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Diesel Powertrains for Underground Mining Mobile Equipment

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ABSTRACT

The results of laboratory characterization of tailpipe emissions for three "clean" engines that meet U.S. EPA Tier 4 final emissions standards were used to assess the viability and effectiveness of repowering existing engines and powering new mobile equipment with those engines as a control strategy for reducing exposure of underground miners to diesel aerosol and criteria gases. 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. It appears that the catalyst formulations used in the exhaust aftertreatment systems of the "clean" engines marketed to the underground mining industry need to be formulated to minimize the potential for generation of secondary NO_2 emissions. The results indicate that the engines fitted with viable SCR/ASC systems present a low-NO_2 alternative. All three "clean" engines were found to have low CO output. Therefore, due to nuances associated with the use of diesel-powered mobile equipment in underground mines, special attention needs to be paid to the selection and potentially optimization of "clean" engines for underground mining applications.

Keywords: Diesel engines, underground mining, emissions, diesel particulate matter, nitrogen dioxide

INTRODUCTION

In the case of underground mining operations, the substantial fraction of energy demand is associated with the use of diesel-powered mobile equipment to load, transport, and drill ore and transport materials and personnel (1,2,3,4,5,6,7,8,9). The diesel engines are ubiquitous due to relatively high efficiency, reliability, and durability. However, the extensive use of the diesel-powered underground mining mobile equipment contributes substantially to the exposure of underground miners to submicron aerosols, also known as diesel particulate matter (DPM), and toxic gases including CO, NO, NO_2, and hydrocarbons (10). The long-term exposure to complex mixtures of submicron aerosols and gas emitted by traditional diesel engines was found to result in adverse pulmonary (11,12,13,14), cardiovascular (15,16,17,18), and other health outcomes (19,20,21). In 2012, based on the available evidence, the International Agency for Research on Cancer (IARC) declared diesel exhaust a Group 1 human carcinogen (22).

The use of diesel engines in underground mines is regulated worldwide (23). In the United States, 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 inby 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 U.S. 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 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 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 "clean" diesel engines that meet EPA Tier 4 final or more stringent standards.

The exposure limits for underground miners for DPM (32,33,34) and criteria gases (35,36,37) emitted by diesel engines were established on the 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): (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 (40,41,42,43,44), (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 "clean" engines that meet more stringent contemporary standards (28,29, 45,46,47,48,49), 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 (51,52,53), (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 (39,54,55,56], and (3) improved control of blow-by emissions via closed crankcase ventilation system (57,58,59), were used in "clean" engines to substantially reduce particulate mass and criteria gaseous emissions. The reductions in particulate concentrations have been complemented with substantial changes in the physical, chemical, and toxicological properties of emitted aerosols (60,61,62,63,64).

Based on those developments, the substitution of the "traditional" diesel engines with contemporary "clean" diesel engines with substantially lower tailpipe and crankcase emissions (56,63,65,66,67) 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 powertrains in a harsh environment over a wide range of duty cycles, higher cost (68), and potential for the inadvertent introduction of new health hazards (39,69,70,71,72), are some of the factors that have so far hindered wider implementation of "clean" 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 selected 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.

METHODOLOGY

The analysis was performed on the results of the evaluations of aerosol and gaseous emissions of three "clean" engines (Engine 1, Engine 2, and Engine 3) that utilize various in-cylinder control strategies and three different exhaust aftertreatment control strategies to meet U.S. 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 "clean" 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 [40] for three different exhaust configurations: (1) muffler (Engine 4), (2) retrofitted with DOC

(AirFlow Catalyst Systems, Model MinNoDOC) (Engine 4 - DOC), and (3) retrofitted with full flow DPF system (NETT Technologies, 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 powertrains (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.

The emissions were characterized for four steady-state engine operating conditions (Table 3) achieved using a 400-kW, water-cooled, eddy-current dynamometer (SAJ, AE400). 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 (78,79). 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.

The 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. The carbon analysis was performed on the triplicate filter samples collected using the custom-made sampling system. The samples were collected on the 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 pre-baked at 800 °C for 4 hours. A nominal sampling flow rate of 12.0 lpm was maintained

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

Table 2. Properties of fuels used in the study

Property	Unit	Engine 1 and 4	Engine 2 and 3
API gravity	^{0}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

by subsonic critical orifices, installed in the 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) (80) performed on the 1.5 cm^2 filter segments using an OC/EC Aerosol Analyzer (Sunset Laboratory Inc., Portland, OR). The results of the analysis performed on the secondary QFFs were used as a dynamic blank correction for the primary QFFs.

The 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. The carbon analysis was performed on the triplicate filter samples collected using the custom-made sampling system. The samples were collected on the 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 pre-baked at 800 °C for 4 hours. A nominal sampling flow rate of 12.0 lpm was maintained by subsonic critical orifices, installed in the manifolds coupled to a single vacuum pump. The EC and OC mass concentrations were determined using thermal optical transmittance-evolve gas analysis (TOT-EGA) [82] performed on the 1.5 cm^2 filter segments using an OC/EC Aerosol Analyzer (Sunset Laboratory Inc., Portland, OR). 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 (17,81,82,83), the mass measurements were complemented with measurements of the number concentrations and size distributions of aerosols with electrical mobility diameters between 5.6 nm to 560 nm. Those were measured with the fast mobility particle sizer (FMPS) spectrometer (TSI, Model 3091). In order to enhance the clarity of the figures, the aerosol size distributions were fitted with log-normal curves using the DistFit software from Chimera Technologies (Forest Lake, MN). The concentrations of CO, NO, and NO_2 in raw exhaust were measured in 20-second intervals using a Fourier transform infrared (FTIR) spectrometer (Gasmet Technologies Oy, Model DX-4000). The exhaust flow rates were calculated using results of measurements of intake flow rates by the laminar flow meters (Meriam, Models Z50MC2-6F and Z50MC2-4) and fuel mass flow rated by the fuel metering system (Max Machinery, Model 710).

RESULTS

The emissions of the aerosols and gases were compared on the level of the tailpipe concentrations. During the 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 criteria gases were measured directly in raw exhaust, the dilution corrections were not necessary for that set of data.

The average EC and OC mass concentrations for all evaluated engines/configurations are shown in Figure 1. For all test conditions, the EC and OC mass concentrations were found to be substantially lower in the exhausts of the "clean" engines (Engine 1, Engine 2, and Engine 3) than in the exhaust of the "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 muffler and comparable to those in the exhaust of Engine 4 retrofitted with DPF (Figure 1). The EC and OC mass concentrations were 74 to 96 percent and 48 to 99 percent, respectively, lower in the exhaust of DOC fitted Engine 1 than the exhaust of Engine 4 operated with the muffler and 64 to 94 percent and 36 to 96 percent, respectively, in the exhaust of Engine 4 operated with the DOC (Figure 1). In the exhaust of Engine 3, the EC and OC mass concentrations were 72 to 88 percent and 23 to 93 percent, respectively, lower in the exhaust of DOC/SCR/ASC fitted Engine 3 than the exhaust of Engine 4 operated with muffler.

The fractions of EC in total carbon (TC=EC+OC) were calculated for the selected cases shown in Figure 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 (Figure 2). Except for the R50 test mode, the EC/TC ratios were higher for the "clean" non-DPF engines (Engines 1 and Engine 3) than for the "traditional" engine (Engine 4 with the muffler).

