Emission-Assisted Maintenance for Advanced Diesel Engines and Exhaust Aftertreatment Systems in Underground Mining

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Abstract

Maintaining the particulate emissions from contemporary diesel engines equipped with diesel particulate filter (DPF) systems at targeted levels and assuring the effectiveness of DPF systems retrofitted to traditional diesel engines are critical to the efforts of underground mining operations to reduce exposures of miners to diesel particulate matter. The methodologies and instrumentation currently used to support the emission-assisted maintenance (EAM) programs for previous generations of diesel engines are in need of improvement to allow for monitoring low concentrations of complex aerosols emitted by the advanced diesel engines. The results showed that of the test conditions currently used in EAM programs, the torque converter stall and hydraulic stall are the most suitable for assessing the effectiveness of the DPF-based advanced aftertreatment systems. The low idle and high idle test conditions, frequently used in EAM programs for traditional engines, did not produce reliable and reproducible data. The solid particle number (SPN) concentrations proved to be more suitable than total particulate number concentrations as a metric for EAM monitoring of diesel aerosols emitted by advanced diesel engines. Both of the evaluated direct reading instruments, TSI 3795-HC and Pegasor Mi3, provided comparably accurate results of assessments of the SPN concentrations in the targeted range of concentrations between 2×10^3 and 3×10^6 #/cm^3. Those proved to be viable EAM tools for determination of the efficiencies and performance degradation of the DPF system. The findings of this study should provide the underground mining industry with valuable information needed to enhance their EAM programs.

1 Introduction

The underground mining industry is making concerted efforts through innovation to reduce miners' exposure to carcinogenic mixtures of several hundreds of different compounds [1] emitted by diesel-powered mobile equipment [2]. It is widely accepted that full-flow diesel particulate filter (DPF) systems are very effective in removing solid particles and some other pollutants emitted by diesel-powered vehicles [3, 4]. Implementation of the engineering control strategies based on substitution of traditional engines with advanced diesel engines and traditional engines retrofitted with viable DPF systems is essential to achieving substantial reductions in exposures of underground miners to diesel particulate matter (DPM) [5, 6]. Selecting the proper engines for the applications, maintaining emissions from those on the best possible levels, and maintaining effectiveness of exhaust aftertreatment devices at desired levels are critical to the success of those strategies.

The emission-assisted maintenance (EAM) programs have the objective of maintaining in-use emissions of diesel engines in underground mining mobile equipment at the best possible level throughout the full useful life. The EAM programs are centered around the periodic emission-assisted technical inspections (PTIs) of the engines and exhaust aftertreatment systems. Some of the basic requirements for implementation of EAM programs are incorporated into the underground mining regulations [7–9]. These data-driven programs require collection of the gaseous and particulate emissions data in regular, typically preventive maintenance

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intervals. The inception of the data collection process typically coincides with the introduction of the engine in the fleet and continues throughout its useful life. The generated data is typically used to (1) protect miner's health, (2) guide decisions on selection of the adequate engines and exhaust aftertreatment systems for the applications, and (3) define maintenance needs and practices. Since the underground mines operate vehicles powered by diesel engines that meet a wide variety of emissions standards, the EAM programs should be optimized for the makeup of the specific fleet. The EAM methodologies, initially developed in 1980s and 1990s for legacy mechanically controlled engines [10, 11], gradually evolved to cover more modern electronically controlled engines and retrofit-type exhaust aftertreatment systems [12–14]. After industry-wide implementation of exhaust aftertreatment systems, the assessment of the effectiveness of those systems in the removal of gaseous and particulate pollutants became an integral part of EAM programs. Deterioration in performance of the wall-flow diesel particulate filter (DPF) systems that can result in the several orders of magnitude higher particulate emissions, became the cornerstone of diesel particulate matter (DPM) control for on-highway vehicles [4, 15, 16] and underground mining vehicles [6, 17]. The monitoring performance of the DPF system is based on the detection of failures due to the formation of pinholes, melting, cracking, or fouling of the filter elements [18, 19] and/or detection of external leaks. Similarly, monitoring of the performance of the diesel oxidation catalysts (DOCs) is important in identifying diminished effectiveness in the removal of carbon monoxide (CO) and hydrocarbons due to leaks, sintering, fouling, or poisoning of the catalyst [20]. The EAM programs should be designed to prevent substantial deterioration in performance of selective catalyst reduction (SCR) systems due to leaks, poor conversion, catalyst deterioration, or urea crystallization [21, 22].

The success of EAM efforts is predicated on the collection of reliable gaseous and particulate emissions data for repeatable test conditions over its entire useful life of power package. In the past, the primary focus of the EAM programs was on measurements of engine-out and aftertreatment-out CO, nitrogen dioxide (NO_2), and nitric oxide (NO) emissions primarily using gas analyzers with electrochemical cells [11–13, 23, 24]. Over time, various methodologies were developed to allow for semi-quantitative assessment of particulate emissions for EAM purposes. Complex processes governing formation and transformation of submicron diesel aerosols on their journey from the combustion chamber to the underground environment and eventually to the instrument sensors or sampling filters make measurement and sampling of diesel aerosols challenging. The efforts to develop and implement relatively simple and inexpensive field methodologies for quantitative assessment of particulate concentrations in raw engine exhaust and downstream of exhaust aftertreatment systems were based on the various methodologies including those relying on opacity measurement [12], laser light scattering measurements [25], collection of filter samples and assessing filter smoke number [13, 23], or collection of filter samples and performing elemental carbon analysis [24].

In underground mining, the in-use emissions from diesel power packages are traditionally established using steady-state tests [11] and occasionally using snap acceleration tests [26] performed on the stationary vehicles and equipment. The alternative based on collection of real-time in-use emissions data from in-service vehicles would require the use of the relatively complex and expensive portable emissions measurement systems (PEMSs) and assessment methodology similar to the one used by the US Environmental Protection Agency (EPA) [23, 27]. The steady-state test conditions used individually or combined for EAM testing of the engines in the parked and secured mobile underground mining equipment are as follows: (1) torque converter stall (TCS), (2) hydraulic stall (HS), (3) low idle (LI), and (4) high idle (HI) [9, 11, 13, 24]. The TCS is used exclusively for testing engines coupled to automatic transmissions through torque converter. The HS is used for testing engines coupled to the hydrostatic transmission and hydraulic motor. At TCS and HS conditions or combination of those, the engine is operated at full throttle, while load is absorbed by torque converter and/or hydraulic pump. The actual engine loads generated by TCS and HS conditions are the function of the engine output and energy absorbed by the specific torque converter or hydraulic pump. The limiting factor in using TCS and HS conditions is overheating of the converter and/or hydraulic systems. The engines, coupled to manual transmission are tested exclusively at LI (0% throttle) and HI (100% throttle) with no load beyond engine parasitic losses. The actual load to the engine during those tests would vary with engine configuration. Wattrus et al. [14] reported that the engine in a load-haul-dump (LHD) vehicle, when operated at the 100% throttle (HI conditions), was loaded by the torque converter and parasitic losses up to approximately 30% of the maximum torque available for that engine speed. By comparing the engine speeds and loads observed for the duty cycle of an LHD vehicle operated in an underground platinum mine in South Africa, Wattrus et al. [14] found that HI and TCS conditions are representative of the typical engine loads and speeds during loading and hauling portions of the observed duty cycle. In the case of light-duty vehicles, the measurements of particle number emissions factors for diesel vehicles at hot low idle were found to correlate well to those obtained during homologation cycles and real-driving emission measurements [28–32].

