with greased aluminum collection substrates and a Teflon coated glass fiber filter (T40HI20, Pall Corporation) at the filter stage.

In this study, the size distribution data obtained with SMPS and ELPI were fitted with log-normal curves using DistFit software from Chimera Technologies (Forest Lake, MN).

A Model CLD 700 AL chemiluminescence analyzer (Eco Physics, Duernten, Switzerland) was used to measure concentrations of NO and NO_2 at the downstream station. The concentration of CO_2 at the downstream station was measured by a Model 602 non-dispersive infrared (NDIR) analyzer (California Analytical Instruments, Incorporated, Orange, CA) and a CarbonCap hand-held recording CO_2 meter (Model GM70, Vaisala Oyj, Helsinki, Finland) to which a HM-70 probe was added to measure relative humidity and temperature.

2.7 Test Modes

The DPF system was examined for four repeatable steady-state engine modes (Table 3).

Table 3. Test Modes

Mode	Description	Engine Speed	Torque	Power
		rpm	Nm	kW
R50	Rated speed 50% load	2950	55.6	17.2
R100	Rated speed 100% load	2950	111.2	34.3
I50	Intermediate speed 50% load	2100	69.1	14.9
I100	Intermediate speed 100% load	2100	136.9	30.6

In a typical test run, the engine was operated for approximately three hours at the selected engine mode. The data shown in this report are results of averaging data obtained over the last hour of the test.

The dilution ratios for R50, R100, I50, and I100 modes were calculated using results of the ventilation measurements to be 148, 149, 183, and 186, respectively.

3 Results and Discussion

3.1 Concentrations and Size Distribution of Aerosols

The results of the measurements with TEOMs, SMPSs, and ELPI at their respective locations are summarized in Table 4. All concentrations are reported as the averages of actual measured values during the last hour of the tests. The results were not corrected for variability in ventilation dilution ratio for the different engine modes.

In the effort to preserve authentic underground mine environment conditions, the experiments were conducted using unconditioned and unfiltered air from the mine ventilation system. In the case of the DPF tests, where the downstream mass concentrations were found to be comparable to the upstream concentrations, even slight test-to-test variation in concentrations and size distributions of aerosols at upstream sampling station were found to have relatively major impact on aerosol mass results. In general, the background number concentration values had much more of an effect on the results for R50 and I50 modes (lower concentrations) than for the R100 and I100 modes (higher concentrations)

Table 4. Total mass and number concentrations

Exhaust Configuration	Test Mode	TEOM		SMPS		ELPI
		Down-stream	Upstream	Down-stream	Upstream	
		µg/m^3	µg/m^3	#/cm^3	#/cm^3	#/cm^3
SM DPF	R50	48.1	37.8	47153	6713	53767
	R100	27.8	22.8	938371	7321	537837
	I50	15.7	12.7	36678	7396	39839
	I100	37.5	34.8	489600	10267	195379
Muffler	R50	105.5	4.6	901797	14814	537230
	R100	148.5	5.8	801639	3782	690172
	I50	109.4	5.9	549682	13138	435222
	I100	1058.8	13.4	1159305	2843	1392670

The variation in upstream size distributions is shown in Figure 4. While during the muffler runs the mass and number concentrations at the upstream station were relatively low and close to lower detection limits of the instruments, the mass concentrations during SM DPF evaluations were found to be substantially higher (see Table 4). Those high upstream mass concentrations were related to relatively higher concentrations of aerosols in the secondary mode with $_{50}d_{ea}$ over 200 nm measured in the background air during those tests (Figure 4).

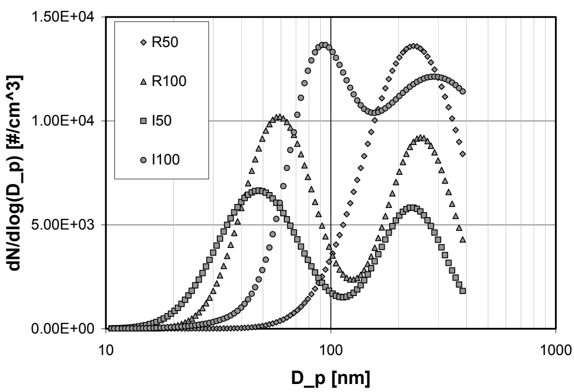

Figure 4. Size distribution of aerosols at the upstream station during SM DPF evaluations

The effectiveness of the DPF system on reducing DPM and gas concentrations was calculated using the results of the concentration measurements for the DPF with those for the muffler. The effectiveness in reducing aerosol mass concentrations in mine air was calculated using downstream and upstream TEOM data using the following formula:

$$Eff_{TEOM} = 1 - \frac{M_{DPF\,d} - M_{DPF\,u}}{M_{md} - M_{mu}} \times 100 \ [\%] \qquad (1)$$

where:
M_{md} = average total mass concentration measured with TEOM during muffler (baseline) test at downstream location [µg/m^3]
M_{mu} = average total mass concentration measured with TEOM during muffler (baseline) test at upstream (background) location [µg/m^3]
$M_{DPF\,d}$ = average total mass concentration measured with TEOM during DPF system test at downstream location [µg/m^3]
$M_{DPF\,u}$ = average total mass concentration measured with TEOM during DPF system test at upstream (background) location [µg/m^3].