The average total number concentrations (TNCs) of aerosol for all evaluated engines/configurations are shown in Figure 3. Only in the case of two "clean" engines (Engine

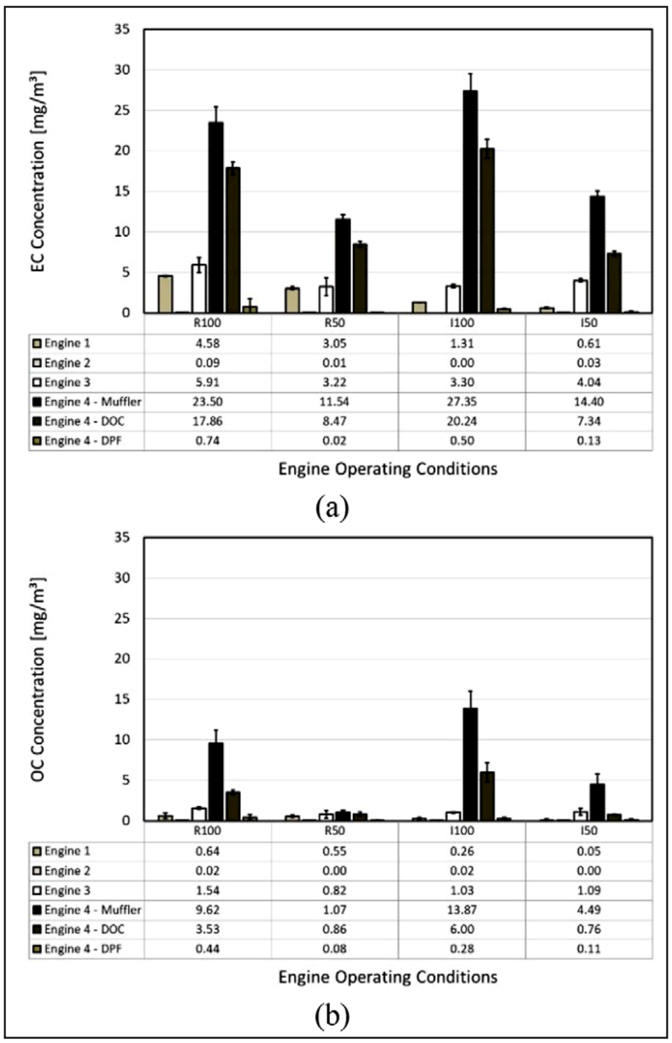

Figure 1. Carbon concentrations: (a) EC and (b) OC. The error bars represent one standard deviation of mean. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

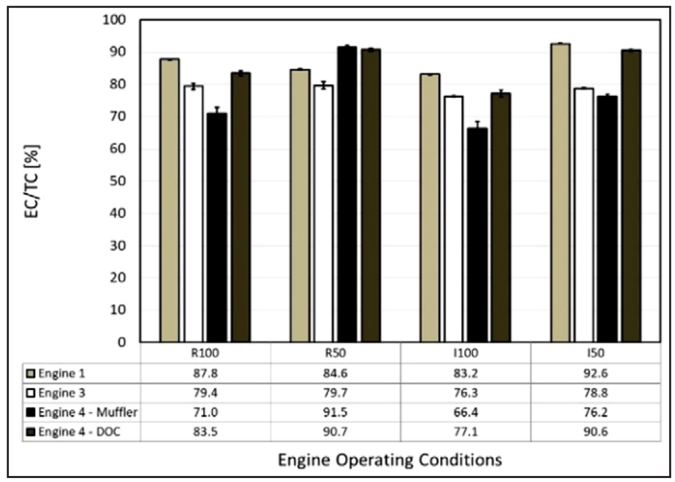

Figure 2. EC in TC

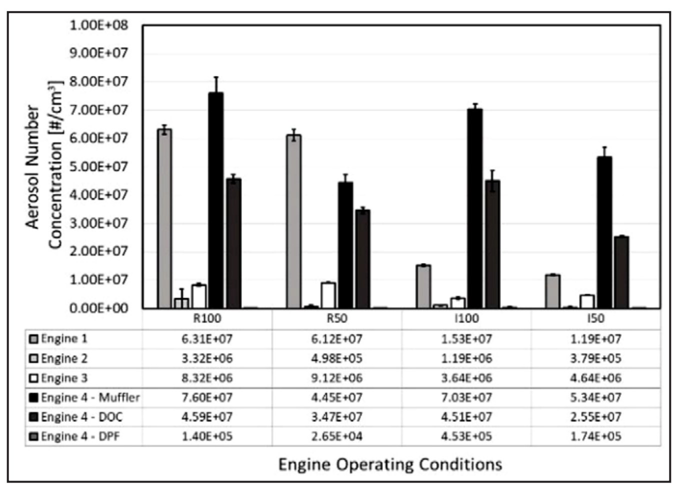

Figure 3. Total aerosol number concentration. The error bars represent one standard deviation of mean. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

2 and Engine 3), the TNCs were lower than corresponding TNCs in the exhaust of the "traditional" engine operated with the muffler or DOC (Figure 3). The lowest TNCs were found in the exhaust of the DOC/DPF-fitted Engine 2. Those were between 155 and 1,679 times lower than 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 DPF, the average TNCs included those intermittent spikes in concentrations coinciding with periodic DPF regeneration events.

The average TNCs were 96 to 99 percent 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 percent and in the exhaust of Engine 4 retrofitted with the DOC by 76 percent. When operated at the R100 condition, the TNCs were 38 percent 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 Engine 1 and Engine 3 were lognormally distributed in single accumulation mode or between accumulation and nucleation modes (Figure 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 "clean" 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 (Figure 4 and Table 4). The TNCs in the filtered exhaust were found to be rather low and quite variable. Generally, the concentrations of

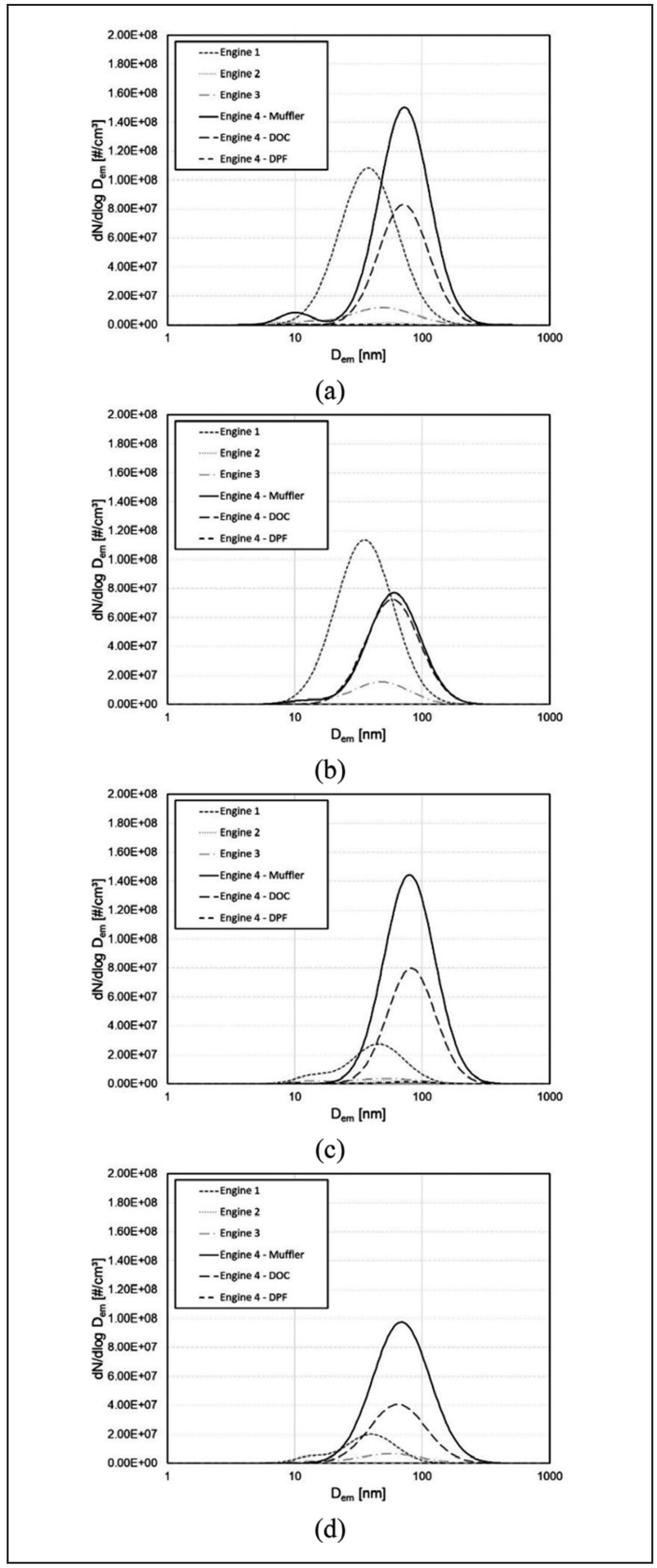

Figure 4. Size distribution of aerosols captured 1,800s into tests for: (a) R100, (b) R50, (c) I100, and (d) I50 engine operating conditions. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

Table 4. Statistical parameters, count median diameter (CMD), spread (σ), and total concentrations, for size distribution of aerosols emitted by the evaluated engines measured 10,800 seconds 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

aerosols in nucleation modes in filtered exhaust were lower than those in corresponding accumulation mode (Table 4).

