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Advanced Diesel Powertrains for Underground Mining Mobile Equipment

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Abstract
Strategies based on the repowering existing and powering new mobile equipment with contemporary diesel engines with substantially lower tailpipe and crankcase emissions are expected to play an important role in the efforts to curtail exposures of underground miners to criteria diesel pollutants. Laboratory characterization of tailpipe emissions for three "clean" engines that meet U.S. Environmental Protection Agency (EPA) Tier 4 final emissions standards were used to assess the viability and effectiveness of those strategies. The evaluated engines were representative of those that achieve the emission standards through implementation of various in-cylinder emissions control strategies, use of crankcase filtration, and use of three types of exhaust aftertreatment systems: (1) diesel oxidation catalytic converter (DOC), (2) combination of DOC and the full-flow wall flow monolith diesel particulate filter (DPF), or (3) combination of DOC, diesel exhaust fluid (DEF)-based selective catalytic reduction (SCR) system, and ammonia slip catalyst (ASC). The study showed that the highest reductions in concentrations of diesel aerosols in underground workings, in terms of both mass and number, could be achieved if the engines, preferably in all power classes, are fitted with viable DPF systems. The use of U.S. EPA Tier 4 final engines equipped with DOC and DOC/SCR/ASC systems could help operators to considerably reduce mass, but not number concentrations of aerosols. The emissions of two of the evaluated engines, one equipped with DOC and the other equipped with DOC/DPF systems, were characterized by substantial secondary NO_2 emissions that would limit the viability of those engines for underground mining applications. The catalyst formulations used in the exhaust aftertreatment systems of the diesel engines marketed to the underground mining industry need to be formulated to minimize the potential for generation of secondary NO_2 emissions. Engines fitted with viable SCR/ASC systems present a low-NO_2 alternative. All three of the evaluated advanced engines were found to have low CO output. Due to nuances associated with the use of diesel-powered mobile equipment in underground mines, the selection and potentially optimization of advanced engines for underground mining applications deserves special consideration.

Keywords Diesel engines · Underground mining · Diesel aerosol emissions · Diesel gaseous emissions · Exhaust aftertreatment technologies · Nitrogen dioxide

1 Introduction

The substantial fraction of energy demand for underground mining operations is associated with the use of diesel-powered mobile equipment to load, transport, and drill ore and transport materials and personnel [1–9]. Diesel engines are omnipresent in underground mining due to relatively high efficiency, reliability, and durability. However, the extensive use of the diesel-powered mobile equipment could contribute substantially to the exposure of underground miners to submicron aerosols, also known as diesel particulate matter (DPM), and toxic gases including carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and hydrocarbons [10]. Long-term exposure to complex mixtures of submicron aerosols and gas emitted by traditional diesel engines was found to result in adverse pulmonary [11–14], cardiovascular [15–18], and other health outcomes [19–21]. In 2012, based on the available evidence, the International Agency for Research on Cancer (IARC) declared diesel exhaust a group 1 human carcinogen [22].

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The use of diesel engines in underground mines is regulated worldwide [23]. In the USA, two independent sets of regulations promulgated by the U.S. Mine Safety and Health Administration (MSHA) standardize the use of diesel equipment in (1) underground coal mines [24] and in (2) underground metal/nonmetal (M/NM) mines [25]. The heavy-duty (HD) diesel power packages used in the in-by areas [26] and the HD diesel engines used in the outby areas of underground coal mines [27] must be MSHA approved [24, 28]. The light-duty (LD) outby diesel engines used in coal mines should be MSHA approved, or U.S. Environmental Protection Agency (EPA) certified [29]. The latter group must exceed the EPA Tier 2 diesel particulate matter emission standards as specified in Table 1 in the 30 CFR 72.502 [30]. The diesel engines used in the US underground metal and nonmetal mines could be MSHA-approved or meet or exceed the power-class specific EPA standards as published in the Table 57.5067–1 of 30 CFR 57.5067 [31]: (1) the engines with a power output lower than 37 kw (50 hp) and higher or equal to 130 kW (175 hp) must meet the EPA Tier 1 standards and (2) the engines with a power output between 37 kW (50 hp) and 130 kW (175 hp) must meet the EPA Tier 2 standards. It is important to note that engines used in the underground mining industry are exempt from complying with the EPA nonroad regulations [29]. Due to attrition and various other reasons, the industry is gradually substituting traditional diesel engines that meet various superseded standards with diesel engines that meet EPA Tier 4 final or more stringent standards.

The exposure limits for underground miners for DPM [32–34] and criteria gases [35–37] emitted by diesel engines were established on a basis of the pertinent occupational health criteria and feasibility of implementation of control technologies and strategies. The various substitution, engineering, and administrative control technologies and strategies are used to control diesel emissions and curtail exposures of occupations to diesel aerosols and gases [8, 38, 39]. Over the past couple decades, the exposures to diesel contaminants have been primarily controlled using a combination of the following engineering strategies [38, 40–44]: (1) powering mobile equipment by engines with the lowest possible particulate and gaseous emissions, (2) using “fresh” air supplied by natural and forced ventilation systems to dilute gaseous and particulate emissions, (3) controlling tailpipe emissions by retrofitting traditional engines with exhaust aftertreatment devices, as well as substituting petroleum-based fuels with alternative fuels, and (4) improving maintenance practices. Lately, those efforts are complemented with efforts on the substitution of the traditional diesel engines with diesel and diesel/hybrid power trains with engines that meet more stringent contemporary standards [28, 29, 45–49], and/or on the elimination of diesel powertrains and replacement of those with battery powertrains [50].

The integration of various emissions controls, such as (1) improved combustion [51–53], (2) extensive use of various exhaust aftertreatment systems based on diesel oxidation catalytic converters (DOC), diesel particulate matter filters (DPF), and selective catalytic reduction (SCR) devices [39, 54–56], and (3) improved control of blow-by emissions via closed crankcase ventilation system [57–59], were used in advanced engines to substantially reduce particulate mass and criteria gaseous emissions. The reductions in particulate

Table 1 The engines evaluated in this study

Designation	Engine 1	Engine 2	Engine 3	Engine 4
Manufacturer and model	Deutz TD2.9 L4	Kubota D1803-CR-T-E4B	Mercedes Benz OM934 LA	Mercedes Benz OM 904 LA
Configuration	I–4	I–3	I–4	I–4
Displacement [l]	2.9	1.8	5.1	4.3
Rated power [kW] @ Engine speed [rpm]	55 @ 2600	37 @ 2700	129 @ 2200	130 @2200
Rated torque [Nm] @ Engine speed [rpm]	260 @ 1600–1800	150 @ 1600	750 @ 1400	675 @ 1400
Aspiration	Turbocharged	Turbocharged	Turbocharged	Turbocharged
Exhaust gas recirculation	Cooled	Cooled	Cooled	Cooled
Exhaust aftertreatment	DOC	DOC/DPF	DOC/SCR/ASC	Muffler DOC DPF
Crankcase breather	Closed and filtered	Closed and filtered	Closed	Open
EPA emission standard	Tier 4 final	Tier 4 final	Tier 4 final	Tier 2
EPA PM emission standard [g/kW-hr]	0.03	0.03	0.02	0.3
MSHA approval	No	No	07-ENA190006	7E-B098
MSHA ventilation rate [m^3/h]	N/A	N/A	10,194	12,743

concentrations have been complicated by substantial changes in the physical, chemical, and toxicological properties of emitted aerosols [60–64].