Similarly, the results of SMPS measurements at downstream and upstream station were used to calculate the effectiveness of the DFE in removal of aerosols by number using the following formula:

$$Eff_{SMPS} = 1 - \frac{N_{DPF\,d} - N_{DPF\,u}}{N_{md} - N_{mu}} \times 100 \ [\%] \qquad (2)$$

where:

N_{md} = average total number concentration measured with SMPS during muffler test at downstream location [#/cm^3]

N_{mu} = average total number concentration measured with SMPS during muffler test at upstream (background) location [#/cm^3]

N_{DPFd} = average total number concentration measured with SMPS during the DPF test at downstream location [#/cm^3]

N_{DPFu} = average total number concentration measured with SMPS during the DPF test at upstream location [#/cm^3].

The same effectiveness was also calculated using ELPI data and similar formula, but the results were not corrected for background concentrations. The results of effectiveness calculations are summarized in Figure 5.

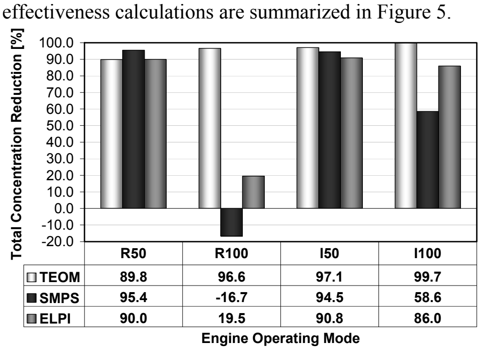

Figure 5. Aerosol mass and number concentration reductions

Results showed that the SM DPF system reduced aerosol mass concentrations, normalized to muffler performance, by approximately 10 fold for R50, by more than 20 fold for R100 and I50, and by more than 100 fold for the I100 engine operating condition. The results of SMPS and ELPI measurements showed that the engine operating mode had more pronounced effects on the number than on the mass of aerosols.

The results of size distribution measurements performed at the downstream sampling station with the SMPS are summarized in Figure 6. High concentrations of nucleation mode aerosols in the downstream mine air during DPF tests for R100 and I100 (Figure 6) modes, resulted in relatively lower reduction or even increase of the total particle concentration for those modes (Figure 5). However, for R50 and I50 modes, the SM DPF system was found to be about equally effective in reducing both the number and the mass of aerosols found in the downstream mine air (Figure 5). The results indicate that the system had substantially lower capacity to form the nucleation mode aerosols for R50 and I50 modes than for R100 and I100 modes (Figure 6). In the cases of R50 and I50 modes, the aerosol reduction efficiencies calculated using ELPI data were found to be slightly lower then those calculated using background corrected SMPS data. However, in the cases of R100 and I100 modes, a tendency of ELPI was to underestimate concentrations of nucleation mode aerosols (Figure 7). This resulted in slightly higher efficiencies calculated using ELPI than SMPS data. Despite that, it can be concluded that ELPI results fully corroborate the aforementioned SMPS results.

For the muffler, the majority of aerosols downstream were found in the single agglomeration mode for all engine operating modes. However, for the SM DPF system when operated at the higher loads, R100 and I100, which exhibited higher exhaust temperatures (Table 5), the aerosols were primarily concentrated in single nucleation mode. When the engine with SM DPF was operated at the lower load and lower temperature modes (Table 5), R50 and I50, the majority of the aerosols were concentrated in accumulation modes The SM DPF was found to be very effective in reducing accumulation mode aerosols in mine air for all test conditions.

Table 5. Average exhaust temperatures

Mode	Exhaust Temperature at Inlet of Device	Temperature at Outlet from Device
	°C	°C
R50	309.8 ± 5.5	258.6 ± 4.1
R100	536.9 ± 2.3	440.4 ± 2.1
I50	258.1 ± 5.0	217.7 ± 4.2
I100	542.0 ± 8.1	441.8 ± 8.8

The analysis of the results of simultaneous measurements performed with SMPS and ELPI showed relatively good agreement in size distributions measured by these two instruments. This agreement is illustrated for SM DPF tests in Figure 7.