The effects of the evaluated engines/configurations on the CO, NO_2, and NO concentrations were studied using data summarized in Figure 5. The CO emissions for Engine 1, Engine 2, and Engine 3, all fitted with catalyzed devices, were mutually comparable and substantially lower than corresponding CO emission from Engine 4, in all exhaust configurations (Figure 5a). The data showed that 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 (Figure 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 (Figure 6).

The results of additional 900-second tests conducted at intermediated and rated speeds showed that for the exhaust temperatures in the range between 250 °C and 350 °C, the observed fraction of NO_2 in NOx (NOx = NO + NO_2) in the exhaust of Engine 1, expressed as a percentage, exceeded sixty (Figure 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 forty (Figure 6b).

The NO emissions were decisively lowest in the exhaust of Engine 3, fitted with the DOC/SCR/ASC system (Figure 5c). The NO_2 emissions from the same engine were comparable to those of Engine 4 in all exhaust configurations (Figure 5b). The results of additional 900-second tests conducted at intermediated and rated speeds showed

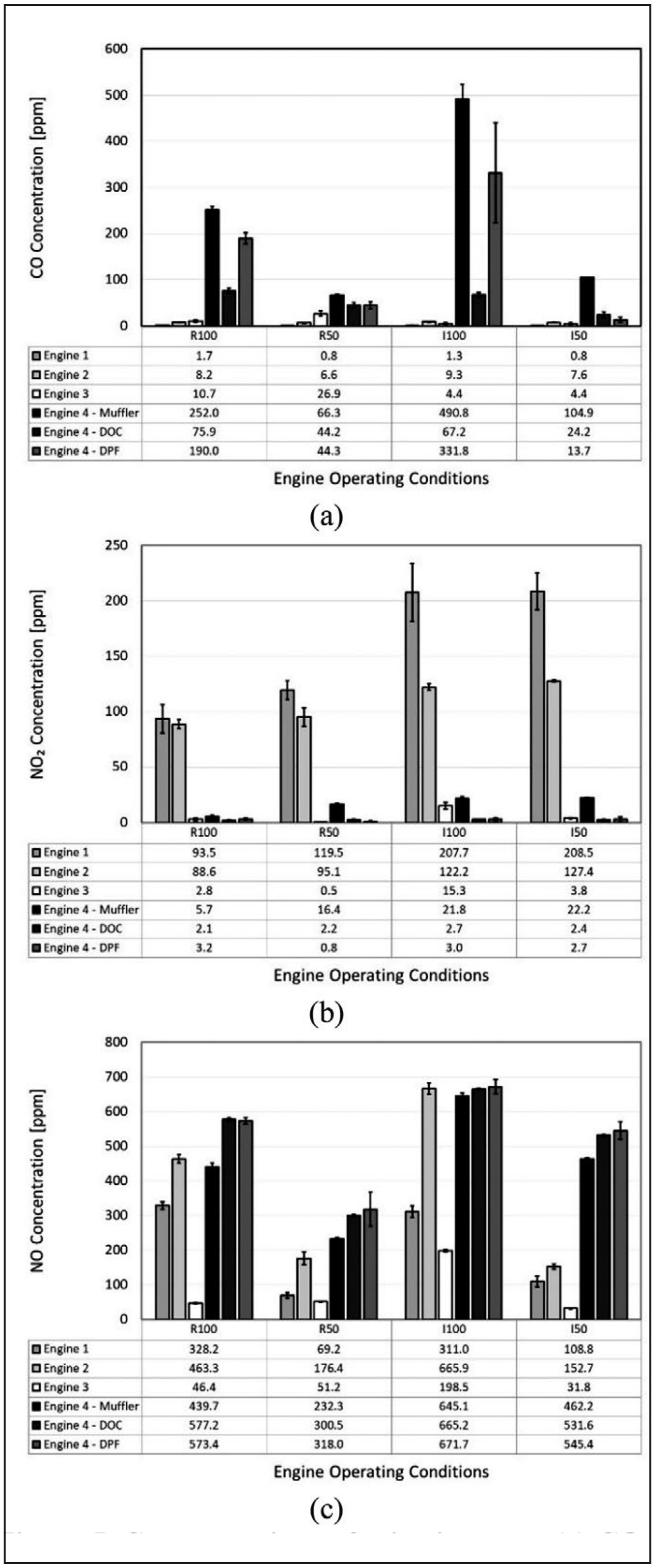

Figure 5. Concentrations of criteria gases: (a) CO, (b) NO_2, and (c) NO. The error bars represent one standard deviation of mean. The results for Engine 3 and Engine 4 were adopted from a previous publication [39]

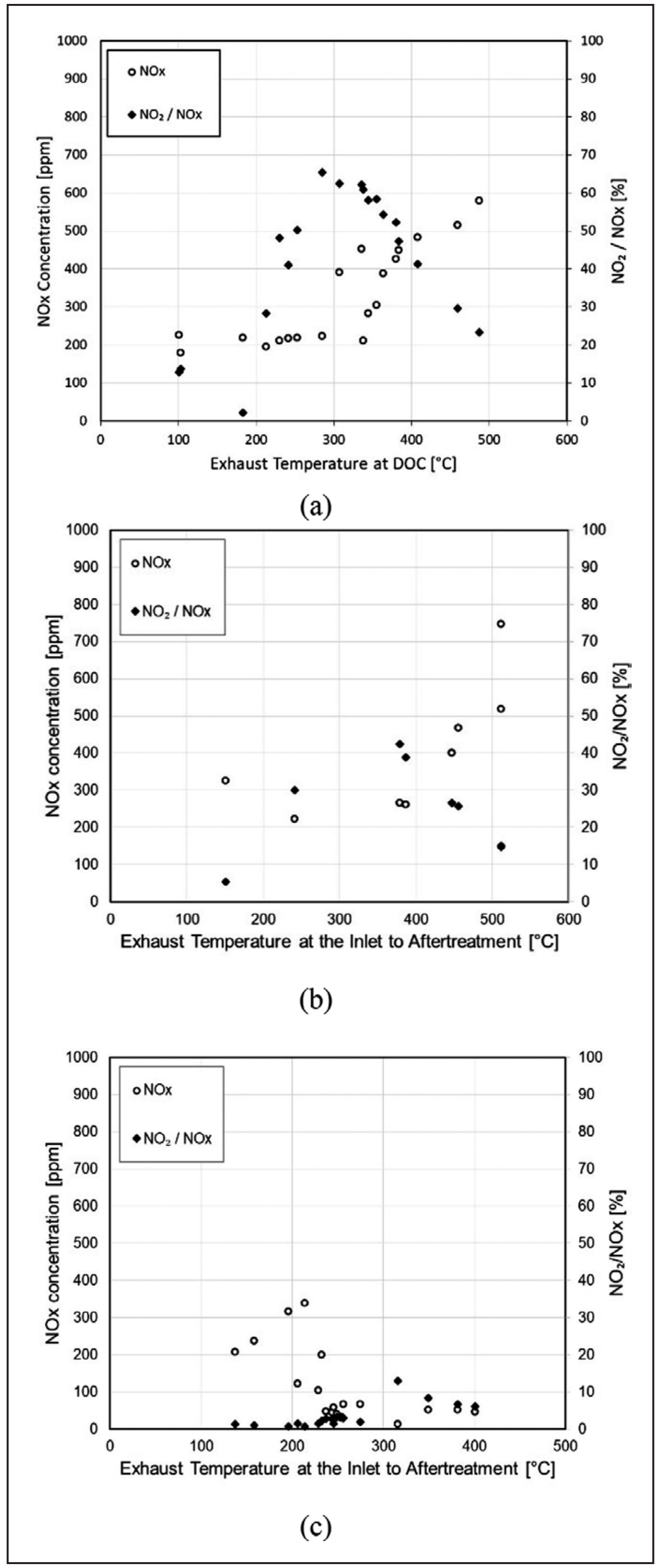

Figure 6. Dependance of NOx emissions and the NO_2/NOx relationship on exhaust temperature at the inlet to the exhaust aftertreatment devices for: (a) Engine 1, (b) Engine 2, and (c) Engine 3

that the observed fraction of NO_2 in NOx in the exhaust of Engine 3 expressed as a percentage did not exceed thirteen (Figure 6c).

