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Diesel Aerosols in an Underground Coal Mine

Aleksandar D. Bugarski[1], **Shawn Vanderslice**[1], **Jon A. Hummer**[1], **Teresa Barone**[1], **Steven E. Mischler**[1], **Shad Peters**[2], **Steve Cochrane**[2], **Jared Winkler**[2]

[1]Office of Mine Safety and Health Research, National Institute for Occupational Safety and Health, 626 Cochrans Mill Rd, Pittsburgh, PA 15236, USA

[2]Blue Mountain Energy (BME), Deserado Mine, Rangely, CO, USA

Abstract

The case study was conducted in an underground coal mine to characterize submicron aerosols at a continuous miner (CM) section, assess the concentrations of diesel aerosols at the longwall (LW) section, and assess the exposures of selected occupations to elemental carbon (EC) and total carbon (TC). The results show that aerosols at the CM sections were a mixture of aerosols freshly generated at the outby portion of the CM section and those generated in the main drifts that supply “fresh air” to the section. The relatively low ambient concentrations and personal exposures of selected occupations suggest that currently applied control strategies and technologies are relatively effective in curtailing exposures to diesel aerosols. Further reductions in EC and TC concentrations and personal exposures to those would be possible by more effective curtailment of emissions from high-emitting light duty (LD) vehicles.

Keywords

Diesel aerosols; Underground; Mining; Coal

1 Introduction

Diesel-powered vehicles of various vintages are used in underground coal mines to support production and to transport equipment, materials, and people [1]. Since exposure to a complex mixture of aerosols and gaseous components emitted by diesel-powered equipment was shown to result in adverse pulmonary [2], cardiovascular [3], and other health outcomes [4], the long-term occupational exposure of underground miners became a major concern for the mining industry, labor, and regulators. The decision of the International Agency for Research on Cancer (IARC) to classify diesel exhaust as a group 1 carcinogen [5] further heightens the urgency to address this concern.

Engines in diesel-powered vehicles currently used in USA underground coal mines [1] are Mine Safety and Health Administration (MSHA) approved or Environmental Protection Agency (EPA) certified [6, 7]. Due to good durability, low maintenance costs, availability of rebuild programs, and potentially some regulatory and economic factors, legacy

Aleksandar D. Bugarski, abugarski@cdc.gov.

engines remain the primary source of power for underground coal mining fleets [1]. The advancement in engine and exhaust aftertreatment technologies over the past couple of decades resulted in technologies that offer major reductions in emissions levels and changes in the properties of emitted aerosols [8]. Most of the engines approved by the MSHA in recent years are characterized by very low particulate emissions [9].

In the late 1980s and early 1990s, high-emitting diesel-powered vehicles, customarily operated without effective diesel particulate matter (DPM) control technologies, contributed 65% of the mass of respirable aerosols at four coal mines in the USA [10]. The limited number of samples collected by Birch and Noll [11] showed that DPM made up a substantial fraction of respirable dust in dieselized coal mines in the USA in the early 2000s. More recent studies showed that emissions from diesel-powered vehicles are the primary contributor to the number but not mass concentrations of aerosols in contemporary underground mining operations [12–14]. Often, the relatively small fleets of extensively used heavy-duty (HD) vehicles powered by large high-emitting engines are considered to be the major contributors to concentrations of submicrometer particles in underground mines. However, the contribution of light-duty (LD) vehicles, typically present in large numbers in contemporary underground mining fleets [1], could be substantial [13].

Sampling and analysis of diesel aerosols in underground mines is challenging due to the complex, diverse, and dynamic nature of aerosols emitted by diesel engines and interference with other potential sources of submicron aerosols. Collection of the representative DPM, samples in underground coal mines could be adversely affected by the presence of coal and rock dust containing OC and EC [15, 16]. Since the majority of the mass in DPM samples is associated with submicron aerosols and the majority of the mass of mechanically generated dust is associated with micron aerosols [11], the size-selective DPM sampling is conducted using the 10-mm Dorr-Oliver style cyclone and DPM cassette (SKC, 225–317) with a four-nozzle, single-stage impactor [17]. The cyclone is used to remove coarse dust and improve performance and life of the impactor, and the impactor is used to eliminate respirable dust from the DPM samples. The DPM samples collected on quartz fiber filters are analyzed for EC and OC using NIOSH Method 5040 [18]. The method is based on thermal-optical transmittance/evolved gas analysis (TOT-EGA) performed on a 1.5 cm^2 sample punched out of the quartz fiber filter. An accurate determination of exposures of underground miners to OC fraction of TC, particularly on the sub-100 $\mu g/m^3$ levels, requires extremely careful sample preparation, sampling, and analysis [19]. The study conducted by Birch and Noll [11] showed that, with an appropriate sampler design and use of EC as a surrogate for DPM, the methodology currently used in the metal and nonmetal mines most likely can be used in many coal mines for DPM exposure monitoring.