Based on those developments, substitution of traditional diesel engines with contemporary diesel engines with substantially lower tailpipe and crankcase emissions [56, 63, 65–67] has been expected to evolve into an effective control strategy for the curtailment of exposures to criteria pollutants in underground mines. So far, the engineering challenges associated with the operation of these complex power trains in a harsh environment over a wide range of duty cycles, higher cost [68], and potential for the inadvertent introduction of new health hazards [39, 69–72] are some of the factors that have hindered wider implementation of advanced engine technologies in the underground mining industry. The secondary emissions of NO_2 [72, 73], sub-23 nm aerosols [74], and toxic metals [75, 76] as well as a reduction in the size of emitted aerosols [77] are identified as some of the issues that require close scrutiny prior to deployment of these control technologies in confined spaces of underground mines, often ventilated with limited quantities of fresh air.

This study is conducted with the objective of evaluating the emissions from the selected engines that comply with the EPA Tier 4 final standards [29] and use the results to assess the viability and effectiveness of repowering existing mobile equipment and powering new mobile equipment with similar engines as a control strategy for reducing the exposure of underground miners to criteria pollutants.

2 Methodology

The analysis was performed on the results of the evaluations of aerosol and gaseous emissions of three advanced engines (Engine 1, Engine 2, and Engine 3) that utilize various in-cylinder control strategies and three different exhaust aftertreatment control strategies, to meet EPA Tier 4 final emissions standards for the corresponding power classes (Table 1): (1) DOC (Engine 1), (2) DOC and the wall flow monolith silicon carbide DPF (Engine 2), and (3) DOC, diesel exhaust fluid (DEF) based SCR system, and ammonia slip catalyst (ASC) system (Engine 3). For comparative purposes, the emissions for these three advanced engines were contrasted to those of the traditional engine that conform with the EPA Tier 2 emissions standards (Engine 4). The emissions for Engine 4 were previously evaluated and reported [39] for three different exhaust configurations: (1) muffler (Engine 4), (2) retrofitted with DOC (AirFlow Catalyst Systems, Wayland, NY, Model MinNoDOC) (Engine 4—DOC), and (3) retrofitted with full flow DPF system (NETT Technologies, Mississauga, ON, Model Green Trap 1100) (Engine 4—DPF). The emissions for Engine 4 are comparable to those of the relatively large number of diesel engines currently used in underground mining power trains [9].

The engines were evaluated using ultra-low sulfur diesel fuels from two batches with properties shown in Table 2. The DEF (32.5 percent urea) was used in Engine 4.

Evaluation took place at the engine test cell equipped with a 400-kW, water-cooled, eddy-current dynamometer (SAJ, AE400). The test cell was ventilated using unconditioned ambient air. The temperature and relative humidity inside the test cell were monitored and controlled by adjustments of the ventilation flow rate by variable frequency fans. Over the course of data collection, cell temperature and relative humidity were spread over in the relatively wide ranges (14 to 32 °C, and 24–71%).

Emissions were characterized for four steady-state engine operating conditions (Table 3). The selected conditions were the subset of the International Organization for Standardization (ISO) 8-mode test cycle [78] used by MSHA to approve engines for use in underground operations [24]. The additional tests were performed for Engine 1 and Engine 3 to obtain better insight into the effects of the catalyzed devices on the NO_2 emissions as a function of exhaust temperature [79, 80]. Those data were gathered for the range of exhaust temperatures achieved by operating the engines at the engine-specific intermediate and rated speeds while gradually increasing loads to those engines.

Aerosol sampling and measurements were performed downstream of the two-stage partial dilution system (Dekati, Tampere, Finland, Model FPS4000) in the exhaust diluted nominally 30 times. Carbon analysis was performed on triplicate filter samples collected using a purpose-built sampling system, where samples were collected on a tandem 37-mm quartz fiber filters (QFFs, Pall Corporation, Ann Arbor, MI, 2500QAT-UP) enclosed in five-piece cassettes (SKC, Eighty Four, PA, 225-3050LF, and 225–304). To minimize organic carbon (OC) contamination of the media, the QFFs were prebaked at 800 °C for 4 h. A nominal sampling flow rate of 12.0 lpm was maintained by subsonic critical orifices, installed in

Table 2 Properties of fuels used in the study

Property	Unit	Engines 1 and 4	Engines 2 and 3
API gravity	^{O}API	39.00	34.30
Specific gravity	-	0.83	0.85
Aromatics	% volume	21.70	29.10
Olefins	% volume	3.10	1.00
Paraffins	% volume	75.20	69.90
Cetane number	-	47.30	43.70
Flash point	K	340	331
Heat of combustion	MJ/kg	45.90	46.00
Sulfur content	% weight	5.60	6.90

Table 3 Engine operating conditions for the evaluated engines

Engine	Engine operating conditions	Rated speed –100% load (R100)	Rated speed – 50% load (R50)	Intermediate speed – 100% load (I100)	Intermediate speed – 50% load (I50)
Engine 1	Engine speed [rpm]	2600	2600	1400	1400
	Torque [Nm]	184	92	233	116
	Power [kW]	50	25	43	21
Engine 2	Engine speed [rpm]	2700	2700	1600	1600
	Torque [Nm]	122	61	142	71
	Power [kW]	34	17	24	12
Engine 3	Engine speed [rpm]	2200	2200	1400	1400
	Torque [Nm]	542	271	719	359
	Power [kW]	125	63	105	53
Engine 4	Engine speed [rpm]	2200	2200	1400	1400
	Torque [Nm]	515	258	637	319
	Power [kW]	119	59	93	47

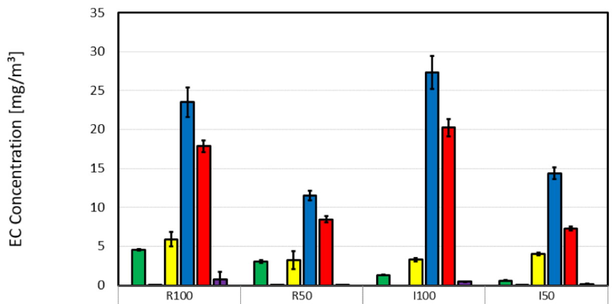
manifolds coupled to a single vacuum pump. The elemental carbon (EC) and OC mass concentrations were determined using thermal optical transmittance-evolved gas analysis (TOT-EGA) [81] performed on 1.5-cm^2 filter segments using an OC/EC Aerosol Analyzer (Sunset Laboratory Inc., Portland, OR). The OC/EC analyzer was calibrated daily using a sucrose solution. The results of the analysis performed on the secondary QFFs were used as a dynamic blank correction for the primary QFFs.