DISCUSSION

Minimizing the contribution of diesel-powered mobile equipment to concentrations of aerosols and gases plays an important role in the efforts to reduce exposures of underground miners to diesel aerosols and gases (38). The advancements in the nonroad diesel engine technologies made over the past couple decades led to substantial improvements in combined tailpipe and blow-by emissions. As a result, the operators got the opportunity to repower the existing equipment and power new mobile equipment with "clean" 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.

It is important to recognize that 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 ($19 \leq kW < 37$, $37 \leq kW < 56$, $56 \leq kW < 130$) and represent different emission control solutions. The study was conducted with objectives of closer examination of the tailpipe emissions for "clean" engines and gaining additional insight into the effectiveness and viability of those engines as a control strategy for 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 "clean" engines, similar to the ones evaluated in this study (Engine 1, Engine 2, and Engine 3), with low EC and OC mass emissions (Figure 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 current mass-based standards (32,33,34). However, if used, the "clean" 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 (Figure 3 and Figure 4). Only "clean" 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 (Figure 1 and Figure 3). The use of advanced in-cylinder combustion controls strategies, particularly higher injection pressures (51,52,53), 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 diameters (Figure 4, Table 4) and generally contributed less to the mass concentrations of EC than accumulation mode aerosols emitted by "traditional" engines (Figure 1). That was the case even for Engine 1 operated at R50 test conditions where number concentrations of aerosols in the accumulation mode were higher than corresponding number concentrations of aerosols in the accumulation mode for "traditional" engine (Table 4), but mass concentrations of EC were substantially lower (Figure 1). For the test and measurement conditions generated in this study, the concentrations of nucleation mode aerosols and sub-23 nm aerosols were found to be relatively low when compared with concentrations of accumulation mode aerosols (Figure 4 and Table 4). The concentrations of nucleation mode aerosols could be potentially higher if hot exhaust of the test engines is released in the underground environment characterized by meteorological conditions favoring nucleation (84).

The results of this study showed that emissions of highly toxic NO_2 could be quite an important factor influencing selection and use of "clean" 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 to "traditional" engines (NO_2 = 0.01 – 0.20 NOx) (39,85), the NO_2 exposures have been historically maintained below action levels (e.g., one half of the 5 ppm MSHA ceiling limit) (35,37,86) by means of "fresh" air 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 (40,87). However, the introduction of certain types of catalyzed exhaust aftertreatment devices characterized by elevated secondary NO_2 emissions changed that paradigm (39,79,88,89). In the exhaust of Engine 1 and Engine 2 evaluated in this study, the concentrations of NO_2 exceeded 200 ppm (NO_2 > 0.65 NOx) and 125 ppm (NO_2 > 0.45 NOx), respectively. In this case, Engine 1 would be operated in the U.S. underground metal/nonmetal mines, and the quantities of air needed to dilute NO_2 to the corresponding permissible exposure level (PEL) should be 3.5 times higher than those needed to dilute the next criteria gas, CO_2, to the corresponding PEL. In the similar case involving Engine 2, the quantities of air needed to dilute NO_2 should be 1.6 times higher than those needed to dilute the next criteria gas, NO, to the corresponding PEL. Depending on circumstances, providing additional quantities of "fresh" air needed to address elevated NO_2 concentrations might be technologically challenging and potentially cost-prohibitive

(90). This would be the case, particularly for the operations in the Canadian provinces that adopted the PEL for NO_2 based on the current ACGIH® TLV® of 0.2 ppm (91), or for the operations in the European Union member states that have to comply with the 8-hour 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 (92,93) for underground mining applications and incorporation of NO_2 control technologies such as SCR in the 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 (39,79). 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 (48) 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 for NO and NO_2 emissions.

In addition to relatively low tailpipe emissions, "clean" engines should have an advantage over "traditional" engines in terms of the relatively low blow-by emissions. In the case of "traditional" engine, 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 (59,94,95). In the case of "clean" 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 "clean" diesel engine technologies has the potential to substantially change the physical and chemical properties of diesel aerosols and the composition of criteria gases in the underground workings. 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 (96,97,98,99,100). The additional information on the aerosol chemistry might be needed to properly assess the health risk associated with exposure to those diesel aerosols (96,97,100). Since NO_2 was identified as one of the primary toxic components of the exhaust of "clean" diesel engines (62), the monitoring of NO_2 exposures should be strengthened to protect the health of the workers spending time downwind of those engines.

CONCLUSION

The results of this study confirmed that widespread implementation of "clean" diesel technologies, similar to those evaluated in this study, could help the industry to substantially reduce the contribution of diesel-powered mobile equipment to mass concentrations of EC and OC in underground mines. The results indicate that the highest reductions in contributions to both mass and number concentrations of diesel aerosols could be achieved if selected "clean" engines, preferably in all pertinent power classes, are equipped with viable full-flow DPF systems. The significant reductions in mass concentrations of EC and OC, at somewhat lower levels from those achievable with the "clean" engines fitted with the full-flow DPF systems, could be expected if "traditional" engines are replaced with the "clean" engines equipped with DOC and DOC/SCR/ASC systems. However, in the case of "clean" engines that are not fitted with DPF systems, the reductions in number concentrations could be substantially lower than those in mass concentrations.

For the generated test conditions, the aerosols emitted by "clean" engines were found to be bimodally distributed between nucleation and accumulation modes. The size of accumulation mode aerosols emitted by the non-DPF "clean" engines were noticeably 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 relatively low, substantially lower than those of accumulation mode aerosols.

The secondary NO_2 emissions for the "clean" engines fitted with the DOC and DOC/DPF systems proved to be one of the major factors affecting the selection of "clean" engines for underground mining applications. The catalyst formulations in the similar systems used in underground mining applications need to be formulated to efficiently control CO and HC emissions and support DPF regeneration without substantially promoting secondary NO_2 emissions. The integration of SCR/ASC into "clean" engine systems destined for the underground mining applications could potentially provide an alternative solution to NO_2 emissions. The relatively low CO 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 the several aspects critical to the process of selection of diesel engines and exhaust aftertreatment systems for underground mining applications need to be considered in order to avoid diminishing the overall benefits of implementing "clean" diesel technologies. With few caveats, the engine certification processes under jurisdictions of EPA and similar agencies across the globe are an important useful source of information on diesel emissions. However, due to nuances associated with 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; e.g., 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 catalyzed exhaust aftertreatment systems for the "clean" engines operated in the sections of mines ventilated with limited quantities of air.

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DISCLAIMER

The findings and conclusions of this publication have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be constituted to represent any agency determination or policy. Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

[1] Bugarski, Aleksandar D. and John D. Potts (2018), "Exposures of underground miners to diesel particulate matter in the United States," 24th Annual Mining Diesel Emission Conference (MDEC Conference. Toronto, Ontario, Canada, October 2–4.).

[2] Saarikoski, Sanna, Laura Salo, Matthew Bloss, Jenni Alanen, Kimmo Teinilä, Felipe Reyes, Yeanice Vázquez, Jorma Keskinen, Pedro Oyola, Topi Rönkkö, and Hikka Timonen (2019), "Sources and characteristics of particulate matter at five locations in an underground mine," Aerosol and Air Quality Research, 19: 2613–2624 https://doi.org/10.4209/aaqr.2019.03.0118.