Rapid advancements of diesel engine technologies primarily driven by gradual tightening of heavy-duty diesel engine emissions standards [33–36] have been driving

demand for improvements in the emission measurement methodologies [37–39]. The contemporary diesel engines are relying extensively on the use of sensors that can provide a wealth of information for diagnostic purposes. The on-board diagnostics (OBD)–based inspection and maintenance programs were found to be a cost-effective methodology for monitoring emissions of nitrogen oxides (NOx) for heavy-duty diesel engines [19, 21, 22]. However, Durbin et al. [40] proposed that the OBD-based inspection and maintenance programs for the on-highway, heavy-duty vehicle powered with advanced engines should be supplemented with the periodic roadside monitoring of criteria emissions using a remote sensing device (RSD) and mini-portable emissions measurement systems (mini-PEMS). The OBD-based methodologies, primarily based on differential pressure measurements, were found to be inadequate for detecting failures of DPF systems on light-duty vehicles [41]. Therefore, those programs need to be complemented with periodic inspections of aftertreatment systems. Belgium, Germany, the Netherlands, and Switzerland authorities introduced the PTI requirements for DPF-equipped, light-duty, on-highway vehicles based on solid (non-volatile) particulate number (SPN) measurements [31, 41].

The measurement of particulate emission from in-use contemporary diesel engines equipped with DPF systems was found to be quite challenging due to low mass concentrations and complex properties of diesel aerosols. The traditional mass-based particle emission measurement methodologies such as the gravimetric analysis performed on the filter samples collected from a full-flow constant-volume sampler (CVS) or a partial-flow dilution systems [33–36] or those based on the use of mass-based real-time monitoring instrumentation [42, 43] were shown to be inadequate for monitoring particulate emissions for engines equipped with DPF systems [37, 38, 42, 44]. The methodologies based on the measurements of opacity [43, 45, 46] and qualitative assessment of filter smoke numbers using the soot test procedure [47], extensively used over past decades to support EAM programs for traditional diesel engines, were found to be inadequate for monitoring DPF-out DPM emissions typically a couple magnitude lower than engine-out DPM emissions [15, 29, 32, 44, 48].

Measuring SPN concentrations of aerosols with diameters larger than 23 nm is widely accepted as the most suitable method for assessing the effectiveness of contemporary diesel control technologies [28, 30, 36, 41, 49]. A minimum diameter of 23-nm size was selected with the intention of capturing the smallest solid carbon and metallic particles and excluding volatile/nucleation mode particles. The methodologies based on counting solid particulates were recently adopted for the PTI of DPF systems on light-duty on-road [15, 16, 29, 48] and heavy-duty on-road vehicles [50]. Lately, the concerns over the health impact of sub-23 nm

aerosols, primarily generated during the engine start and acceleration phases, prompted the initiatives to evaluate the feasibility of including the solid aerosols with diameters as low as 10 nm in measurement practices [51].

Most of the portable instruments designed to measure SPN concentrations of diesel exhaust operate on one of two following principles: (1) light scattering counting of aerosols enlarged by condensation of the various fluids on those (condensation particle counters) [16, 32, 39, 52, 53] or (2) electrical detection of aerosols charged using unipolar diffusion chargers [31, 32, 54–57]. The instrumentation developed for the PTI of DPFs on large fleets of diesel-powered passenger cars in some of the European Union countries could be adopted for underground mining applications.

The repeatability of SPN concentration measurements depends on effective conditioning of the exhaust samples, primarily on the elimination of volatile/nucleation mode particles [28, 37, 38, 48]. The suppression of formation and removal of volatile particles from the sampling stream are typically achieved through use of (1) the primary hot dilution (150–200 °C), (2) the evaporation (> 300 °C) and removal in the systems with denuders or catalytic strippers, and (3) the suppression of subsequent nucleation of volatile materials by secondary dilution [44, 58, 59].

The objective of this study was to advance the current EAM practices and evaluate instrumentation that can be used to support operation of contemporary engines equipped with advanced exhaust aftertreatment systems in underground mining.

2 Methodology

The experimental work was conducted using the turbocharged three-cylinder, 1.8-l Kubota D1803-CR-T-E4B engine rated at 37.0 kW (49.6 hp) at 2700 rpm and 150.5 Nm (111.0 lb-ft) at 1600 rpm. This engine is equipped with a cooled EGR and exhaust aftertreatment system made of the DOC followed by the wall-flow monolith silicon carbide DPF (DOC + DPF). The engine complies with the US EPA Tier 4 final standards for the engines with output below 37 kW (50 hp) [60] but does not have the approval from the Mine Safety and Health Administration (MSHA).

The engine was coupled with a 400-kW, water-cooled, eddy-current dynamometer (SAJ, AE400) that allowed for operation at nine steady-state engine operating conditions (Table 1). Eight of those conditions are modes specified in the ISO 8178-C1 [61] and the ninth is HI. The LI and HI operating conditions were included directly in the test matrix, while TCS and HS operating conditions, defined by engine and equipment used in the specific vehicle, were emulated by I75 and I50 operating conditions. The engine was fueled with ultralow sulfur diesel (ULSD). The results

Table 1 Engine operating conditions

Engine operating condition	Nominal engine speed [rpm]	Torque [Nm]	Torque [ft-lb]	Power [kW]	Power [hp]	Temperature at the inlet to DOC [°C]
R100	2700	122.0	90.0	34.5	46.3	511.2
R75	2700	91.5	67.5	25.9	34.7	447.1
R50	2700	61.0	45.0	17.3	23.1	386.3
R10	2700	12.2	9.0	3.5	4.6	240.8
I100	1600	142.4	105.0	23.9	32.0	511.3
I75	1600	106.8	78.8	17.9	24.0	455.4
I50	1600	71.2	52.5	11.9	16.0	378.4
LI	900	6.8	5.0	0.6	0.9	150.6
HI	2700	6.8	5.0	1.9	2.6	-

Table 2 Properties of the ULSD fuel used for this study

Property	Test method	Unit	Value
Specific gravity	ASTM D1298	-	0.853
Aromatics content	ASTM D1319	% volume	29.1
Olefins content	ASTM D1319	% volume	1.0
Paraffin content	ASTM D1319	% volume	69.9
Cetane number	ASTM D613	-	43.7
Flash point	ASTM D93	K	331
Heat of combustion	ASTM D240	MJ/kg	46.0
Sulfur content	ASTM D5453	ppm by weight	6.9

of the analyses performed on the fuel sample are shown in Table 2.