Since the adverse effects of exposure to nanosized and ultrafine aerosols were linked not only to their mass concentrations but also to their number concentrations and size [17, 82–85], the mass measurements were complemented with measurements of the number concentrations and size distributions of aerosols, with electrical mobility diameters between 5.6 and 560 nm, measured with a fast mobility particle sizer (FMPS) spectrometer (TSI, Shoreview, MN, Model 3091) [86, 87]. In order to enhance the clarity of the figures, the aerosol size distributions were fitted with log-normal curves using DistFit software from Chimera Technologies (Forest Lake, MN). Concentrations of CO, NO, and NO_2 in raw exhaust were measured in 20-s intervals using a Fourier transform infrared (FTIR) spectrometer (Gasmet Technologies Oy, Vantaa Finland, Model DX-4000). Exhaust flow rates were calculated using results of measurements of intake flow rates by the laminar flow meters (Meriam, Cleveland, OH, Models Z50MC2-6F and Z50MC2-4) and fuel mass flow rated by the fuel metering system (Max Machinery, Healdsburg, CA, Model 710).

3 Results

The emissions of the aerosols and gases were compared on the level of tailpipe concentrations. During post-processing, the aerosol concentrations that were measured in the diluted exhaust were corrected for the actual dilution rates and reported as the raw exhaust concentrations. Since the concentrations of the criteria gases were measured directly in raw exhaust, dilution corrections were not necessary for that set of data.

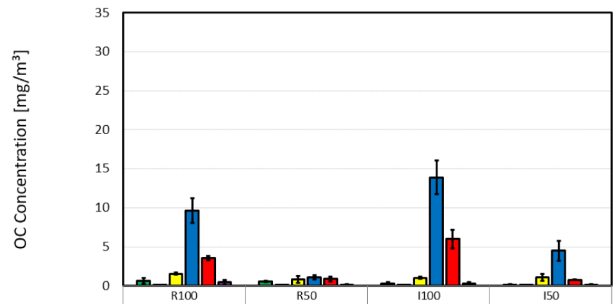
Understanding of the effects on EC and OC mass emissions is critical to assessing control technologies and strategies intended for underground mining use where monitoring of personal exposures to DPM is predicated to the use of EC and total carbon (TC = EC + OC) as a surrogate [3234–]. The average EC and OC mass concentrations for all engines/configurations evaluated in this study are shown in Fig. 1. For all test conditions, the EC and OC mass concentrations were found to be substantially lower in the exhausts of advanced engines (Engine 1, Engine 2, and Engine 3) than in the exhaust of a traditional engine (Engine 4). Both, EC and OC mass concentrations were two to three orders of magnitude lower in the exhaust of the DOC/DPF-equipped Engine 2, than in the exhaust of Engine 4 fitted with a muffler, and were comparable to those in the exhaust of Engine 4 retrofitted with DPF (Fig. 1). The EC and OC mass concentrations were 74 to 96% and 48 to 99%, respectively, lower in the exhaust of



	R100	R50	I100	I50
Engine 1	4.58	3.05	1.31	0.61
Engine 2	0.09	0.01	0.00	0.03
Engine 3	5.91	3.22	3.30	4.04
Engine 4 - Muffler	23.50	11.54	27.35	14.40
Engine 4 - DOC	17.86	8.47	20.24	7.34
Engine 4 - DPF	0.74	0.02	0.50	0.13

Engine Operating Conditions

(a)



	R100	R50	I100	I50
Engine 1	0.64	0.55	0.26	0.05
Engine 2	0.02	0.00	0.02	0.00
Engine 3	1.54	0.82	1.03	1.09
Engine 4 - Muffler	9.62	1.07	13.87	4.49
Engine 4 - DOC	3.53	0.86	6.00	0.76
Engine 4 - DPF	0.44	0.08	0.28	0.11

Engine Operating Conditions

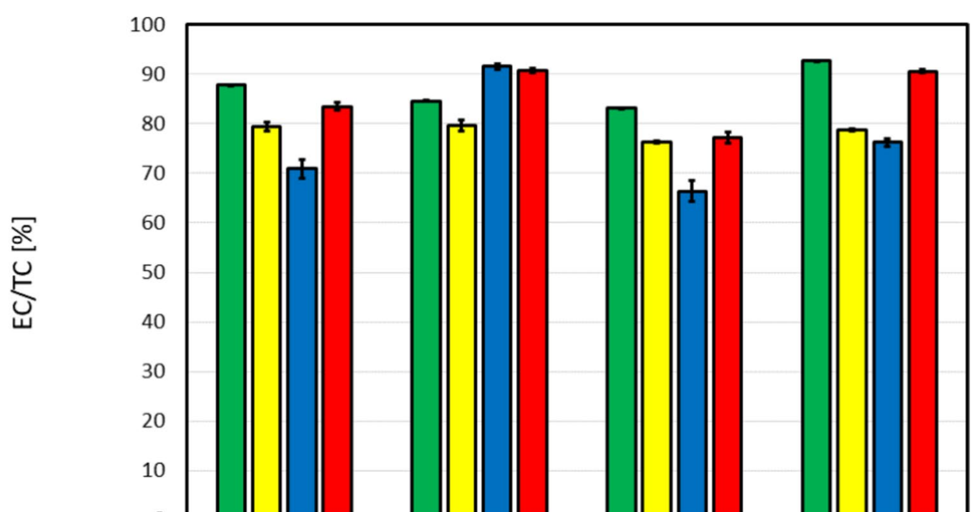
(b)

Fig. 1 Carbon concentrations. **a** EC. **b** OC. The error bars represent one standard deviation of mean. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

DOC-fitted Engine 1 than the exhaust of Engine 4 operated with muffler and 64 to 94% and 36 to 96%, respectively, in the exhaust of Engine 4 operated with the DOC (Fig. 1). In the exhaust of Engine 3, the EC and OC mass concentrations were 72 to 88% and 23 to 93%, respectively, lower in the exhaust of DOC/SCR/ASC fitted Engine 3 than the exhaust of Engine 4 operated with muffler.