[3] Saarikoski, S, K. Teinilä, H. Timonen, M. Aurela, T. Laaksovirta, F. Reyes, Y. Váasques, P. Oyola, P. Artaxo, A.S. Pennanen, S. Junttila, M. Linnainmaa, R.O. Salonen, and R. Hillamo (2018), "Particulate matter characteristics, dynamics and sources in an underground mine," Aerosol. Sci. Technol. 52(1):114–122. https://doi.org/10.1080/02786826.2017.1384788.

[4] Katta, Anil K., Matthew Davis, and Amit Kumar (2020), "Development of disaggregated energy use and greenhouse gas emission footprints in Canada's iron, gold, and potash mining sector," Resource, Conservation & Recycling 152: 104485. https://doi.org/10.1016/j.resconrec.2019.104485.

[5] Bugarski, Aleksandar D., Jon A. Hummer, Shawn Vanderslice, and Michael R. Shahan (2020), "Characterization of aerosols in an underground mine during a longwall move," Mining, Metallurgy & Exploration (MM&E 37:1065–1078. https://doi.org/10.1007/s42461-020-00209-6.

[6] Bugarski, Aleksandar D., Shawn Vanderslice, Jon A. Hummer, Teresa L. Barone, Steven E. Mischler, Shawn Peters, Steve Cochrane, and Jared Winkler (2021), "Diesel aerosols and gases in an underground coal mine," Tukkaraja P (Ed): Proceedings of the 18th North American Mine Ventilation Symposium (NAMVS) 2021, June 12–17, 2021, Rapid City, South Dakota, USA, 95–104, https://doi.org/10.1201/9781003188476-10.

[7] Gren, Louise, Annette M. Krais, Eva Assarsson, Karin Broberg, Malin Engfeldt, Christian Lindh, Bo Strandberg, Joakim Pagels, and Maria Hedmer (2022), "Underground emissions and miners' personal exposure to diesel and renewable diesel exhaust in a Swedish iron ore mine," International Archives of Occupational and Environmental Health 95:1369–1388, https://doi.org/10.1007/s00420-022-01843-x.

[8] Halim A., J. Lööw, J. Johansson, J. Gustafsson, A. van Wageningen, K. Kocsis (2022), "Improvement of working conditions and opinions of mine workers when battery electric vehicles (BEVs are used instead of diesel machines - Results of field trial at the Kittilä Mine, Finland," Mining, Metallurgy & Exploration 39:203–219. https://doi.org/10.1007/s42461-021-00506-8.

[9] MSHA (2024a), "National coal diesel inventory," Mine Safety and Health Administration. Available from https://egov.msha.gov/DieselInventory/ViewDieselInventoryExternal.aspx. (Accessed on July 10, 2024).

[10] MSHA (2024b), "Personal Health Samples," U.S. Department of Labor, Mine Safety and Health Administration. Available from https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp. (Accessed May 2024).

[11] Attfield, Michael D., Patricia L. Schleiff, Jay H. Lubin, Aaron Blair, Patricia A. Stewart, Roel Vermeulen, Joseph B. Coble, and Debra T. Silverman, (2012), "The Diesel Exhaust in Miners study: A cohort mortality study with emphasis on lung cancer," J Natl Cancer Inst 104:869–883. https://doi.org/10.1093/jnci/djs035.

[12] Silverman, Debra T., Claudine M. Samanic, Jay H. Lubin, Aaron E. Blair, Patricia A. Stewart, Roel Vermeulen, Joseph B. Coble, Nathaniel Rothman, Patricia L. Schleiff, William D. Travis, Regina G. Ziegler, Sholom Wacholder, and Michael D. Attfield (2012), "The Diesel Exhaust in Miners Study: A nested case-control study of lung cancer and diesel exhaust," J Natl Cancer Inst 104:855–868. https://doi.org/10.1093/jnci/djs034.

[13] Vermeulen, Roel, Debra T. Silverman, Eric Garshick, Jelle Vlaanderen, Lützen Portengen, and Kyle Steenland (2014), "Exposure-response estimates for diesel engine exhaust and lung cancer mortality based on data from three occupational cohorts," Environ Health Perspect.122(2 :172–7. https://doi.org/10.1289/ehp.1306880.

[14] Du, Mengran, Graham L. Hall, Peter Franklin, A.W.(Bill) Musk, Benjamin J. Mullins, Nicholas de Klerk, Novak S.J. Elliott, Nita Sodhi-Berry, Fraser Brims, and Alison Reid (2020), "Association between diesel engine exhaust exposure and lung function in Australian gold miners," International Journal of Hygiene and Environmental Health, 226:113507, https://doi.org/10.1016/j.ijheh.2020.113507.

[15] Brook, Robert D., Sanjay Rajagopalan, C. Arden Pope 3rd, Jeffrey R. Brook, Aruni Bhatnagar, Ana V. Diez-Roux, Fernando Holguin, Yuling Hong, Russell V. Luepker, Murray A. Mittleman, Annette Peters, David Siscovick, Sidney C. Smith, Jr, Laurie Whitsel, and Joel D. Kaufman (2010), "Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association," Circulation 121(21) :2331–78. https://doi.org/10.1161/CIR.0b013e3181dbece1.

[16] Mills, Nicholas L., Mark R. Miller, Andrew J. Lucking, Jon Beveridge, Laura Flint, A. John F. Boere, Paul H. Fokkens, Nicholas A. Boon, Thomas Sandstrom, Anders Blomberg, Rodger Duffin, Ken Donaldson, Patrick W.F. Hadoke, Flemming R. Cassee, and David E. Newby (2011), "Combustion-derived nanoparticulate induces the adverse vascular effects of diesel exhaust inhalation," Eur Heart J 32(21): 2660–2671. https://doi.org/10.1093/eurheartj/ehr195.

[17] Franck, Ulrich, Siad Odeh, Alfred Wiedensohler, Birgit Wehner, Olf Herbarth (2011), "The effect of particle size on cardiovascular disorders - The smaller the worse." Science of The Total Environment 409 (20): 4217–4221. https://doi.org/10.1016/j.scitotenv.2011.05.049.

[18] Krajnak, Kristine, Hong Kan, Janet A. Thompson, Walter McKinney, Stacey Waugh, Tim South, Dru Burns, Ryan Lebouf, Jared Cumpston, Theresa Boots, and Jeffrey S. Fedan (2024), "Biological effects of diesel exhaust inhalation. III cardiovascular function." Inhalation Toxicology 36(3): 189–204. https://doi.org/10.1080/08958378.2024.2327364.

[19] Power, Melinda C., Marc G. Weisskopf, Stacey E. Alexeeff, Brent A. Coull, Avron Spiro III, and Joel Schwartz (2011), "Traffic-related air pollution and cognitive functions in a cohort of older men," Environ. Health Perspec 119:682–687. https://doi.org/10.1289/ehp.1002767.

[20] Nejad, Sayeh Heidari, Ryusuke Takechi, Benjamin J. Mullins, Corey Giles, Alexander N. Larcombe, Dean Bertolatti, Krassi Rumchev, Satvinder Dhaliwal, John Mamo (2015), "The effect of diesel exhaust exposure on blood-brain barrier integrity and function in a murine model," J Appl Toxicol. 35(1): 41–7. https://doi.org/10.1002/jat.2985.

[21] Naughton, Sean X., and Pasinetti, Giulio M. (2021), "Role of diesel exhaust exposure in promoting Alzheimer's disease susceptibility by impairing glymphatic drainage of amyloid beta (aβ) and other toxic metabolites from the brain," Alzheimer's Dement. 17: e056165. https://doi.org/10.1002/alz.056165.

[22] IARC (2012), "Diesel engine exhaust carcinogenic," IARC Press Release No. 213, June 12, World Health Organization. International Agency for Research on Cancer, Lyon, France.