The experimental setup depicted in Fig. 1 was used for the evaluation of the methodology and instrumentation. Sixty-three different emission profiles were created by varying nine engine operating conditions (Table 1), measurement locations (upstream and downstream of the DOC + DPF system), and six integrity conditions of the DOC + DPF system (Fig. 1). The evaluations were performed six times for each of those profiles.

The DOC + DPF system was evaluated when fully functional (D-0) and when compromised (D-1 through D-5) by introducing external leaks around the DOC and DPF elements (Fig. 1). The leaks were created by incorporating the stainless-steel bypass lines with the internal diameters of 1.75 mm (D-1), 3.05 mm (D-2), 4.60 mm (D-2), 7.75 mm (D-3), and 10.92 mm (D-5).

Two direct reading instruments, designed for PTI measurements of SPN concentrations in diesel engine exhaust, were evaluated in this study: (1) High-Concentration Nanoparticle Emissions Tester (TSI, Model 3795-HC) and (2) particle monitoring system (Pegasor, Model Mi3). The fast mobility particle sizer spectrometer (FMPS, TSI, Model 3091) and scanning mobility particle sizer spectrometer (SMPS, Model 3936) were used to measure concurrently total (solid and volatile) particle number (TPN) concentrations and size distributions of aerosols in the exhaust diluted using the partial dilution tunnel (Dekati, Model FPS400) (Fig. 1). The measurements with all four direct reading instruments were performed from the custom-designed manifolds attached to the exhaust pipe upstream and downstream of the DOC + DPF system (Fig. 1). The data was collected concurrently with all four direct reading instruments for six consecutive runs.

The 3795-HC condition the exhaust sample in the primary dilutor (10:1 dilution), catalytic stripper, and secondary dilutor (20:1) (Fig. 2). Two-stage dilution allows for measurements over a wide range of number concentrations typically observed upstream and downstream of DPF systems. The catalytic stripper which removes more than 99% volatile compounds [58] allows for measurement of SPN concentrations. The condensation particle counter (CPC) (Fig. 3) is used in the 3795-HC to quantify SPN concentrations leaving the catalytic stripper. In the CPC, the fraction of flow carrying the aerosol sample is initially flown through a saturator that houses a wick supersaturated with isopropanol alcohol. The evaporated alcohol is condensed on the aerosols in the condenser to build micron-size aerosols that are counted using light scattering methodology. The response time of the 3795-HC is 2.5 ± 0.5 s. Boveroux et al. [31] showed that the probe needs to be inserted in the exhaust pipe for at least 7 s before measurement with 3795-HC could be performed.

The Pegasor Mi3 is a real-time particle monitoring system (Fig. 4) that employs the Pegasor Particle Sensor (PPS) (Fig. 5) detector [57, 62]. The PPS measures particles suspended in gas using the diffusion charging methodology. The aerosol sample (5 lpm) is introduced in the instrument via heated line. The sample is heated to 200 °C to keep the volatile compounds in the gas phase. In the ejector at the inlet to the PPS, the sample is mixed with clean sheet air flow (10 lpm) carrying positive ions generated by a corona discharge. The charged aerosols are carried toward the sensor. The ions
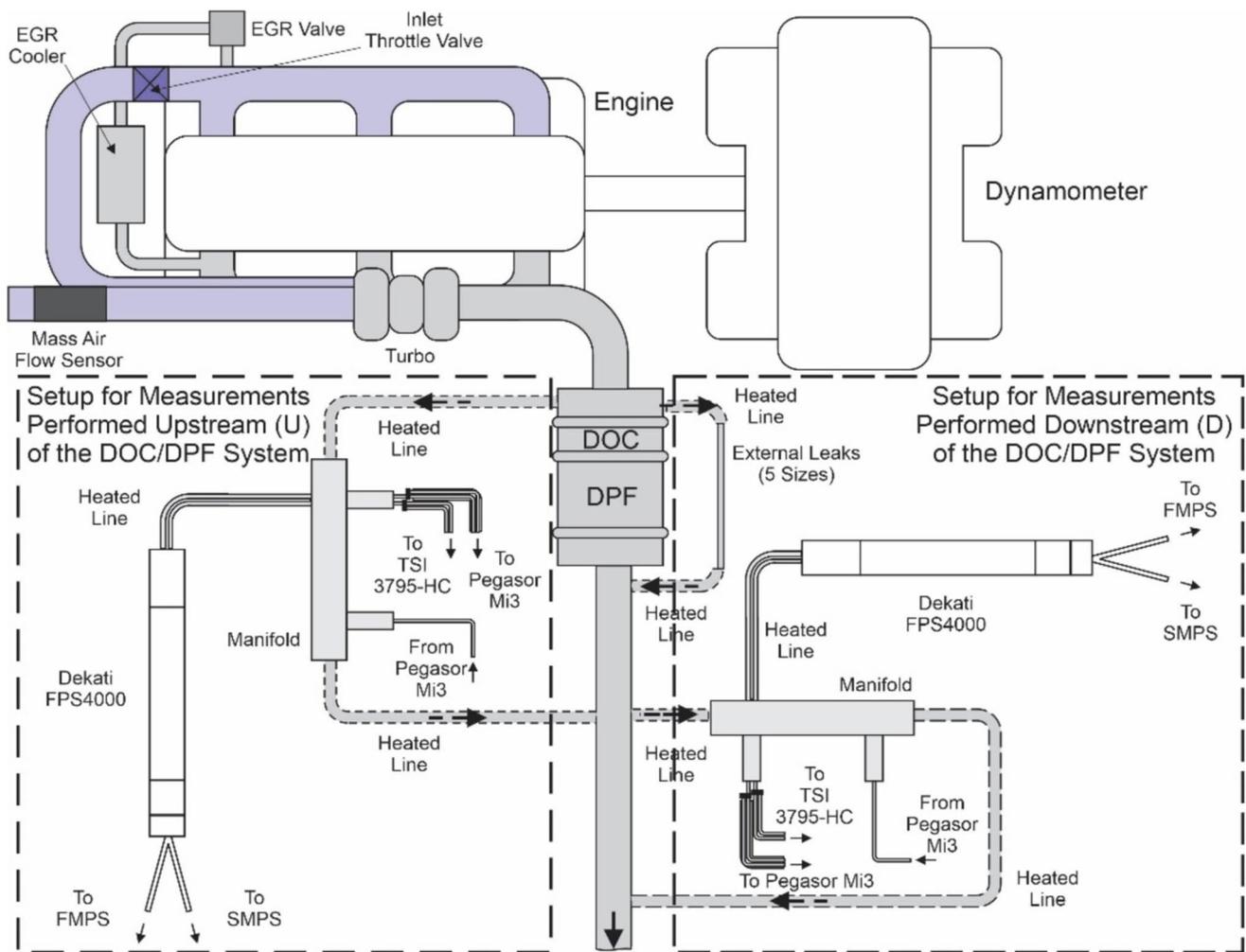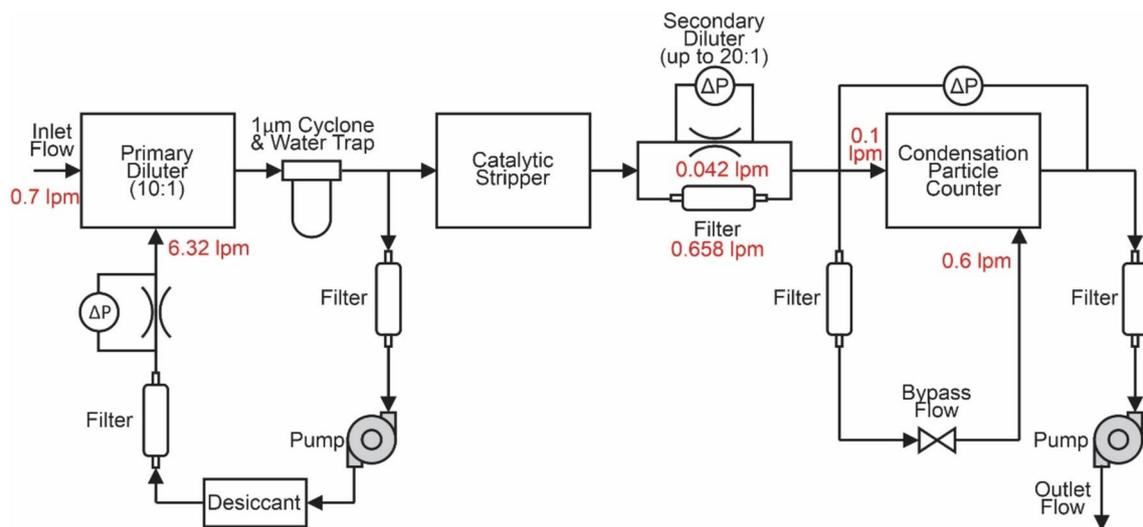
Fig. 1 The experimental setup