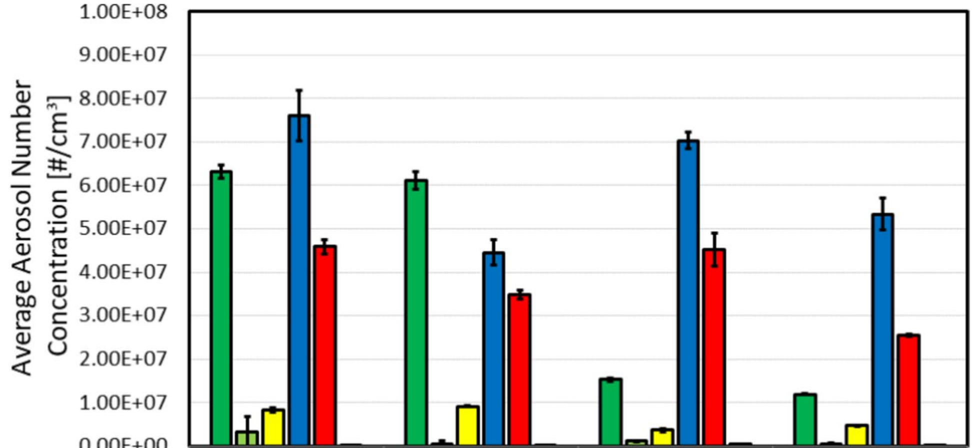
The data on the fractionation of EC and OC in TC is critical to assessment of the exposures and effectiveness of the DPM control technologies and strategies [32]. The fractions of EC in TC of the selected engines evaluated in this study are shown in Fig. 2. Due to high uncertainty associated with establishing the EC/TC ratios for the low-emitting Engine 2 (fitted with DOC/DPF system), those results were excluded from this analysis. The EC was found to make a large majority of TC in the exhausts of Engine 1 and Engine 3 (Fig. 2). Except for the R50 test mode, the EC/TC ratios were higher for the advanced non-DPF engines (Engines 1 and Engine 3) than for the traditional engine (Engine 4 with the muffler).

Fig. 2 EC in TC



	R100	R50	I100	I50
Engine 1	87.8	84.6	83.2	92.6
Engine 3	79.4	79.7	76.3	78.8
Engine 4 - Muffler	71.0	91.5	66.4	76.2
Engine 4 - DOC	83.5	90.7	77.1	90.6

Engine Operating Conditions



	R100	R50	I100	I50
Engine 1	6.31E+07	6.12E+07	1.53E+07	1.19E+07
Engine 2	3.32E+06	4.98E+05	1.19E+06	3.79E+05
Engine 3	8.32E+06	9.12E+06	3.64E+06	4.64E+06
Engine 4 - Muffler	7.60E+07	4.45E+07	7.03E+07	5.34E+07
Engine 4 - DOC	4.59E+07	3.47E+07	4.51E+07	2.55E+07
Engine 4 - DPF	1.40E+05	2.65E+04	4.53E+05	1.74E+05

Engine Operating Conditions

Fig. 3 Total aerosol number concentrations. The error bars represent one standard deviation of mean. The results for Engine 3 and Engine 4 were adopted from previous publication [39]

The average total number concentrations (TNCs) of aerosols for all evaluated engines/configurations are shown in Fig. 3. Only in exhaust of two advanced engines (Engine 2 and Engine 3), were the TNCs lower than the corresponding TNCs measured in the exhaust of the traditional engine operated with muffler or DOC (Fig. 3). The lowest TNCs were found in the exhaust of the DOC/DPF-fitted Engine 2 and were between 155 and 1679 times lower than the corresponding TNCs in the exhaust of Engine 4 fitted with the muffler, and somewhat higher than those in the exhaust of Engine 4 retrofitted with DPF. It is important to note that in the case of Engine 2, unlike in the case of Engine 4 retrofitted with a DPF, the average TNCs included those intermittent spikes in concentrations coinciding with periodic DPF regeneration events. The average TNCs were 96 to 99% lower in the exhaust of Engine 3 than in the exhaust of Engine 4 fitted with the muffler for all test conditions. The engine operating conditions were found to have a profound effect on TNCs of aerosols in the exhaust of the DOC-fitted Engine 1. The concentrations were substantially higher when that engine was operated at rated speed (R100 and R50) conditions than at intermediate speed (I100 and I50) conditions. When operated at the R50 condition, the TNCs of aerosols in the exhaust of Engine 1 exceeded those in the exhaust of Engine 4, fitted with the muffler, by 38% and in the exhaust of Engine 4, retrofitted with the DOC, by 76%. When operated at R100 condition, the TNCs were 38% higher in the exhaust of Engine 1 than in the exhaust of Engine 4 fitted with DOC. For I100 and I50 conditions, the TNCs were substantially lower in the exhaust of Engine 1 than in the exhaust of Engine 4 fitted with the muffler or retrofitted with the DOC.

The aerosols in the unfiltered exhaust of Engines 1 and Engine 3 were lognormally distributed in single accumulation mode or between accumulation and nucleation modes (Fig. 4 and Table 4). The nucleation mode aerosols with count median diameters (CMDs) smaller than 14 nm were found in the exhaust of almost all evaluated engines/configurations and for almost all operating conditions. The concentrations of those were found to be substantially lower than the corresponding concentrations of accumulation mode aerosols. The CMDs of the accumulation mode aerosols emitted by the non-DPF advanced engines were noticeably smaller than the corresponding CMDs of the aerosols emitted by the traditional engine in non-DPF configurations. In cases of the Engine 2, the aerosols in the filtered exhausts were lognormally distributed between single accumulation mode and single nucleation modes (Fig. 4 and Table 4). The TNCs in the filtered exhaust were found to be substantially lower than in the unfiltered exhaust of other tested engines and quite variable. Generally, the concentrations of aerosols in nucleation modes in the filtered exhaust were lower than those in the corresponding accumulation mode (Table 4).