[23] Gangal, Mahe (2019), "Summary of Worldwide Underground Mine Diesel Regulations," 25th Mining Diesel Emissions Council (MDEC) Conference, October. Available from https://mdec.ca/2019/S8P1_Mahe_Gangal.pdf (Accessed in August 2024).

[24] 61 Fed. Reg. 55411 (1996), "Approval, exhaust as monitoring, and safety requirements for the use of diesel-powered equipment in underground coal mines; final rule," 30 CFR Part 7. Mine Safety and

Health Administration. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[25] 66 Fed. Reg. 5907 (2001), "Engines. Safety and health standards: Underground metal and non-metal mines: 30 CFR Part 57," Mine and Safety Health Administration. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[26] MSHA (2024c), "Permissible Power Packages Approved Under Part 7," https://arlweb.msha.gov/TECHSUPP/ACC/lists/07pwrpkg.pdf. (Accessed July 10, 2024).

[27] MSHA (2024d), "Approved diesel engines. Available at https://egov.msha.gov/ReportView.aspx?ReportCategory=EngineAppNumbers. (Accessed July 10, 2024).

[28] 26 Fed. Reg. 645 (1961), "30 CFR Part 36. Approval requirements for permissible mobile diesel-powered transportation equipment," Mine Safety and Health Administration. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[29] 69 Fed. Reg. 38958 (2004), "40 CFR Parts 9, 69, 80, 86, 89, 94, 1039, 1048, 1051, 1065, and 1068. Control of emissions of air pollution from nonroad diesel engines and fuel; final rule," Environmental Protection Agency. U.S. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[30] 66 Fed. Reg. 5705 (2001), 30 CFR 72.502: "Requirements for nonpermissible light-duty diesel-powered equipment other than generators and compressors," Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[31] 66 Fed. Reg. 5909 (2001), 30 CFR 57.5067: "Safety and health standards: Underground metal and non-metal mines," Engines. Mine Safety and Health Administration. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[32] 70 Fed. Reg. 32996 (2005), "30 CFR 57.5060: Limit on Exposure to Diesel Particulate Matter. Safety and Health Standards-Underground Metal and Nonmetal Mines," Mine Safety and Health Administration. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[33] EU (2019), "Directive (EU) 2019/130 of the European Parliament and of the Council of 16 January 2019 amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work."

[34] AIOH (2013), "Diesel particulate matter & occupational health issues. Position Paper," Australian Institute of Occupational Hygienists (AIOH). AIOH Exposure Standards Committee. July.

[35] 50 Fed. Reg. 4096 (1985), 30 CFR 57.5001: "Safety and Health Standards. Underground metal and non-metal mines. Exposure limit for airborne contaminants," Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[36] EU (2017), "Commission Directive (EU) 2017/164 of 31 January 2017 establishing a fourth list of indicative occupational exposure limit values pursuant to Council Directive 98/24/EC, and amending Commission Directives 91/322/EEC, 2000/39/EC and 2009/161/EU."

[37] Safe Work Australia (2024), "Workplace exposure standards for airborne contaminants," Safe Work Australia. Available at: https://www.safeworkaustralia.gov.au/doc/workplace-exposure-standards-airborne-contaminants-2024. (Accessed July 2024).

[38] Bugarski, Aleksandar D., Samuel Janisko, Emanuele G. Cauda, James D. Noll, and Steven E. Mischler (2012), "Controlling Exposure - Diesel Emissions in Underground Mines," Society for Mining, Metallurgy, and Exploration. ISBN-13: 9780873353601, Available from: http://smemi.personifycloud.com/PersonifyEbusiness/Store/ProductDetails.aspx?productId=116967 (Accessed on April 19, 2023).

[39] Bugarski, Aleksandar D., Jon A. Hummer, Shawn Vanderslice and Teresa Barone (2020), "Retrofitting and re-powering as a control strategy for curtailment of exposure of underground miners to diesel aerosols," Min Metall Explor. 37(2): 791–802. https://doi.org/10.1007/s42461-019-00146-z.

[40] Haney, Robert A. (2012), "Ventilation requirements for modern diesel engines." In: Calizaya F., Nelson M.G. (Eds.): Proceedings of the 14th U.S./North American Mine Ventilation Symposium, University of Utah, Salt Lake City, UT.

[41] Stinnette, J. Daniel (2013), "Establishing total airflow requirements for underground metal/non-metal mines based on the diesel equipment fleet." M.A.Sc.

Thesis. Department of Mining Engineering, Queen's University, Kingston, ON.
[42] Halim, Adrian (2016), "Ventilation requirements for diesel equipment in underground mines - Are we using the correct values?," In: Brune J.F. (Ed): Proceedings of the 16th North American Mine Ventilation Symposium. Colorado School of Mines. Golden, CO.
[43] Allen, Cheryl and Jozef Stachulak (2019), "Mobile equipment power source-Impact on ventilation design," In: Chang, X. (ed.) Proceedings of the 11th International Mine Ventilation Congress. Springer, Singapore. https://doi.org/10.1007/978-981-13-1420-9_1.
[44] Saeidi N. and C. Allen (2022), "A discussion on underground mine ventilation design considerations for diesel vs. battery electric mobile equipment." CIM Journal, 14(1), 48–55. https://doi.org/10.1080/19236026.2022.2096398.
[45] EU (1998), "Directive 97/68/EC of the European Parliament and of the Council of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery." Official Journal of the European Union.
[46] EU (2004), "Directive 2004/ 26/EC of the European Parliament and of the Council of 21 April 2004 amending Directive 97/68/EC on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery."
[47] EU (2016), "EU 2016/1628: Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No. 1024/2012 and (EU) No. 167/2013, and amending and repealing Directive 97/68/EC." Available: https://eur-lex.europa.eu/eli/reg/2016/1628/oj. (Accessed July 2024).
[48] 61 Fed. Reg. 55411 (1996), "30 CFR Part 7: Approval, exhaust as monitoring, and safety requirements for the use of diesel-powered equipment in underground coal mines; final rule." Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.
[49] 71 Fed. Reg. 28924 (2006), "Mine Safety and Health Administration: 30 CFR 57. Diesel particulate matter exposure of underground metal and nonmetal miners. Limit on concentration of diesel particulate matter," Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.
[50] GMG (2022), "Recommended practices for battery electric vehicles in underground mining," Version 3. Global Mining Guidelines Group (GMG), The Electric Mine Working Group. https://gmggroup.org/recommended-practices-for-battery-electric-vehicles-in-underground-mining-version-3/ (Accessed in September 2024).
[51] Lähde, Tero, Topi Rönkkö, Matti Happonen, Christer Söderström, Annele Virtanen, Anu Solla, Matti Kytö, Dieter Rothe, and Jorma Keskinen (2011), "Effect of fuel injection pressure on a heavy-duty diesel engine nonvolatile particle emission," Environ. Sci. Technol. 45:2504–2509. https://doi.org/10.1021/es103431p.
[52] Nousiainen, Pekka, Seppo Niemi, Topi Rönkkö, Panu Karjalainen, Jorma Keskinen, Heino Kuuluvainen, Liisa Pirjola, and Henna Saveljeff (2013), "Effect of injection parameters on exhaust gaseous and nucleation mode particle emissions of a Tier 4i nonroad diesel engine," SAE Technical Paper 2013-01-2575. https://doi.org/10.4271/2013-01-2575.
[53] Lucachick, Glenn, Arron Avenido, Winthrop Watts, David Kittelson, and William Nortrop (2014), "Efficacy of in-cylinder control of particulate emissions to meet current and future regulatory standards," SAE Technical Paper 2014-01-1597. https://doi.org/10.4271/2014-01-1597.
[54] Bugarski, Aleksandar D., George H. Schnakenberg Jr., Jon A. Hummer, Emanuele Cauda, Samual J. Janisko, and Larry D. Patts (2009), "Effects of diesel exhaust aftertreatment devices on concentrations and size distribution of aerosols in underground mine air," Environmental Science and Technology 43: 6737–6743. https://doi.org/10.1021/es9006355.
[55] Bugarski, Aleksandar D., Jon A. Hummer, Jozef S. Stachulak, Arthur Miller, Larry D. Patts, and Emanuele G. Cauda (2016), "Emissions from a diesel engine using Fe-based fuel additives and sintered metal filtration system," Annals of Occupational Hygiene 60(2):52–62. https://doi.org/10.1093/annhyg/mev071.
[56] Dallmann, Tim, and Aparna Menon (2016), "Technology pathways for diesel engines used in non-road vehicle and equipment. The International

Council on Clean Transportation," White paper. September. Retrieved from https://theicct.org/sites/default/files/publications/Non-Road-Tech-Pathways_white-%20paper_vF_ICCT_20160915.pdf (Accessed May 2024).