The current MSHA regulations [20, 21] indirectly limit exposures of underground coal miners in the USA to DPM by (1) requiring certification of the engines used in underground coal mines, (2) prescribing engine-specific ventilation rates (VRs) for all approved engines [9], and (3) limiting diesel particulate matter emissions for the HD permissible equipment to 2.5 g/h, HD nonpermissible equipment to 2.5 g/h, and LD equipment to 5.0 g/h. The LD equipment that is powered with engines that meet or exceed the US Environmental Protection Administration (EPA) Tier 2 particulate matter emission standards are also deemed to comply. MSHA limits exposures of underground coal miners to gas-specific threshold limit values (TLVs®) as specified by the American Conference of Governmental Industrial Hygienists (ACGIH®) in 1972 [22]. MSHA [7] requires that all diesel-powered vehicles are ventilated by the engine-specific VR [9] defined as the quantity of fresh air needed to dilute criteria gaseous emissions (CO, CO_2, NO, and NO_2).

Achieving the tailpipe emissions standard of 2.5 g/h for HD permissible vehicles is possible through the use of clean fuels, implementation of effective maintenance programs, and extensive use of high-efficiency exhaust aftertreatment technologies such as full-flow diesel particulate filter (DPF) systems and filtration systems with disposable filter elements (DFEs). In 2018, over 97% of the 318 permissible HD vehicles and over 90% of 1270 nonpermissible HD vehicles in the USA were equipped with filtration systems [23]. The DPF and DFEs systems used in the HD and some LD applications are those verified by MSHA [24]. In the case of the highest emitting MSHA-approved engines [9], DPF and DFE systems need to be as much as 96% effective in the removal of DPM [9]. In contrast, the filtration systems are sparsely used on LD equipment. Of the more than 3200 pieces of nonpermissible LD equipment operating in US coal mines in 2020, less than half had emissions below the 5.0 g/h limit [23].

The analysis of MSHA DPM personal sampling compliance data for metal and nonmetal underground mines in the USA for the period from 2008 through 2019 [25] showed that various improvements in diesel technologies and mining methodologies resulted in a gradual decline in the industry-wide average exposures of underground miners to elemental carbon (EC) and total carbon (TC) concentrations in the mines [26]. Since monitoring of personal exposure of underground coal miners in the USA to diesel aerosols is not mandated or regularly conducted, an adequate set of data is not available to validate the effectiveness of the adopted approach to controlling exposures of coal miners to diesel aerosols. Limited information on recent exposures to DPM is available for Australian [27, 28] but not for American underground coal miners.

This case study was conducted with the objectives to (1) characterize submicron aerosols at a continuous miner section during two typical production shifts in an underground coal mine, (2) assess the concentrations of diesel aerosols at the longwall section during three production shifts, and (3) assess the exposures of selected occupations to EC and TC during three production shifts. The findings in this study should help underground coal mine operators and other mine personnel in identifying the potential sources of exposures to diesel aerosols, recognizing levels of the exposures to these aerosols, developing potential control strategies, and ultimately improving the working environment.

2 Methodology

The sampling for this study was conducted at the Blue Mountain Energy Deserado Mine, an underground coal mine in Rio Blanco County, CO, at 1750 m (5740 ft) above sea level. At the time of the study, the mine was operating a single longwall section. Access for the new longwall panel was concurrently under development using continuous miner and room-and-pillar methodology. The openings at the continuous miner (CM) and longwall sections are 6.1-m (20-ft) wide and 4.3-m (14-ft) high. Ventilation air was supplied to the mine through a large surface fan and directed via a set of control doors to the working areas. The CM section was ventilated using the concept depicted in Fig. 1.

The mine's diesel-powered fleet consists of five permissible HD, thirteen nonpermissible HD, and forty-five nonpermissible LD pieces of equipment. During the shifts when sampling was performed, all HD permissible and nonpermissible vehicles and approximately 70% of LD vehicles were being used in underground operations. All diesel-powered vehicles were fueled with ultra-low sulfur fuel with less than 15 ppm of sulfur by weight.