The effects of the evaluated engines/configurations on the CO, NO_2, and NO concentrations were studied using the data summarized in Fig. 5. The CO emissions for Engine 1, Engine 2, and Engine 3, all fitted with catalyzed devices, were mutually comparable and substantially lower than the corresponding CO emissions from Engine 4, in all exhaust configurations (Fig. 5a). The data showed that

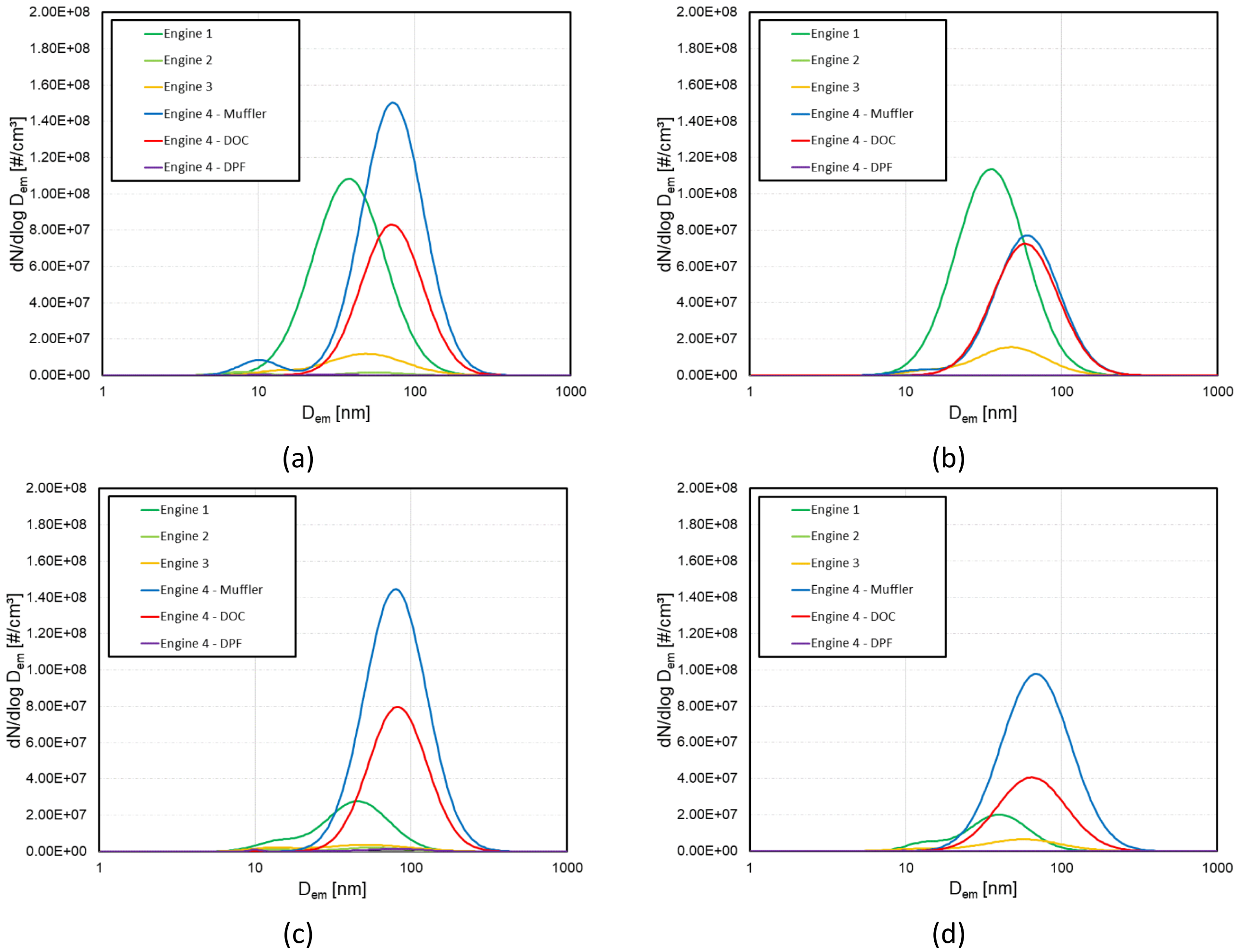


Fig. 4 Size distribution of aerosols captured 1800s into tests for **a** R100, **b** R50, **c** I100, and **d** I50 engine operating conditions. The results for Engine 3 and Engine 4 were adopted from previous publication [39]

catalyzed devices fitted to Engine 1, Engine 2, and Engine 3 were more effective in oxidizing CO than the devices washcoated with NO_2-suppressing catalyst formulations and retrofitted to Engine 4.

The NO_2 emissions from the catalyzed system fitted to Engine 1 and Engine 2 were substantially higher than corresponding NO_2 emissions from Engine 3 and Engine 4 in all tested configurations (Fig. 5b). Effective oxidation of NO to NO_2 over a wide range of exhaust temperatures, in the presence of the catalysts in the exhaust aftertreatment device fitted to Engine 1 and Engine 2, is likely the primary source for high concentrations of NO_2 in the exhausts of Engine 1 and Engine 2 (Fig. 6). The results of additional 900-s tests conducted at intermediate and rated speeds, showed that for the exhaust temperatures in the range between 250 and 350 °C, the observed fraction of NO_2 in NO*x* (NO*x* = NO + NO_2) in the exhaust of Engine 1, expressed as a percentage, exceeded 60 (Fig. 6a). For the similar temperature range, in the exhaust of Engine 2, the observed fraction of NO_2 in NOx expressed as a percentage exceeded 40 (Fig. 6b).

The NO emissions were lowest in the exhaust of Engine 3, fitted with DOC/SCR/ASC system (Fig. 5c). The NO_2 emissions from the same engine were comparable to those of Engine 4 in all exhaust configurations (Fig. 5b). The results of additional 900-s tests conducted at intermediated and rated speeds showed that the observed fraction of NO_2 in NO*x* in the exhaust of Engine 3 expressed as a percentage did not exceed 13 (Fig. 6c).

4 Discussion

Minimizing the contribution of diesel-powered mobile equipment to the concentrations of aerosols and gases plays an important role in reducing the exposure of underground miners to diesel aerosols and gases [38]. Advancements in the nonroad diesel engine technologies made over the

Table 4 Statistical parameters, count median diameter (CMD), spread (σ), and total concentration, for size distribution of aerosols emitted by the evaluated engines measured 10,800 s from the beginning of each test. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