[57] Tatli, Emre, and Nigel Clark (2009), "Crankcase particulate emissions from diesel engines," Fuels and Lubricants 1(1): 1334–1344. https://doi.org/10.4271/2008-01-1751.

[58] Johnson, Ben T. (2012), "Experimental analysis of crankcase oil aerosol generation and control," Loughborough University. Thesis.

[59] Scheiber, Kai-Michael, Niclas Nowak, Magnus L. Lorenz, Jürgen Pfeil, Thomas Koch, and Gerhard Kasper (2021), "Comparison of four diesel engines with regard to blow-by aerosol properties as a basis for reduction strategies based on engine design and operation," Automot. Engine Technol. 6, 79–90. https://doi.org/10.1007/s41104-021-00075-4.

[60] Khalek, Imad A., Mathew G. Blanks, Patrick M. Merritt, and Barbara Zielinska (2015), "Regulated and unregulated emissions from modern 2010 emissions-compliant heavy-duty on highway diesel engines," J. Air Waste Manage. Assoc. 65(8): 987–1001. https://doi.org/10.1080/10962247.2015.1051606.

[61] Khalek, Imad A., Thomas L. Bougher, Patrick M. Merritt, and Barbara Zielinska (2011), "Regulated and unregulated emissions from highway heavy-duty diesel engines complying with U.S. Environmental Protection Agency 2007 emissions standards," J. Air Waste Manage. Assoc. 61(4): 427–442. https://doi.org/10.3155/1047-3289.61.4.427.

[62] McDonald, Jacob D., Melanie Doyle-Eisele, JeanClare Seagrave, Andrew P. Gigliotti, Judith Chow, Barbara Zielinska, Joe L. Mauderly, Steven K. Seilkop, and Rodney A. Miller (2015), "Part 1. Assessment of carcinogenicity and biologic responses in rats after lifetime inhalation of new-technology diesel exhaust in the ACES bioassay. In: Advanced Collaborative Emissions Study (ACES): Lifetime Cancer and Non-Cancer Assessment in Rats Exposed to New-Technology Diesel Exhaust," Research Report 184. Health Effects Institute, Boston.

[63] Ruehl, Chris, Jorn D. Herner, Seungju Yoon, John F. Collins, Chandran Misra, Kwangasam Na, William H. Robertson, Subhasis Biswas, M.-C. Oliver Chang, and Alberto Ayala (2015), "Similarities and differences between traditional and clean diesel PM," Emission Control Sci Technol 1:17–23. https://doi.org/10.1007/s40825-014-0002-7.

[64] Mayer, Andreas C.R., Joerg Mayer, Max Wyser, Fritz Legerer, Jan Czerwinski, Thomas W. Lutz, Timothy V. Johnson, and Mark Z. Jacobson (2024), "Particulate filters for combustion engines to mitigate global warming. Estimating the effects of a highly efficient but underutilized tool," Emission. Control Sci. Technol. https://doi.org/10.1007/s40825-023-00236-x.

[65] Biswas, Subhasis, Shaohua Hua, Vishal Verma, Jorn D. Herner, William H. Robertson, Alberto Ayala, and Costantinos Sioutas (2008), "Physical properties of particulate matter (PM) from late model heavy-duty diesel vehicles operating with advanced PM and NOx emission control technologies," Atmospheric Environment 42: 5622- 5634. https://doi.org/10.1016/j.atmosenv.2008.03.007.

[66] Fiebig, Michael, Andreas Wiartalla, Bastian Holdenbaum, and Sebastian Kiesow (2014), "Particulate emissions from diesel engines: Correlation between engine technology and emissions," J Occup Medic Toxic 9(1):6. https://doi.org/10.1186/1745-6673-9-6.

[67] 85 Fed. Reg. 3306 (2020). "40 CFR Parts 86 and 1036 [EPA-HQ-OAR-2019-0055; FRL-10004-16-OAR]: Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine Standards," Environmental Protection Agency.

[68] Dallmann, Tim, Francisco Posada, and Anup Bandivadekar, (2018), "Cost of emission reduction technologies for diesel engines used in non-road vehicles and equipment," The International Council on Clean Transportation," Working paper 2018-10. https://theicct.org/sites/default/files/publications/Non_Road_Emission_Control_20180711.pdf (Accessed in September 2024).

[69] Czerwinski, Jan, Jean-Luc Péterman, Pierre Comte, J. Lemaire, Andreas Mayer (2007), "Diesel NO/NO_2/NOx Emissions - New Experiences and Challenges," SAE Technical Paper 2007-01-0321. https://doi.org/10.4271/2007-01-0321.

[70] Heeb, Norbert V., Peter Schmid, Martin Kohler, Erika Gujer, Markus Zennegg, Daniela Wenger, Adrian Wichser, Andrea Ulrich, Urs Gfeller, Peter Honegger, Kerstin Zeyer, Lukas Emmenegger, Jean-Luc Petermann, Jan Czerwinski, Thomas Mosimann, Markus Kasper, and Andreas Mayer (2008), "Secondary effects of catalytic diesel particulate filters," Environ Sci Technol 42(10): 3773–3779. https://doi.org/10.1021/es7026949.

[71] Mayer, Andreas, Jan Czerwinski, Markus Kasper, Gerhard Leutert, Norbert Heeb, Andrea Ulrich, and Francois Jaussi (2010),"VERT particle filter test procedure and quality standard for new and in-use diesel engines," Journal of KONES Powertrain and Transport, 17(4).

[72] Karthikeyan, Subramanian, Errol M. Thomson, Prem Kumarathasan, Josée Guénette, Debbie Rosenblatt, Tak Chan, Greg Rideout, and Renaud Vincent (2013), "Nitrogen dioxide and ultrafine particles dominate the biological effects of inhaled diesel exhaust treated by a catalyzed diesel particulate filter," Toxicological Sciences 135 (2): 437–450. https://doi.org/10.1093/toxsci/kft162.

[73] Feng, Xiangyu, Yunshan Ge, Chaochen Ma, Jianwei Tan, Linxiao Yu, Jiaqiang Li, and Xin Wang (2014),"Experimental study on the nitrogen dioxide and particulate matter emissions from diesel engine retrofitted with particulate oxidation catalyst," Science of The Total Environment 472: 56–62. https://doi.org/10.1016/j.scitotenv.2013.11.041.

[74] Samaras, Z., Rieker, M., Papaioannou, E., van Dorp, W.F., Kousoulidou, M., Ntziachristos, L., Andersson, J., Bergmann, A., Hausberger, S., Keskinen, J., Karjalainen, P., Martikainen, S., Mamakos, A., Haisch, Ch., Kontses, A., Toumasatos, Z., Landl, L., Bainschab, M., Lähde, T,. Piacenza, O., Kreutziger, P., Bhave, A.N., Lee, K.F., Akroyd, J., Kraft, M., Kazemimanesh, M., Boies, A.M., Focsa, C., Duca, D., Carpentier, Y., Pirim, C., Noble, J.A., Lancry, O., Legendre, S., Tritscher, T., Spielvogel, J, Horn, H.G., Pérez, A., Paz, S., Zarvalis, D., Melas, A., Baltzopoulou, P., Vlachos, N.D., Chasapidis, L., Deloglou, D., Daskalos, E., Tsakis, A., Konstandopoulos, A.G., Zinola, S., Di Iorio, S., Catapano, F., Vaglieco, B.M., Burtscher, H., Nicol, G., Zamora, D., and Maggiore, M. (2022), "Perspectives for regulating 10 nm particle number emissions based on novel measurement methodologies," J. Aerosol Sci. 162: 105957. https://doi.org/10.1016/j.jaerosci.2022.105957.