Filtration systems were used on all HD vehicles. All five permissible HD load-haul-dump vehicles ("scoops") are powered with the permissible power package, (Dry Systems Technologies, Woodridge, IL, 6CTAA8.3) that consists of a Cummins C8.3 engine fitted with the intrinsically safe exhaust aftertreatment system, DST M250 with M30 disposable filter element (DFE). All but one of the engines in the nonpermissible HD vehicles were retrofitted with DPF systems that are made, depending on engine size, with a single or dual 87% efficient, off-board regenerated silicon carbide element. One of the HD vehicles, ASV RC-30, was equipped with a custom-made filtration system, DST M270 with M30 DFE. Forty-four of the LD vehicles, some of those emitting as high as 15.56 g/h of diesel particulate matter (DPM) [9], were not equipped with filtration systems. The CDTI DPF system was fitted also to the LD hauler Getman LRD-220.

Sampling and measurements at the continuous miner (CM) section were performed at the CM outby monitoring station (OMS) (Fig. 1). The CM OMS was placed four crosscuts outby of the face in the central entry, which supplies fresh air to the face. During the observed shifts, a single electric-powered CM machine was used to mine coal at all three faces. Two shuttle cars were used to haul coal and rock cut by the CM machine to the breaker placed at the beginning of the conveyor belt. A single diesel-powered scoop (DST H25XSH) was used to clean the faces.

At the CM OMS, the Fast Mobility Particle Sizer (FMPS, TSI Model 3091) was used during all three shifts (S1–S3) to measure number concentrations and size distribution of aerosols with an electrical mobility diameter from 5.6 to 560 nm at 1 Hz frequency.

During each of two shifts (S2 and S3), custom sampling trains were used to collect a set of six ambient DPM samples for carbon analysis. Each of those trains used a respirable cyclone (Zefon International, Ocala, FL, Zefon Nylon Dorr-Oliver Cyclone) to eliminate coarse aerosols and an impactor internal to the DPM sampling cassettes (SKC, Eighty Four, PA, 225–317) to eliminate respirable dust from the samples. The samples were collected on the primary and secondary quartz fiber filters (Millipore Sigma, Darmstadt, Germany, AQFA03700). The nominal sampling flow rates of 2.0 lpm were maintained using critical flow orifices installed in two common manifolds. A single vacuum pump (Oerlikon Leybold Vacuum, Cologne, Germany, Segovac SV25B) was used to draw 2.0 lpm through all samples.

Two ambient DPM samples for EC and organic carbon (OC) analysis were collected at the longwall (LW) OMS (Fig. 2) for each of the three shifts (S1–S3). During those shifts, the longwall section was ventilated with approximately 37.76 m^3/s (80,000 cfm) of air. The sampling train for collection of the ambient DPM samples consisted of the Dorr-Oliver cyclone (Zefon International, Zefon Nylon Dorr-Oliver Cyclone), DPM cassette (SKC, 225–317), and pump (Zefon International, Escort LC). All sampling was done at a nominal sampling flow rate of 2.0 lpm.

The personal DPM samples for EC and OC analysis were collected for the following occupations: (1) permissible scoop (DST H25XSH) operator, (2) shield hauler (Getman LRD-220) operator, (3) shift supervisor, and (4) outby foreman. The permissible scoop operator and shield hauler operator were sampled for three shifts (S1–S3). The shift supervisor was sampled for two shifts (S1 and S2), and the outby foreman for one shift (S3). Except for a couple of short trips to bring supplies from the fifth crosscut to the permissible zone and for a short maintenance intervention, the permissible scoop was primarily operated inby of the CM OMS. The shield hauler was used outby of the CM OMS primarily to haul the trailer with various supplies from the portal to the CM section. The shield hauler operator was spending part of the time in the filtered and pressurized environmental enclosure of the shield hauler and part of the time operating other vehicles such as the ASV RC-100 with open canopy to offload the trailer. The shift supervisor and outby foreman spent a majority of their time in the well-ventilated outby area of the mine. The sampling trains and methodology used to collect the personal DPM samples were identical to the ones used to collect the ambient samples at the longwall headgate. The collection of the personal samples was initiated at the portal during morning briefings and stopped at the portal at the end of each shift. All DPM samples were analyzed at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division (PMRD) using NIOSH Method 5040, a thermo-optical transmittance (TOT) method [18]. The analysis was performed using an OC/EC Aerosol Analyzer (Sunset Laboratory Inc., Portland, OR).