Mode	Exhaust aftertreatment	Nucleation			Accumulation 1			Accumulation 2		
		CMD	σ	Total conc	CMD	σ	Total conc	CMD	σ	Total conc
		Nm	-	#/cm^3	Nm	-	#/cm^3	Nm	-	#/cm^3
R100	Engine 1				37.9	1.690	6.19E+07			
	Engine 2	7.8	1.360	6.18E+05	55.5	1.510	6.82E+05			
	Engine 3	12.4	1.310	5.82E+05	48.7	1.760	7.31E+06			
	Engine 4 – muffler	10.1	1.340	2.68E+06	72.6	1.570	7.38E+07			
	Engine 4 – DOC				71.5	1.570	4.08E+07			
	Engine 4 – DPF	10.0	1.130	4.72E+04	29.7	1.560	1.16E+05			
R50	Engine 1				35.3	1.680	6.42E+07			
	Engine 2	10.0	1.130	1.25E+04	18.9	2.100	1.07E+05			
	Engine 3	13.7	1.400	9.12E+05	47.6	1.650	8.48E+06			
	Engine 4 – Muffler	12.1	1.400	1.05E+06	60.3	1.600	3.95E+07			
	Engine 4 DOC				58.6	1.620	3.81E+07			
	Engine 4 – DPF	9.3	1.160	9.22E+03	31.3	1.190	2.84E+03	85.6	1.310	5.07E+03
I100	Engine 1	13.8	1.390	1.91E+06	45.5	1.590	1.40E+07			
	Engine 2	12.5	1.490	4.60E+05	56.3	1.590	1.10E+06			
	Engine 3	12.4	1.400	6.60E+05	51.5	1.910	2.61E+06			
	Engine 4 – Muffler				79.5	1.580	7.20E+07			
	Engine 4 – DOC				82.2	1.540	3.75E+07			
	Engine 4 – DPF	10.0	1.100	1.05E+05	31.4	1.350	7.71E+04	80.5	1.480	6.31E+05
I50	Engine 1	13.1	1.320	1.32E+06	39.7	1.550	9.63E+06			
	Engine 2	13.0	1.380	1.53E+04	56.1	1.550	4.71E+04			
	Engine 3	12.1	1.560	6.08E+05	56.5	1.740	3.95E+06			
	Engine 4 – Muffler				68.7	1.670	5.46E+07			
	Engine 4 – DOC				64.5	1.660	2.25E+07			
	Engine 4 – DPF	9.7	1.140	3.77E+04	26.8	1.380	3.28E+04	45.9	1.630	8.96E+04

past couple decades have led to substantial improvements in combined tailpipe and blow-by emissions. As a result, operators have had the opportunity to repower the existing mobile equipment and power new mobile equipment with advanced nonroad diesel engines that comply with the EPA Tier 4 final and superior standards [29, 47] and address some of the health issues associated with exposure to diesel aerosols and gases.

The technical solutions used to lower the tailpipe emissions and meet regulatory requirements are driven by various technical and economic parameters [56, 68] and those are often very specific to the power class of the engine [29, 47, 56]. The engines evaluated in this study belong to different power classes (19 ≤ kW < 37, 37 ≤ kW < 56, 56 ≤ kW < 130) and represent different emission control solutions. The study was conducted with the objectives of closer examination of the tailpipe emissions for advanced engines and to gain additional insight into the effectiveness and viability of those engines as a control strategy for the curtailment of exposure of underground miners to diesel aerosols and criteria gases.

Based on the results of this study, the substitution of the traditional engines with advanced engines, similar to the ones evaluated in this study (Engine 1, Engine 2, and Engine 3) with low EC and OC mass emissions (Fig. 1), could be used by the mining industry as a strategy to control EC and TC mass concentrations in underground workings and potentially maintain personal exposure below the current mass-based standards [32–34]. However, if used, the advanced engines that are not fitted with DPF systems, such as Engine 1 and Engine 3, would still measurably contribute to number concentrations of aerosols in those workings (Figs. 3 and 4). Only advanced engines with the integrated DPF systems, similar to the one used in Engine 2, would contribute little to both mass and number concentrations of aerosols (Figs. 1 and 3). The use of advanced in-cylinder combustion controls strategies, particularly higher injection pressures and modified injection timing [51–53], resulted in changes in size distributions of aerosols. In the case of clean engines that are not fitted with DPF systems, the accumulation mode aerosols were characterized by measurably smaller median