[75] Wiseman, Clare L.S. and Fathi Zereini (2009), "Airborne particulate matter, platinum group elements and human health: A review of recent evidence," Science of The Total Environment 407(8): 2493–2500. https://doi.org/10.1016/j.scitotenv.2008.12.057.

[76] Liu, Z. Gerard, Nathan A. Ottinger, and Christopher M. Cremeens (2015), "Vanadium and tungsten release from V-based selective catalytic reduction diesel aftertreatment," Atmospheric Environment 104: 154–161. https://doi.org/10.1016/j.atmosenv.2014.12.063.

[77] Herner, Jorn D., Shaohua Hu, William H. Robertson, Tao Huai, M.-C. Oliver Chang, Paul Rieger, and Alberto Ayala (2011), "Effect of advanced aftertreatment for PM and NOx reduction on heavy-duty diesel engine ultrafine particle emissions," Environ Sci Technol. 45(6): 2413–9. https://doi.org/10.1021/es102792y.

[78] He, Chao, Jiaqiang Li, Zhilei Ma, Jianwei Tan, and Longqing Zhao (2015), "High NO_2/NOx emissions downstream of the catalytic diesel particulate filter: An influencing factor study," Journal of Environmental Sciences 35: 55–61. https://doi.org/10.1016/j.jes.2015.02.009.

[79] Bugarski, Aleksandar D., Jon A. Hummer, and Garry M. Robb (2015), "Diesel oxidation catalytic converters for underground mining applications," In: Jong, E., Sarver, E., Schafrik, S., Luxbacher, K. eds. Proceedings of the 15th North American Mine Ventilation Symposium, Blacksburg, VA, June 19–23: 289–296.

[80] NIOSH (2016), "Monitoring diesel exhaust in the workplace. In: NIOSH Manual of Analytical Methods (NMAM), 5th Edition, Chapter DL," Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health DHHS (NIOSH) Publication No. 2014–151.

[81] Kelly, Frank J. and Julia C. Fussell (2012), "Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter," Atmospheric Environment 60: 504–526. https://doi.org/10.1016/j.atmosenv.2012.06.039.

[82] Steiner, Sandro, Christopher Bisig, Alke Petri-Fink, and Barbara Rothen-Rutishauser (2016), "Diesel exhaust: Current knowledge of adverse effects and underlying cellular mechanisms," Arch Toxicol. 90(7): 1541–53. https://doi.org/10.1007/s00204-016-1736-5.

[83] Schraufnagel, Dean E. (2020), "The health effects of ultrafine particles," Exp Mol Med 52: 311–317. https://doi.org/10.1038/s12276-020-0403-3.

[84] Rönkkö, Topi, Annele Virtanen, Kati Vaaraslahti, Jorma Keskinen, Liisa Pirjola, and Maija Lappi (2006), "Effect of dilution conditions and driving parameters on nucleation mode particles in diesel exhaust: Laboratory and on-road study," Atmospheric

Environment 40(16): 2893–2901. https://doi.org/10.1016/j.atmosenv.2006.01.002.

[85] Tang, Shida K., Lisa Graham, Ling Shen, Xialiang Zhou, and Thomas Lanni (2004), "Simultaneous determinations of carbonyls and NO_2 in exhaust of heavy-duty trucks and transit buses by HPLC following 2,4-Dinitrophenylhydrazine cartridge collection," Env Sci Tech 38: 5968–5976. https://doi.org/10.1021/es0353356.

[86] 80 Fed. Reg. 52991 (2015), 30 CFR 75.322: "Mandatory Safety Standards. Underground coal mines. Harmful quantities of noxious gases." Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

[87] Rubeli, Brent and Mahe Gangal (2013), "Engine certification testing and ventilation rates for Tier 4, Update. Report CMIN-2013 (037)," Mining Diesel Emissions Council (MDEC) Conference, October. Available from https://mdec.ca/2013/. (Accessed in September 2024).

[88] MSHA (2011), "Reissue of P02-07 - Compliance with Diesel Particulate Matter Standard in Underground Coal Mines," U.S. Department of Labor, Mine Safety and Health Administration, Program Information Bulletin No. P11-26. (https://arlweb.msha.gov/regs/complian/PIB/2011/pib11-26.asp.

[89] Stachulak Jozef, Mahe Gangal, Cheryl Allen (2014), "The effects of diesel oxidation catalyst on NO_2 emissions from mining vehicles," In: von Glenn F, Biffi M eds. Proceedings of the 10th International Mine Ventilation Congress. Sun City, South Africa: The Mine Ventilation Society of South Africa: 293–297.

[90] Banasiewicz, A. (2021), "Analysis of historical changes in the limit value of nitrogen oxides concentrations for underground mining," IOP Conf. Ser.: Earth Environ. Sci. 684 012018. https://doi.org/10.1088/1755-1315/684/1/012018.

[91] ACGIH (2024), "Threshold Limit Values (TLV®) and Biological Exposure Indices (BEI®s) for chemical substances and physical agents and biological exposure indices," Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

[92] Johansen, Keld, Søren Dahl, Gurli Mogense, Søren Pehrson, Jesper Schramm and Anders Ivarsson (2007), "Novel base metal-palladium catalytic diesel filter coating with NO_2 reducing properties," SAE Technical Paper 2007-01-1921. https://doi.org/10.4271/2007-01-1921.

[93] Khair, Magdi K., Patrick M. Merritt, Qilong Lu, Jacques Lemaire, Jean-Paul Morin, and Keld Johansen (2009), "Catalytic formulation for NO_2 suppression and control," SAE Int. J. Fuels Lubr. 1(1): 803–812.

[94] Zielinska, Barbara, David Campbell, Douglas R. Lawson, Robert G. Ireson, Christopher S. Weaver, Thomas W. Hestreberg, Timothy Larson, Mark Davey, and L-J. Sally Liu (2008), "Detailed characterization and profiles of crankcase and diesel particulate matter exhaust emissions using speciated organics," Env Sci Tech 42: 5661–5666. https://doi.org/10.1021/es703065h.

[95] Kissner, Gerd and Stephan Ruppel (2009), "Highly efficient oil separation systems for crankcase ventilation," SAE Technical Paper 2009-01-0974, 2009, https://doi.org/10.4271/2009-01-0974.

[96] Alföldy, B., B. Giechaskiel, W. Hofmann, and Y. Drossinos (2009), "Size-distribution dependent lung deposition of diesel exhaust particle," Journal of Aerosol Science 40(8): Pages 652–663. https://doi.org/10.1016/j.jaerosci.2009.04.009.

[97] Giechaskiel, B., A. Alföldy, and Y. Drossinos, (2009), "A metric for health effects studies of diesel exhaust particles," Journal of Aerosol Science 40 (8): 639–651. https://doi.org/10.1016/j.jaerosci.2009.04.008.

[98] Cauda, Emanuele G., Bon K. Ku, Arthur L. Miller, and Teresa L. Barone (2012), "Toward developing a new occupational exposure metric approach for characterization of diesel aerosols," Aerosol Science and Technology 46(12): 1370–1381. https://doi.org/10.1080/02786826.2012.715781.

[99] Viitanen, Anna-Kaisa, Sanni Uuksulainen, Antti J. Koivisto, Kaarle Hämeri, and Timo Kauppinen (2017), "Workplace measurements of ultrafine particles-A literature review," Annals of Work Exposures and Health 61(7): 749–758. https://doi.org/10.1093/annweh/wxx049.

[100] Landwehr, Kathrine R., Alexander N. Larcombe, Alison Reid, and Benjamin J. Mullins (2021), "Critical review of diesel exhaust exposure health impact research relevant to occupational settings: Are we controlling the wrong pollutants?," Expo Health 13: 141–171. https://doi.org/10.1007/s12403-020-00379-0.