3 Results and Discussion

Traces of the instantaneous number concentrations of aerosols measured with the FMPS at the CM OMS for S1, S2, and S3 are shown in Fig. 3a. A multitude of processes contributing to the generation and transformation of the diesel aerosols [29] upwind of the CM OMS resulted in a very transient nature of the traces. The concentrations averaged over the entire 6-h measurement periods are given in Fig. 3b. The error bars represent the standard deviations of the means for all concentrations measured during the pertinent shifts.

Size distributions of aerosols at the CM OMS for the selected instances of the 6-h measurements (Fig. 3) are shown for all three shifts in Fig. 4. The statistical parameters of the size distributions, including electrical mobility count median diameter (CMDs), geometric standard deviation (σ), and total number concentrations (TNC) [30] are provided in Table 1. In general, the distributions of submicron aerosols were found to be bimodal. The overwhelming fraction of the observed aerosols was found to be formed by agglomeration of primary and nucleated particles and adsorption and condensation of volatile materials on those and present in the agglomeration mode. The number concentrations of aerosols formed via gas-to-particle conversion of the semi-volatile and low-volatile precursors, found in so-called nucleation mode, were comparable to those of aerosols in the corresponding agglomeration modes only during periods of relatively low total number concentrations. Apart from the distributions associated with the spikes in the number concentrations, the electrical mobility CMDs for the agglomeration mode aerosols were between 52 and 67 nm (Fig. 4).

Based on observation of the diesel vehicle traffic, the highest spikes in the concentrations were associated with intermittent appearances and operation of the LD vehicles powered by relatively high-DPM-emitting engines in the vicinity of the CM OMS. The single modal size distributions of aerosols measured at the CM OMS during episodes of relatively high aerosol number concentrations (Fig. 4) are indicative of older technology engines (Tier 3 or older) that are not retrofitted with filtration systems [31, 32]. The bimodal distributions observed during the periods of moderate and low total number concentrations are characteristic of the contributions from engines retrofitted with DPFs [32]. During the periods when neither LD nor HD vehicles were operated at the outby parts of the CM section, the diesel-powered vehicles operated in the main entries, which supplied “fresh air” to the sections, were the major source of single-modal-distributed aerosols with relatively low number concentrations (Fig. 3, e.g., 21,600 s into S1, 7402 s into S2, 5540 s into S3).

The average concentrations of OC, EC, and TC at the CM OMS and at LW OMS are shown in Fig. 5a and b, respectively. The error bars are the standard deviation of the means for three concurrently collected diesel particulate matter (DPM) samples. For S2 and S3, the concentrations of OC, EC, and TC at CM OMS and LW OMS were found to be comparable. The exposures of OC, EC, and TC for four occupations during S1, S2, and S3 are shown in Fig. 6.

The average TC/EC ratios for the triplicate ambient samples collected at the CM OMS, the duplicate ambient samples collected at the LW OMS, and the TC/EC ratios for the selected personal exposure samples for S1, S2, and S3 are summarized in Table 2. Since the OC levels in the samples collected for the shift supervisor and outby foreman were below LOQ, the TC/EC ratios were not calculated for those workers. The EC was found to make between 52 and 72% of TC for the ambient samples collected at the CM OMS and LW OMS and between 60 and 83% for the personal samples collected for the permissible scoop and shield scoop operators.

4 Conclusions

The results show that aerosols at the CM OMS, and most likely at the LW OMS, were a mixture of the aerosols freshly generated at the outby portion of the CM section and those generated in the main entries that supply “fresh air” to the sections and carried to the sections by the ventilation air flow. The multitude of intermittent activities of diesel-powered vehicles at the CM section and upwind from that section contributed to the continuous changes in concentrations and physical properties of aerosols (Fig. 3). The results suggest that LD vehicles were major contributors to the concentrations of aerosols at the CM OMS.

When LD vehicles were not present at the section, the contribution of the nonpermissible HD vehicles became apparent. The role of retrofitted HD vehicles was relatively minor because those were equipped with noncatalyzed DPF systems to keep DPM emissions under 2.5 g/h level.