Fig. 2 Schematic of high-concentration nanoparticle tester (TSI Model 3795-HC)
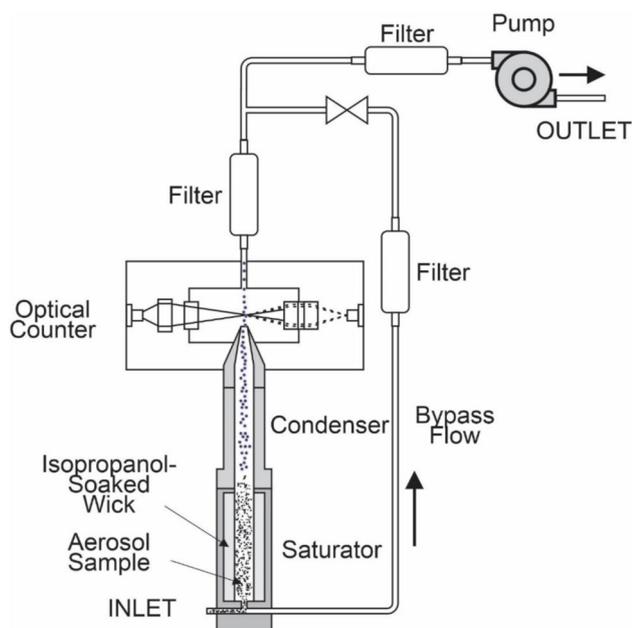
Fig. 3 Schematic of condensation particle counter (CPC) used in the TSI Model 3795-HC

that do not get attached to the aerosols are removed from the stream by the ion trap. The fact that the escaping current carried by aerosols is proportional to the aerosol concentrations is used to calibrate the electrical output signal for various kinds of aerosols including certain diesel aerosols [57]. The Mi3 also has an optional internal diluter (10:1) that is used when very high aerosol concentrations are measured [63]. The theoretical response time of the Mi3 is 0.2 s. Bover-oux et al. [31] found that measurement with Mi3 can be performed within 4 to 6 s after the probe is inserted in the exhaust pipe.

The FMPS [65] and SMPS [66] were used as the reference instruments for measurement of size distributions and TPN of aerosols in the diluted exhaust with an electrical mobility diameter between 5.6 to 560 nm and 10 to 400 nm, respectively. At the inlet section of the FMPS spectrometer, aerosols are neutralized and then charged using two unipolar diffusion chargers. Consequently, aerosols are classified according to their electrical mobility. The mobility section consists of a central rod divided in three insulated sections and 22 electrometers. The number-weighted aerosol size distributions are calculated for 32 size channels every 1 s. The FMPS spectrometer operates at 10 lpm and has relatively low diffusion losses. The SMPS spectrometer used in this study consisted of (1) a differential mobility analyzer (DMA, TSI Model 3081) and (2) a condensation particle counter (CPC, TSI Model 3776). The DMA, also known as an electrostatic classifier, is used to classify polydisperse submicron aerosols from a 1 lpm sampling stream according to their

electrical mobility [66–69]. Once aerosols in the individual size ranges are classified in the DMA, their concentration is measured by the CPC. The full range of particle sizes is obtained by gradually changing the voltage on the collector rod. The result for a full scan is obtained in at least 60 s. The two-stage partial dilution system (Dekati, Model FPS400) was used to dilute raw exhaust and allow for measurements with FMPS and SMPS spectrometers. The presented results of FMPS and SMPS measurements were corrected for the dilution. In the case of measurements performed with FMPS, the TPN concentrations of aerosols with diameters larger than 25 nm (FMPS$_{25+}$ TPN) were calculated by subtracting TPN concentrations of aerosols smaller than 25 nm from the TPN concentrations of all aerosols in the FMPS measurement range.

3 Results

The variety of created emission profiles allowed for the evaluation of the instruments over a wide range of conditions and concentrations of single modally and bimodally distributed aerosols. The average TPN concentrations measured with the FMPS spectrometer ranged between 5.0×10^2 and 6.5×10^7 #/cm^3 (Fig. 6). The corresponding maximum SPN concentrations measured with 3795-HC and Mi3 were 6.1×10^7 #/cm^3.

For all conditions, the TPN concentrations of aerosols measured with FPMS and SMPS showed a strong linear relationship (Fig. 7). Consequently, only the FMPS data was used in further analyses.

For the majority of test cases, the FMPS size distributions were fitted with log-normal curves using the distfit software (Chimera Technologies, Forest Lake, MN) (Figs. 8, 9, and 10). The exceptions were the cases of the fully functional DOC + DPF system tested at R10, LI, and HI conditions that were characterized by very low concentrations of aerosols that were not log-normally distributed. The FMPS measurements upstream of the DOC + DPF system showed that the size distributions of aerosols emitted by the engine operated over all test modes were single modal with the most of aerosols distributed in the agglomeration modes (Fig. 8). When the engine was operated at the rated speed, intermediate speed, and idle speed, the median diameters (D_{50}) of the aerosols were between 51 and 58 nm, between 54 and 58 nm, and 68 nm, respectively. Few aerosols were found to have diameters below 25 nm.