3.2 Concentrations of Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)

For all four modes the DPF and muffler were found to have comparable effects on NO_x concentrations (Figure 8). However, the fraction of NO_2 in total NO_x was found to be strongly dependent on engine operation mode and exhaust temperature (Table 5) for both muffler and DPF (Figure 11). The NO_2 fractions were found to be substantially higher for low load (R50 and I50) modes than for high load (R100 and I100) modes. The DPFs consistently produced lower NO_2 fraction than the muffler for all four modes.

The results of measurements of nitric oxide (NO) and nitrogen dioxide (NO_2) concentrations at the downstream station are used to calculate the average concentrations of total nitric oxides (NO_x = NO+ NO_2) and percentages of NO_2 in total NO_x over the last hour of the each test. The NO_x concentrations are summarized in Figure 8, while the percentages of NO_2 in total NO_x are shown in Figure 9.

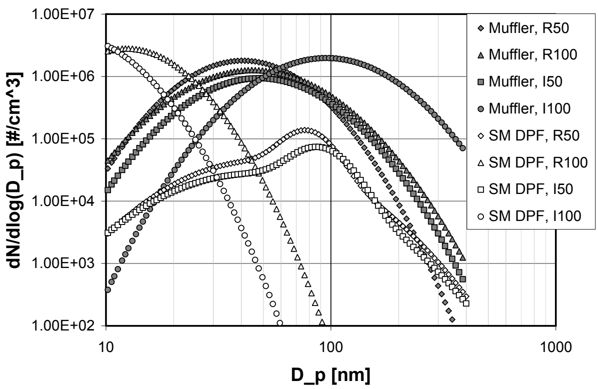

Figure 6. Size distributions for the muffler and DPF measured downstream with SMPS.

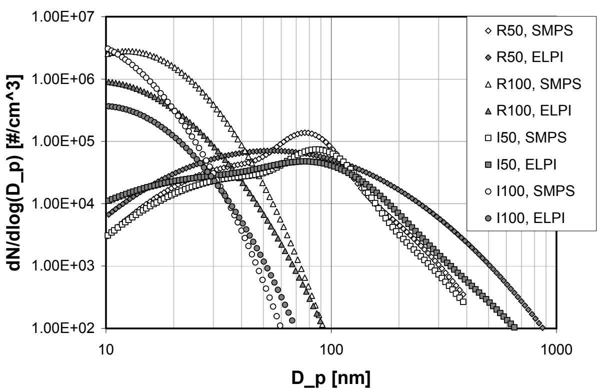

Figure 7. Size distributions measured downstream simultaneously with SMPS and ELPI during DPF tests.

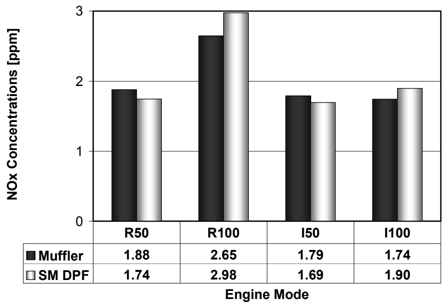

Figure 8. Effects of muffler and DPF on NO_x concentrations for different engine modes [ppm].

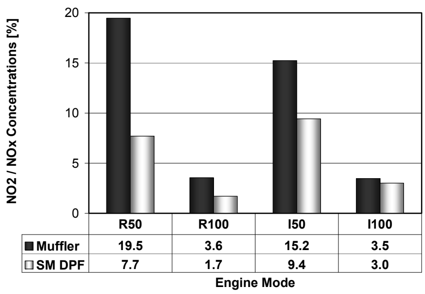

Figure 9. Effects of muffler and DPF on percentages of NO_2 in NO_x for different engine modes.

4 Summary and Conclusion

A series of engine/dynamometer tests at four steady-state engine modes was conducted to evaluate the effects of SM DPF systems on the concentrations and size distribution of diesel aerosols and concentration of nitric oxides in underground mine air, and to compare those with the effects of a standard muffler. The engine load and exhaust temperature were found to be important parameters influencing the effects of this system.

The tests showed that the SM DPF system was very effective in reducing aerosol mass from mine air. Ten fold reductions in mass concentrations were observed for the two low-power R50 and I50 engine modes. The corresponding mass reductions were more than twenty fold at R100 and more than hundred fold for I100, the high power engine modes. In contrast to the mass reduction efficiencies for these two high power modes, the high concentrations of nucleation mode aerosols in the mine air for these modes resulted in a relatively lower reduction or even increase of the total particle concentrations. The DPFs consistently produced lower NO_2 fraction then the muffler for all four modes.

This study should contribute to better understanding the potential for SM DPF to control exposure of underground miners to nano and ultrafine aerosols and nitric oxides.

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Disclaimer

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