The ambient concentrations of EC at the CM OMS and LW OMS (Fig. 5) and personal exposures of selected occupations (Fig. 6) were substantially lower than the current PEL for underground metal and nonmetal miners in the USA (160 $\mu g_{TC}/m^3$) [33] and the recommended PEL for underground miners in Australia (100 $\mu g_{EC}/m^3$) [34]. Those were also lower than the average EC exposures observed for metal and nonmetal miners in the USA for the past decade [25, 26] and comparable to those for Australian underground coal mines [27, 28]. The highest EC and TC exposures were observed for the shield hauler operator that spent some time in the generally unventilated crosscuts storing various supplies. The lowest OC, EC, and TC concentrations were observed for the shift supervisor and outby foreman that spent the majority of the time in the very well-ventilated outby areas. The EC and TC exposures of the scoop operator, who spent the majority of time during S2 and S3 inby of the CM OMS, were within the margin of error of those EC and TC exposures measured concurrently at the CM OMS. Therefore, it can be concluded that the outby traffic was the major contributor to exposures of the permissible scoop operator. Since all nonpermissible HD vehicles were already retrofitted with the relatively efficient exhaust filtration systems [32], further reductions in the EC and TC concentrations and personal exposures to those pollutants would be possible by more effective control of the emissions from the high-emitting LD vehicles.

It is important to note that this case study was limited in scope. Measurements were done during limited periods of time in the single mine capturing few of the plethora of underground coal mining processes. Additional measurements are needed to assess the exposures and characterize diesel aerosols for the other phases of the underground coal mining process such as longwall moves that occur typically once a year. In 2016, 60% of Queensland underground coal mines recorded mean exposures above the shift-adjusted exposure guideline of 100 $\mu g/m^3$ during the longwall moves [28]. Additional measurements are needed in the other underground coal mining operations in the USA to obtain a more comprehensive understanding of these issues.

5 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.

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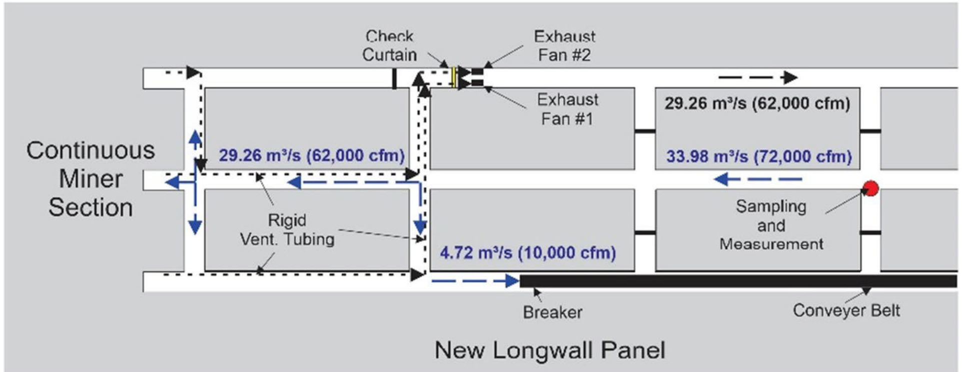


Fig. 1.
The continuous miner (CM) section

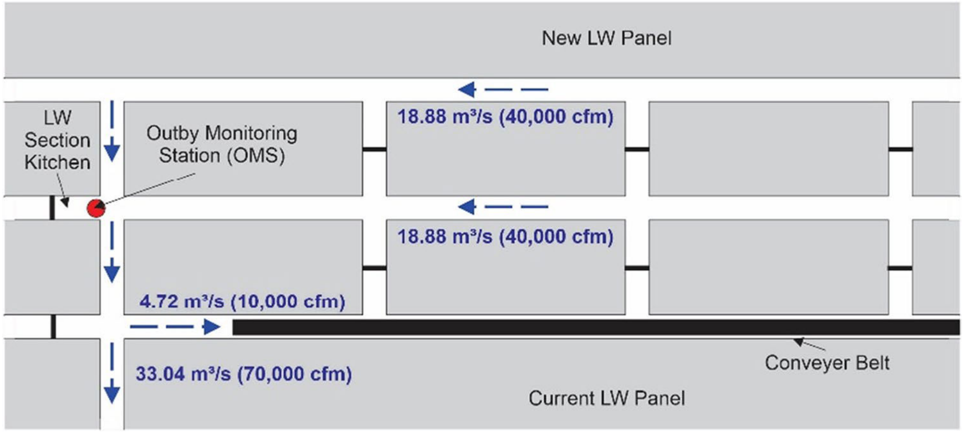
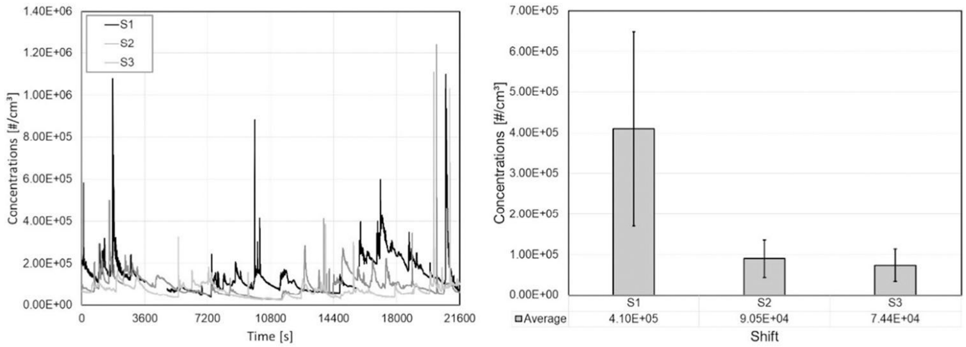