The size distributions of aerosols measured downstream of the fully functional DOC + DPF system (D-0) and downstream of the same system bypassed by various external leaks (D-1 to D-5) were found to be the function of engine operating conditions. When the engine was operated at I100, I75, I50, LI, R75, and R50 conditions, the filtered aerosols
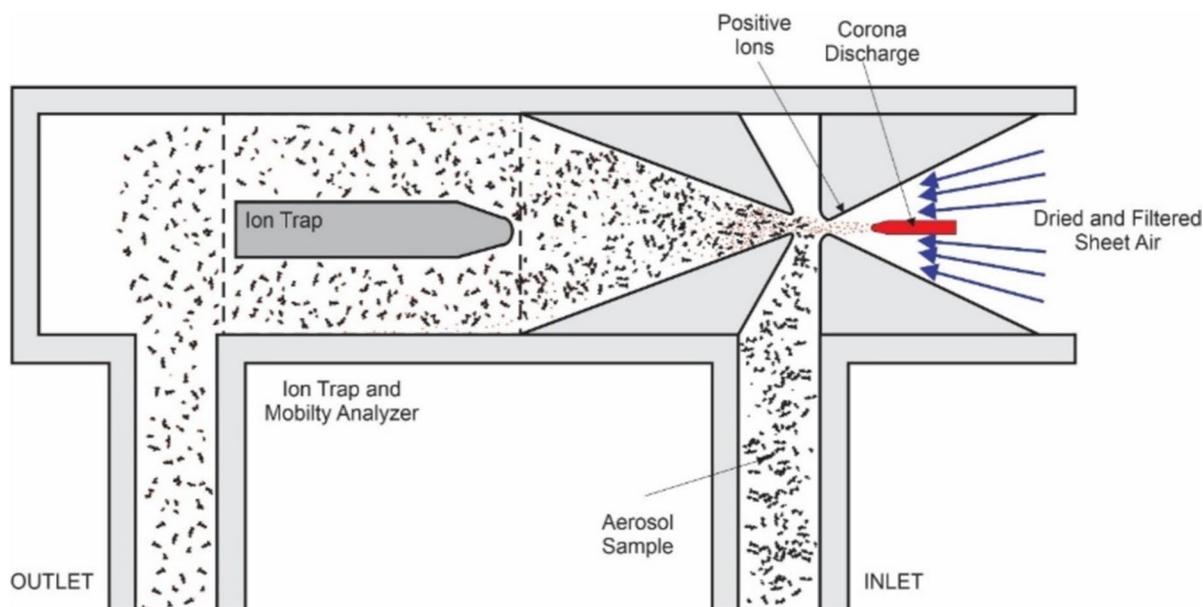
Fig. 4 Flow schematic of Pegasor Mi3 (adapted from [64])

were predominantly distributed in the agglomeration modes with few of those aerosols smaller than 25 nm (Fig. 9). Aerosols emitted from the DOC + DPF system when the engine was operated at R100, R10, and HI conditions were distributed bimodally with substantial fractions of those smaller than 25 nm (Fig. 10). Due to the occurrence of pronounced nucleation modes in exhaust for some of the cases when the engine was operated at R100, the TPN concentrations were not directly proportional to the physical size of the bypass lines.

The aerosols in the agglomeration modes were substantially smaller when the engine was operated at the rated speed (14–58 nm) than at intermediate speed (49–70 nm) modes. Consequently, the concentrations of aerosols with diameters smaller than 25 nm composed a larger fraction of total aerosols in the cases when the engine was operated at the rated speed modes than at the intermediate speed modes.

The SPN engine-out and DOC + DPF system-out concentrations were successfully measured with 3795-HC for all test conditions. In the case of Mi3, the SPN concentrations

Fig. 5 Schematic of Pegasor Particle Sensor (adopted from [57])

Fig. 6 Total aerosol number concentrations measured with FMPS in the exhaust diluted using FPS4000
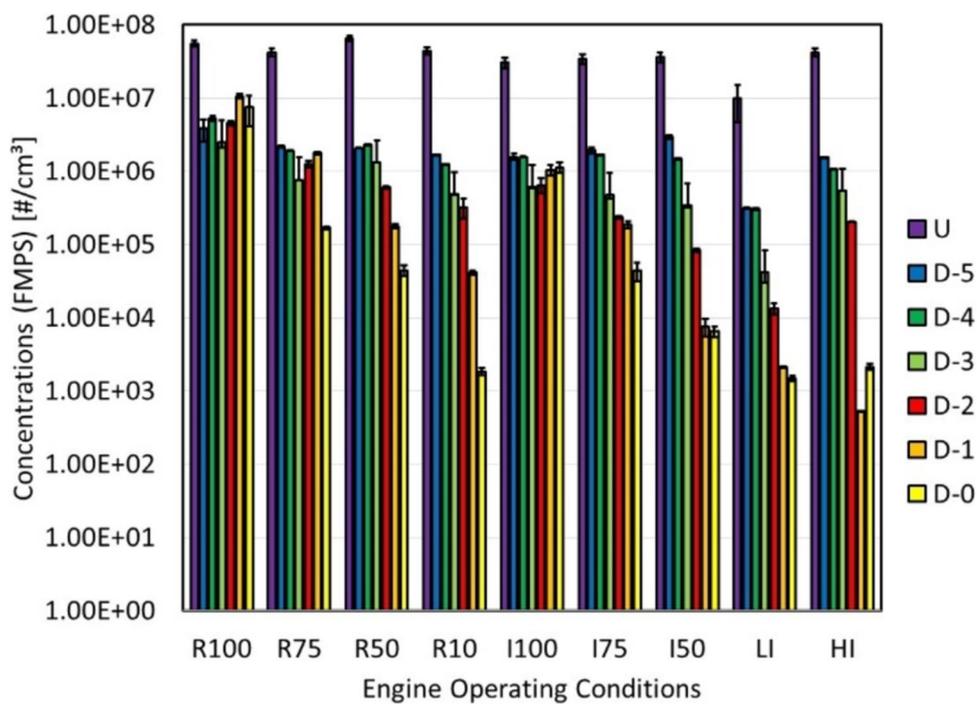
were successfully measured downstream of the DOC + DPF for all test conditions and downstream of the engine for all but R100, R75, and I100 operating conditions. For those conditions, the SPN concentrations exceeded the upper measurement limit of Mi3, and those data points were excluded from further analyses. When all available data is considered, the relations between FMPS TPN and 3795-HC SPN concentrations, FMPS$_{25+}$ TPN and 3795-HC SPN

concentrations, FMPS TPN and Mi3 SPN concentrations, FMPS$_{25+}$ TPN and Mi3 SPN concentrations, and 3795-HC SPN and Mi3 SPN concentrations were found to be linear (Fig. 11). The slopes and R^2 values for the relations between FMPS TPN and FMPS$_{25+}$ TPN and 3795-HC SPN data and between FMPS TPN and FMPS$_{25+}$ and Mi3 SPN data indicate strong linear relationships. However, the wide span of the upstream and downstream TPN and SPN concentrations,