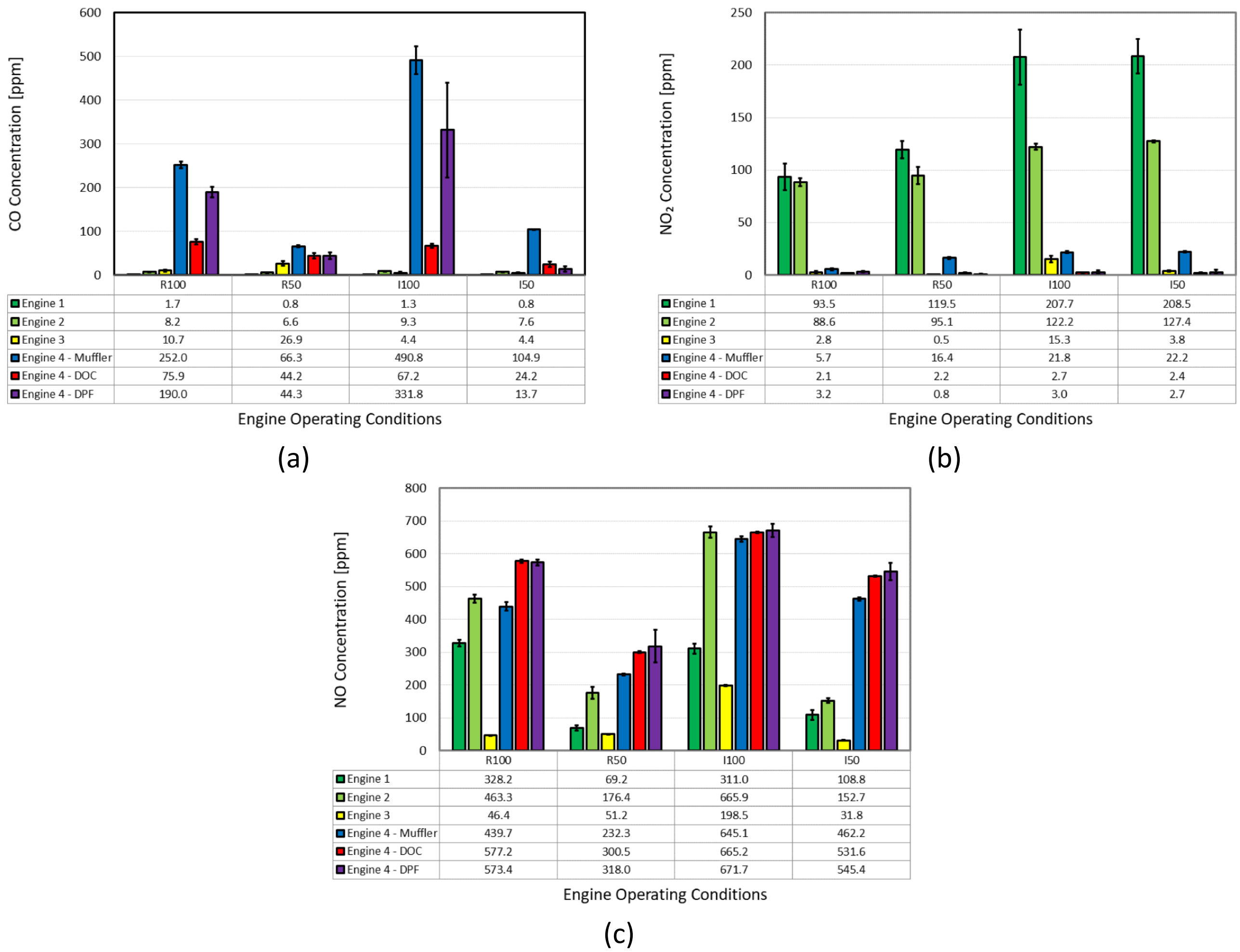


Fig. 5 Concentrations of criteria gases. **a** CO, **b** NO_2. **c** NO. The error bars represent one standard deviation of mean. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

diameters (Fig. 4, Table 4) and generally contributed less to the mass concentrations of EC than accumulation mode aerosols emitted by traditional engines (Fig. 1). These observations are concordant with previous findings on the size distribution of aerosols emitted by advanced non-DPF non-road diesel engines [52, 53]. Under the test and measurement conditions generated in this study, the concentrations of nucleation mode aerosols and sub-23-nm aerosols were lower than the concentrations of accumulation mode aerosols (Fig. 4 and Table 4). The concentrations of nucleation mode aerosols could be higher if the hot exhaust of the test engines is released in the underground environment with local conditions favoring nucleation [85].

The findings are concordant with several previous studies that reported the adverse effects of the catalyzed exhaust aftertreatment devices on NO_2 emissions from mobile underground mining equipment [80, 88, 89]. The results confirmed that emissions of highly toxic NO_2 is an important factor influencing the selection and use of advanced diesel engines, particularly those fitted with catalyzed exhaust aftertreatment devices, in the underground mining industry. In the underground mines that operate engines that emit NO_2 at the levels characteristic of traditional engines ($NO_2 = 0.01 – 0.20\ NOx$) [39, 90], the NO_2 exposures have been historically maintained below action levels (e.g., one-half of the 5-ppm MSHA ceiling limit) [35, 37, 91] by means of dilution using air quantities determined to keep exposures to the other most critical criteria gas, namely CO, NO, or CO_2, below respective personal exposure limits [40, 92]. However, the introduction of certain types of catalyzed exhaust aftertreatment devices characterized by elevated secondary NO_2 emissions changed that paradigm [39, 79, 89, 92, 93]. In the exhaust of Engine 1 and Engine 2, the concentrations of NO_2 exceeded 200 ppm ($NO_2 > 0.65\ NOx$) and 125 ppm ($NO_2 > 0.45\ NOx$), respectively. In the case of Engine 1 that would be operated in a typical US underground metal/nonmetal mine, the quantities of air needed to dilute NO_2 to corresponding PEL would be 3.5 times higher than those needed

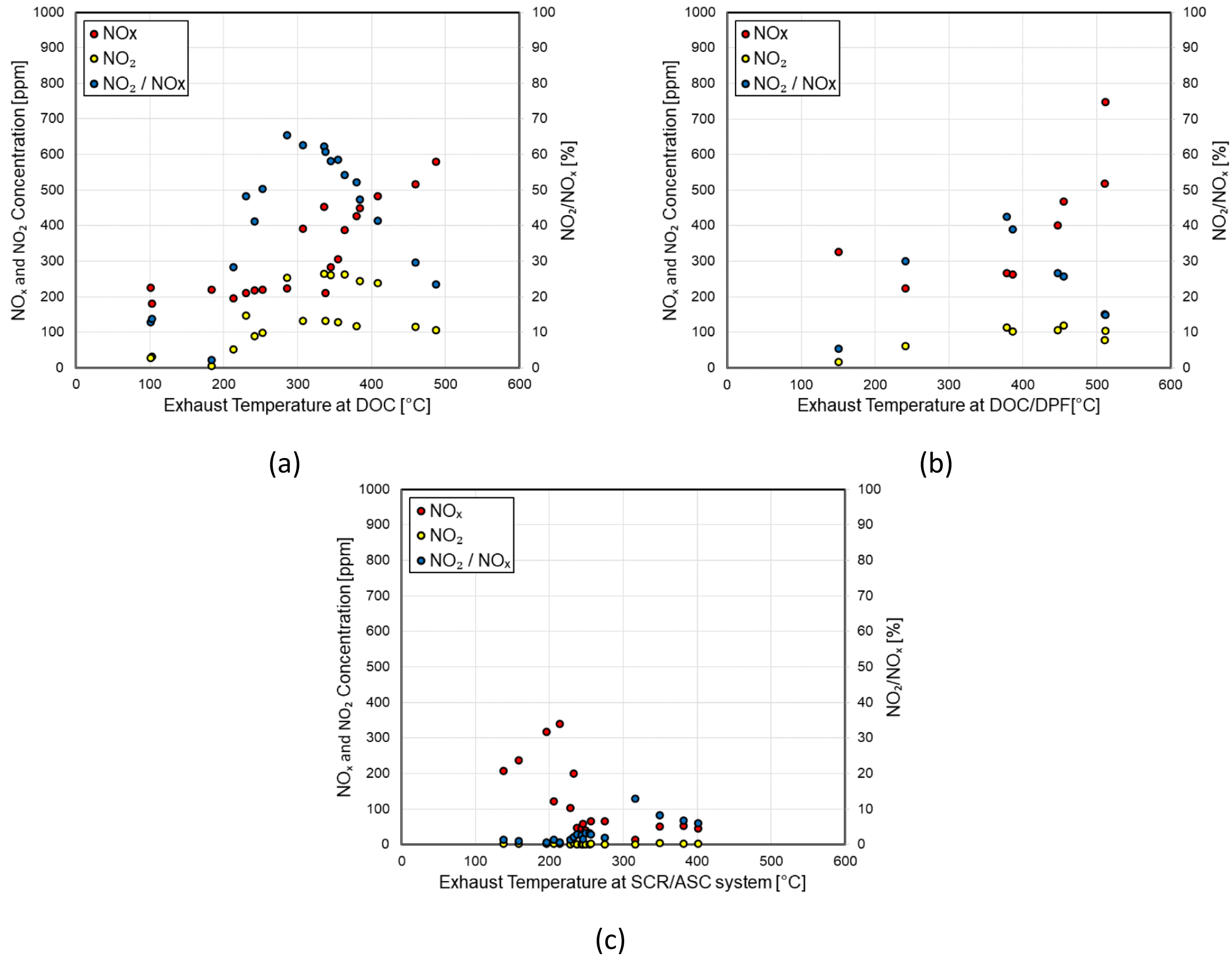


Fig. 6 Dependence of NO*x* emissions and NO_2/NO*x* relationship on exhaust temperature at the inlet to the exhaust aftertreatment devices for **a** Engine 1, **b** Engine 2, and **c** Engine 3