Fig. 2.
The longwall (LW) section



(a) (b)

Fig. 3.

Number concentrations of aerosols measured with the FMPS at the CM during S1, S2, and S3 shifts: **a** traces and **b** average concentrations

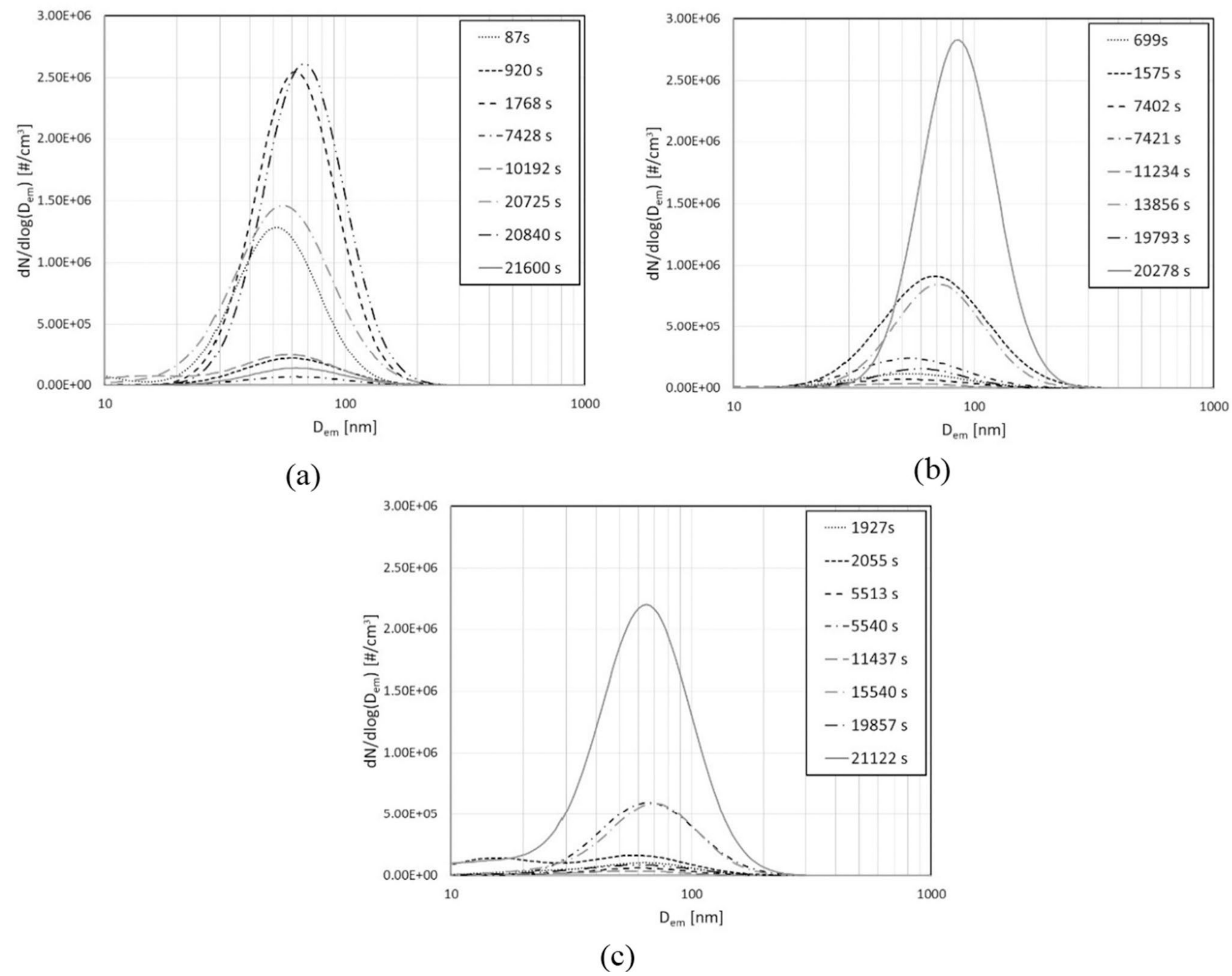
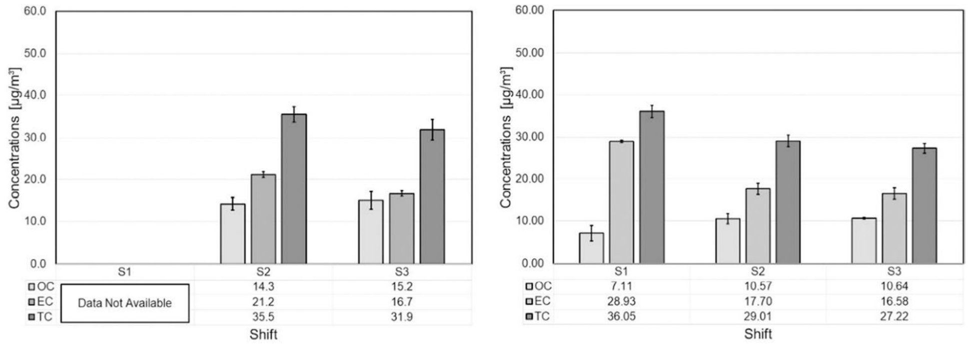