Fig. 7 Concentrations of aerosols obtained with FMPS (FMPS) and SMPS (SMPS)
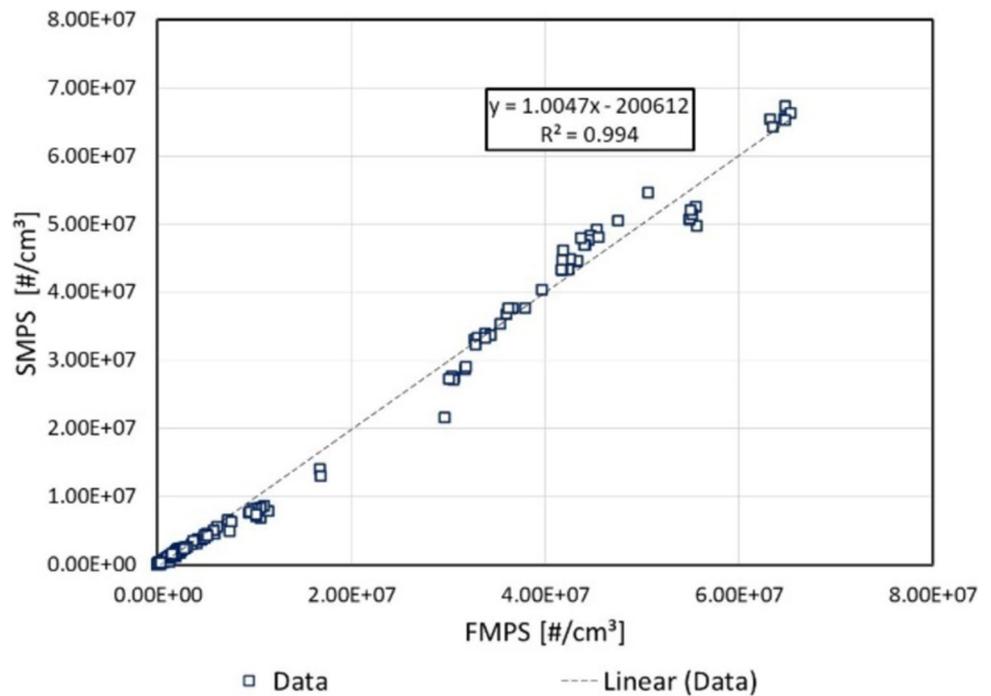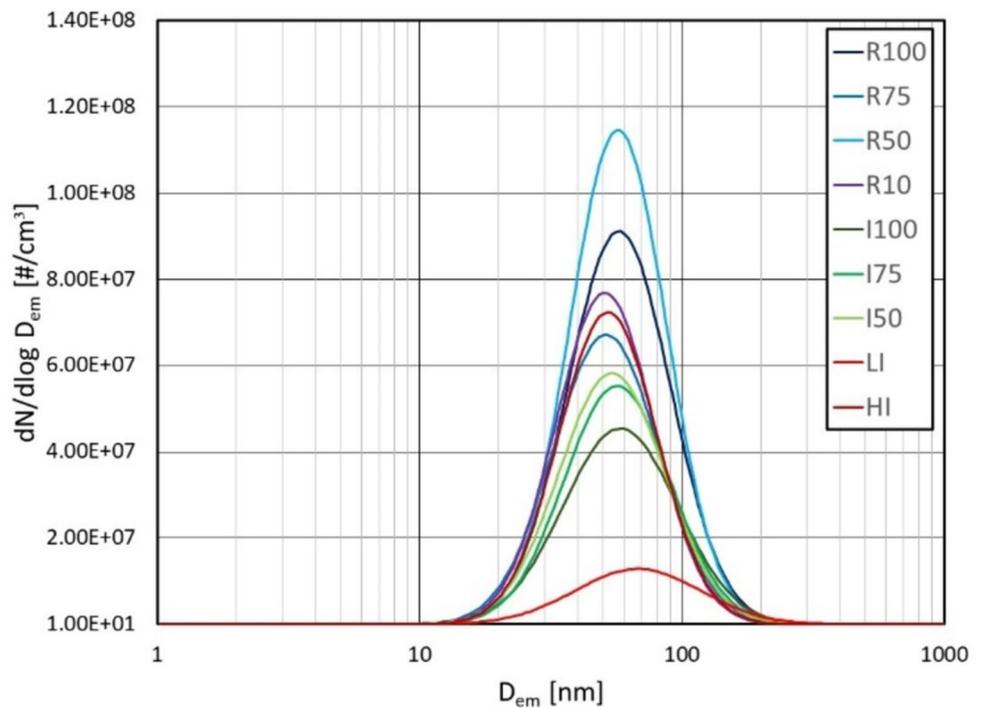

Fig. 8 Size distribution of aerosol upstream of the DOC + DPF system

between one to four orders in magnitude (Fig. 6), contributed to the linearity of those relationships. The SPN concentrations measured with 3795-HC and Mi3 were consistently lower than TPN concentrations measured by FMPS (Fig. 11). The linear relationships between $FMPS_{25+}$ TPN and 3795-HC SPN and $FMPS_{25+}$ TPN and Mi3 SPN data were found to be stronger than those between FMPS TPN

and 3795-HC SPN and FMPS TPN and Mi3 SPN data (Fig. 11).