to dilute the next criteria gas, CO_2, to the corresponding PEL. Similarly, for Engine 2, the quantities of air needed to dilute NO_2 would be 1.6 times higher than those needed to dilute next criteria gas, NO, to corresponding PEL. Depending on circumstances, providing the additional quantities of air needed to address elevated NO_2 concentrations might be technologically challenging and potentially cost-prohibitive [94]. This would be the case, particularly for the operations in the Canadian provinces which adopted the PEL for NO_2 based on the current ACGIH® TLV® of 0.2 ppm [95], or for the operations in the European Union member states that have to comply with the 8-h time weighted average NO_2 PEL of 0.5 ppm and short-term NO_2 PEL of 1.0 ppm [36]. Therefore, optimization of the catalyst formulations [96, 97] for underground mining applications and incorporation of NO_2 control technologies, such as SCR systems, would be critical to protecting the health of underground miners. The results of previous evaluations of NO_2-suppressing catalyst formulations washcoated to the elements in DOC and DPF devices, retrofitted to the traditional engines, demonstrate that CO emissions can be adequately reduced without adversely affecting NO_2 emissions [39, 80]. In the cases of the engines evaluated in this study, the lowest NO_2 emissions were found for the DOC/SCR/ASC equipped Engine 3. The promulgation of the particulate number and more stringent nitrogen oxide (NOx) emission standard [47] should result in the development of the diesel power packages with power outputs between 19 kw (25 hp) and 560 kW (750 hp) that should concurrently manage particulate number concentrations, NO, and NO_2 emissions.

In addition to lower tailpipe emissions, advanced engines should have an advantage over traditional engines in terms of the low blow-by emissions. In the case of traditional engines, blow-by emissions typically vented through the unfiltered or filtered crankcase ventilation system could contribute to the emissions of aerosols and gases, particularly those originating from lubricating oil [59, 98, 99]. In the case of the advanced engines evaluated in this study, the blow-by emissions were vented back to the engine intake through the closed crankcase breather systems and technically integrated with tailpipe emissions. It is important to note that the blow-emissions of Engine 4, equipped with open crankcase ventilation system were not quantified and included in total emissions.

The wide implementation of advanced diesel engine technologies has potential to substantially change the physical and chemical properties of diesel aerosols and the composition of criteria gases in the underground workplaces. In order to better protect the health of underground miners from the adverse effects of exposure to diesel aerosols, the traditionally used mass-based diesel aerosols exposure monitoring methodologies [32––34] might need to be complemented with those using number- and/or surface area-based methodologies [100–104], and additional information on the aerosol chemistry might be needed to properly assess the health risk associated with these exposures [100, 101, 104]. Since NO_2 was identified as one of the primary toxic components of the exhaust of advanced diesel engines [62], the monitoring of NO_2 exposures should be strengthened to protect the health of miners working downwind of those engines.

The emissions data described in this manuscript were obtained for a very limited number of engines evaluated under laboratory conditions for a limited set of steady-state engine operating conditions and environmental conditions. Further evaluation of the larger fleets of mobile equipment powered by advanced engines and operated over the wider variety of actual engine duty cycles in real mining operations and environmental conditions are warranted to further advance the understanding of the potential impacts these technologies might have on the health of underground miners.

5 Conclusion

The results of this study confirmed that widespread implementation of viable advanced diesel technologies could help the industry to substantially reduce the contribution of diesel-powered mobile equipment to elemental and organic carbon mass concentrations. The results indicate that the highest reductions in both mass and number concentrations of diesel aerosols could be achieved if selected engines, preferably in all pertinent power classes, are equipped with viable full-flow diesel particulate filter systems. The significant reductions in elemental and organic carbon mass concentrations, at somewhat lower levels from those achievable with the advanced engines fitted with the full-flow diesel particulate filter systems, could be expected if traditional engines are replaced with the advanced engines equipped with diesel oxidation catalyst and selective catalyst reduction systems. However, in the case of the engines that are not fitted with DPF systems, the reductions in number concentrations could be substantially less than those in mass concentrations.

For the generated test conditions, the aerosols emitted by advanced engines were found to be bimodally distributed between nucleation and accumulation modes. The size of the accumulation mode aerosols emitted by the engines that are not fitted with diesel particulate filter systems were smaller than the sizes of aerosols emitted by the traditional engine, indicating more effective in-cylinder combustion controls. Outside of the regeneration events, the concentrations of nucleation mode aerosols were found to be substantially lower than those of accumulation mode aerosols.

The secondary emissions of nitrogen dioxide proved to be one of the major factors affecting selection of advanced engines fitted with the DOC and DOC/DPF systems for underground mining applications. The catalyst formulations in the similar systems used in underground mining applications need to be formulated to efficiently control carbon monoxide and hydrocarbon emissions and support diesel particulate filter regeneration without substantially promoting secondary nitrogen dioxide emissions. The integration of the selective catalyst reduction systems into advanced engine systems destined for the underground mining applications could potentially provide an alternative solution to nitrogen dioxide emissions. The low carbon monoxide emissions observed for the engines evaluated in this study indicate that controlling those emissions does not present a major challenge.

The limited data set generated in this study indicates that there are several critical aspects that must be considered during the process of creation and selection of diesel engines and exhaust aftertreatment systems for underground mining applications, in order to avoid diminishing the overall benefits of implementing advanced diesel technologies. With few caveats, the engine certification processes under jurisdictions of U.S. Environmental Protection Agency and similar agencies across the globe are an important useful source of information on diesel emissions. However, due to nuances associated with the use of diesel-powered mobile equipment in the underground mines, those processes, primarily tuned toward certification of diesel engines for surface applications, might not provide sufficient information to allow for proper selection of power trains for underground mining applications. Specifically, the information on the performance of the catalyst as a function of duty cycle (exhaust temperatures) appears to be missing information particularly critical to the process of selection of viable catalyzed exhaust aftertreatment systems for the engines operated in the sections of mines ventilated with limited quantities of air.

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Disclaimer

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of company names or products does not constitute endorsement by NIOSH or CDC.

Data Availability The data underlying this article will be shared on reasonable request to the corresponding author.

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