Fig. 4.
Size distributions of aerosols at the CM OMS for: **a** S1, **b** S2, and **c** S3



(a) (b)

Fig. 5.

Average OC, EC, and TC concentrations at: **a** CM OMS and **b** LW OMS

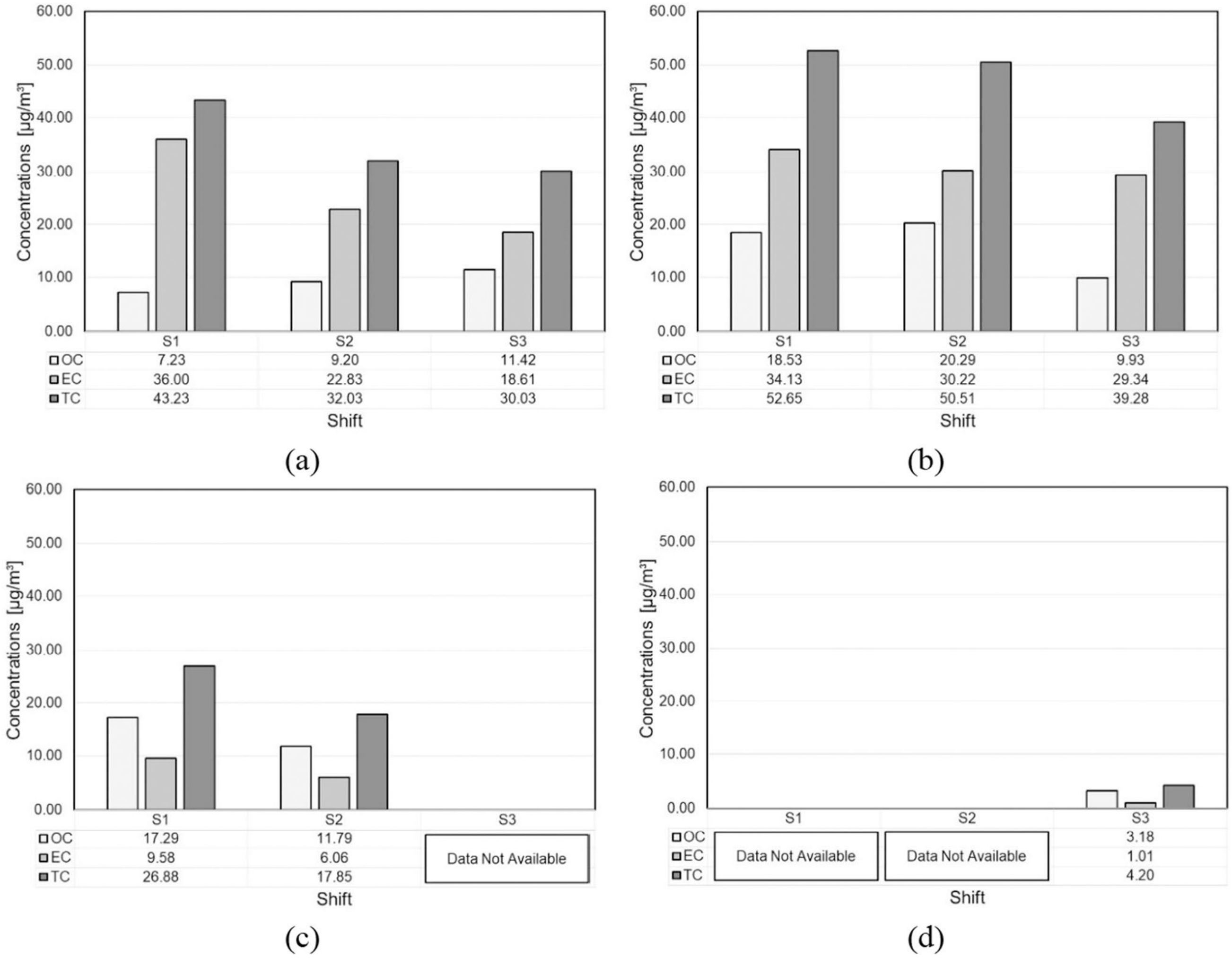


Fig. 6.

The OC, EC, and TC exposures for: **a** permissible scoop operator, **b** shield hauler operator, **c** shift supervisor, and **d** outby foreman (the concentrations of OC and EC are below LOQ)

Table 1

Parameters including CMD, σ, and total number concentrations (TNC) for number distributions of aerosols measured at CM OMS at selected instants

Shift	Elapsed time [s]	Nucleation			Agglomeration		
		CMD	σ	TNC	CMD	σ	TNC
		nm	-	#/cm^3	Nm	-	#/cm^3
S1	87	7.5	1.45	4.08E + 04	51.7	1.49	5.57E + 05
	920				59.9	1.58	1.10E + 05
	1,768				62.0	1.47	1.07E + 06
	7,428	2.7	3.77	1.95E + 04	62.4	1.60	3.54E + 04
	10,192	14.4	1.68	4.19E + 04	58.4	1.56	1.20E + 05
	20,725	25.8	1.96	3.44E + 04	55.4	1.58	7.15E + 05
	20,840				67.2	1.47	1.10E + 06