Further analysis of the downstream data revealed that the FMPS TPN and 3795-HC SPN concentrations and the FMPS TPN and Mi3 SPN concentrations exhibited linear relationships for all but R100 test data (Fig. 12). In the case of R100 data, the high concentrations of nucleation aerosols
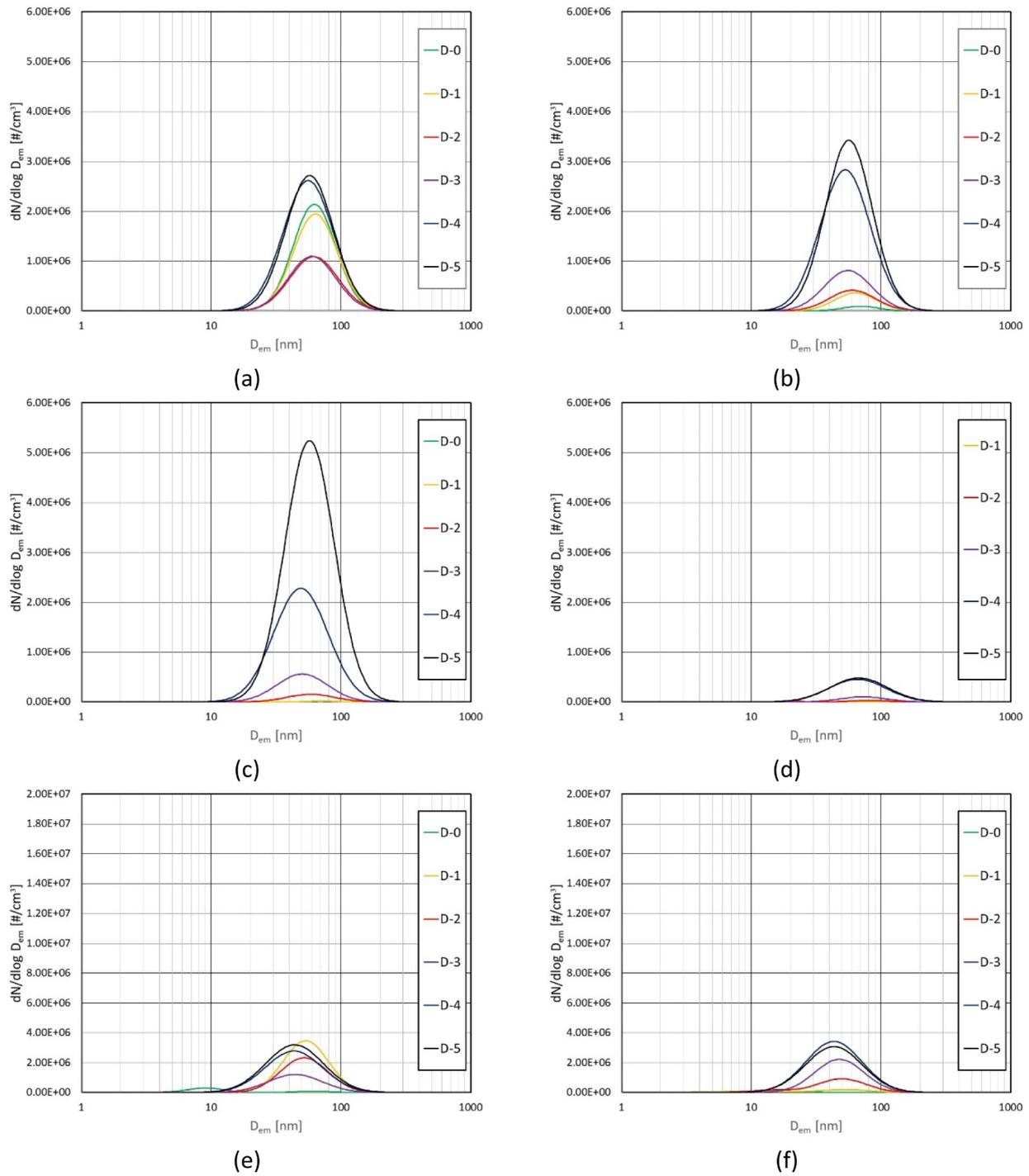
Fig. 9 Size distributions of aerosol downstream of the DOC+DPF system when the engine was operated at **a** I100, **b** I75, **c** I50, **d** LI, **e** R75, and **f** R50 conditions

in the exhaust observed for fully functional and some partially functional configurations (Fig. 10) were primarily responsible for the observed deviations. The linear relationship between the 3795-HC SPN and Mi3 SPN concentration data was found to be tighter for downstream (Fig. 12)

than for the complete set of upstream and downstream data (Fig. 11).

Since the R10 and HI conditions were found to produce similar engine loads and emissions (Figs. 6 and 10) and the R100, R75, R50, and I100 conditions are difficult to produce
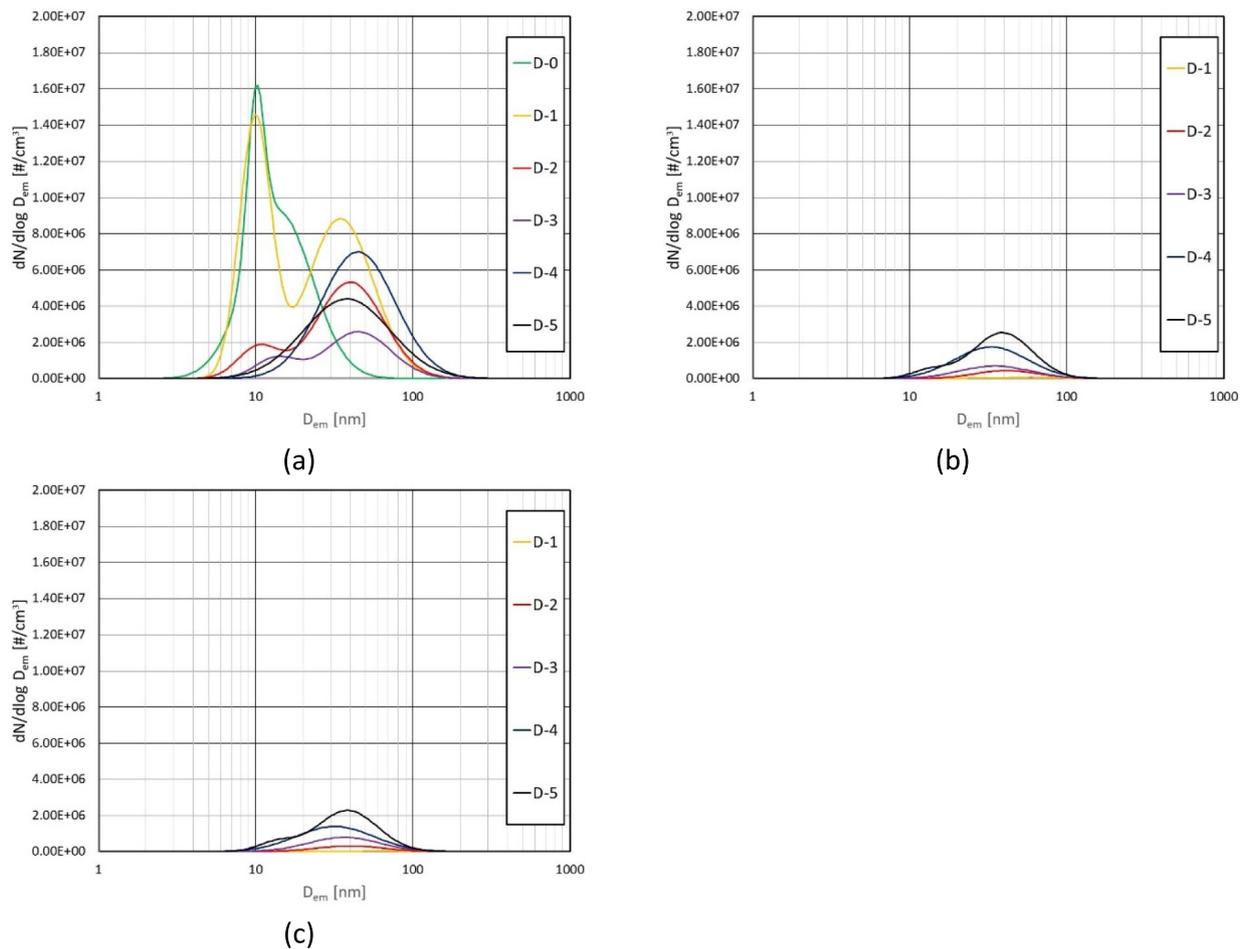
Fig. 10 Size distributions of aerosol downstream of the DOC + DPF system when the engine was operated at **a** R100, **b** R10, and **c** HI conditions

without a chassis dynamometer, the further analysis focused on the data generated for I75, I50, LI, and HI conditions. The first two conditions generate engine speed and load conditions similar to those generated at TCS and HS, popular EAM test conditions. The LI and HI operating conditions present themselves as logical choices for generating EAM data due to simplicity and mechanical reproducibility.