	21,600				62.7	1.55	6.69E + 04
S2	699				53.2	1.71	6.89E + 04
	1,575				68.3	1.64	4.93E + 05
	7,402				52.3	1.78	4.49E + 04
	7,421				53.9	1.67	1.35E + 05
	11,234	11.6	2.43	1.62E + 04	54.9	1.60	1.68E + 04
	13,856				71.1	1.53	3.93E + 05
	19,793				59.1	1.53	7.33E + 04
	20,278				85.5	1.43	1.10E + 06
S3	1,927	24.8	1.79	2.35E + 04	66.8	1.53	4.44E + 04
	2,055	15.1	1.54	6.60E + 04	58.8	1.63	8.75E + 04
	5,513	17.7	1.59	6.83E + 03	61.2	1.57	3.03E + 04
	5,540				66.0	1.59	3.02E + 05
	11,437	19.7	1.58	5.91E + 03	57.9	1.57	1.88E + 04
	15,540	36.1	1.83	4.37E + 04	71.3	1.50	2.45E + 05
	19,857	26.7	1.88	1.32E + 04	63.3	1.65	4.27E + 04
	20,122	17.5	2.33	1.13E + 05	64.9	1.53	1.00E + 06

Table 2

The TC/EC ratios for DPM samples

TC/EC	Shift		
Sample type	S1	S2	S3
	-	-	-
Ambient – CM OMS	-	1.68 ± 0.07	1.91 ± 0.12
Ambient – LW OMS	1.54 ± 0.01	1.64 ± 0.08	1.64 ± 0.07
Personal – permissible scoop operator	1.20	1.40	1.61
Personal – shield hauler operator	1.54	1.67	1.34