In the case of I75, I50, and HI conditions, the FMPS TPN and 3795-HC SPN, FMPS TPN and Mi3 SPN, and 3795-HC SPN and Mi3 SPN concentrations showed fairly strong linear relationships for both the upstream and downstream (Fig. 13) and the downstream only (Fig. 14) data sets. In the case of LI conditions, the low slope numbers indicated a poor relationship between FMPS TPN and 3795-HC SPN data (Figs. 13a and 14a) and between FMPS TPN and Mi3 SPN data (Fig. 14b). These poor relationships could be explained by low SPN concentrations downstream of a fully functional and even slightly compromised DOC + DPF system, just slightly above the low quantification limit of 3795-HC (2000 #/cm^3) and Mi3 (300 #/cm^3). The other

potential factor could be the difference in the physical properties of aerosols generated at LI and other conditions. The relationships between FMPS TPN and 3795-HC SPN data were found to be substantially less dependent on the engine operating conditions than on the corresponding relationships between FMPS TPN and Mi3 SPN data. For I75 and I50 conditions, the slopes indicate a tight relationship between 3795-HC SPN and Mi3 SPN data sets.

The effectiveness of the fully functional and compromised DOC + DPF system in removal of TPN calculated using the FMPS data (FMPS and FMPS$_{25+}$) and in removal of SPN calculated using the 3795-HC and Mi3 data are shown in Fig. 15. The efficiencies for a fully functional and compromised DOC + DPF system in removal of TPN (FMPS) and TPN of aerosols with diameters smaller than 25 nm (FMPS$_{25+}$) ranged between 80 and 100% and 91 and 100%, respectively. The observed efficiencies for the DOC + DPF system, fully functional or compromised, in removal of SPN as measured by 3795-HC were found to be between 94 and 100% (Fig. 15c). Since the engine-out
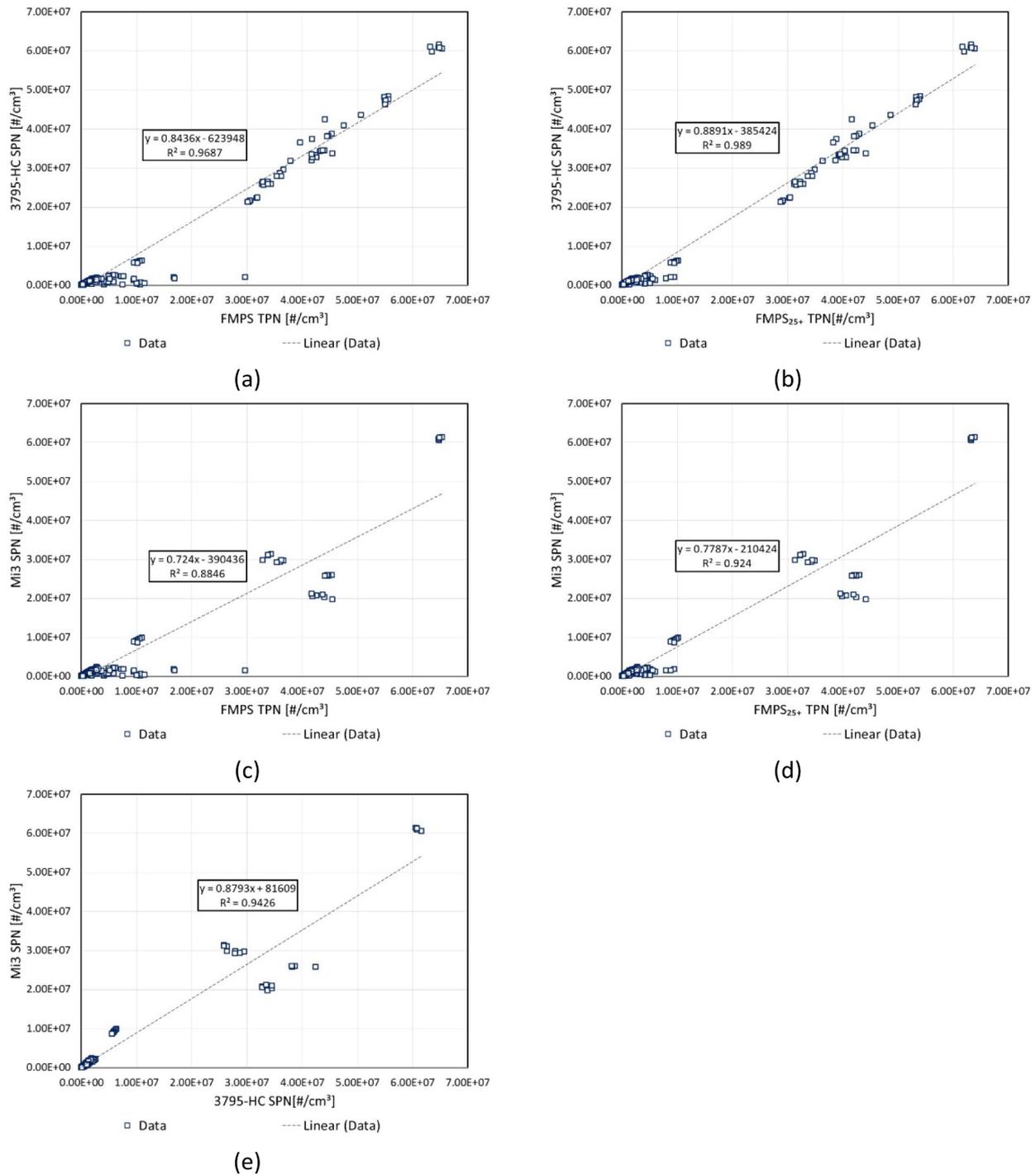
(a)

(b)

(c)

(d)

(e)

Fig. 11 Relationship between **a** FMPS TPN and 3795-HC SPN concentrations, **b** FMPS$_{25+}$ TPN and 3795-HC SPN concentrations, **c** FMPS TPN and Mi3 SPN concentrations, **d** FMPS$_{25+}$ TPN and Mi3 SPN concentrations, and **e** 3795-HC SPN and Mi3 SPN concentrations for both upstream and downstream data (all test modes)

SPN concentrations for R100, R75, and I100 operating conditions exceeded the upper measurement range of Mi3, the effectiveness in the removal of SPN was calculated only for R50, R10, I75, I50, LI, and HI conditions

(Fig. 15). For those conditions, the results were found to be comparable to those assessed using 3795-HC data.

The efficiencies calculated using the results of the FMPS (Fig. 15a) and FMPS$_{25+}$ (Fig. 15b) measurements illustrate
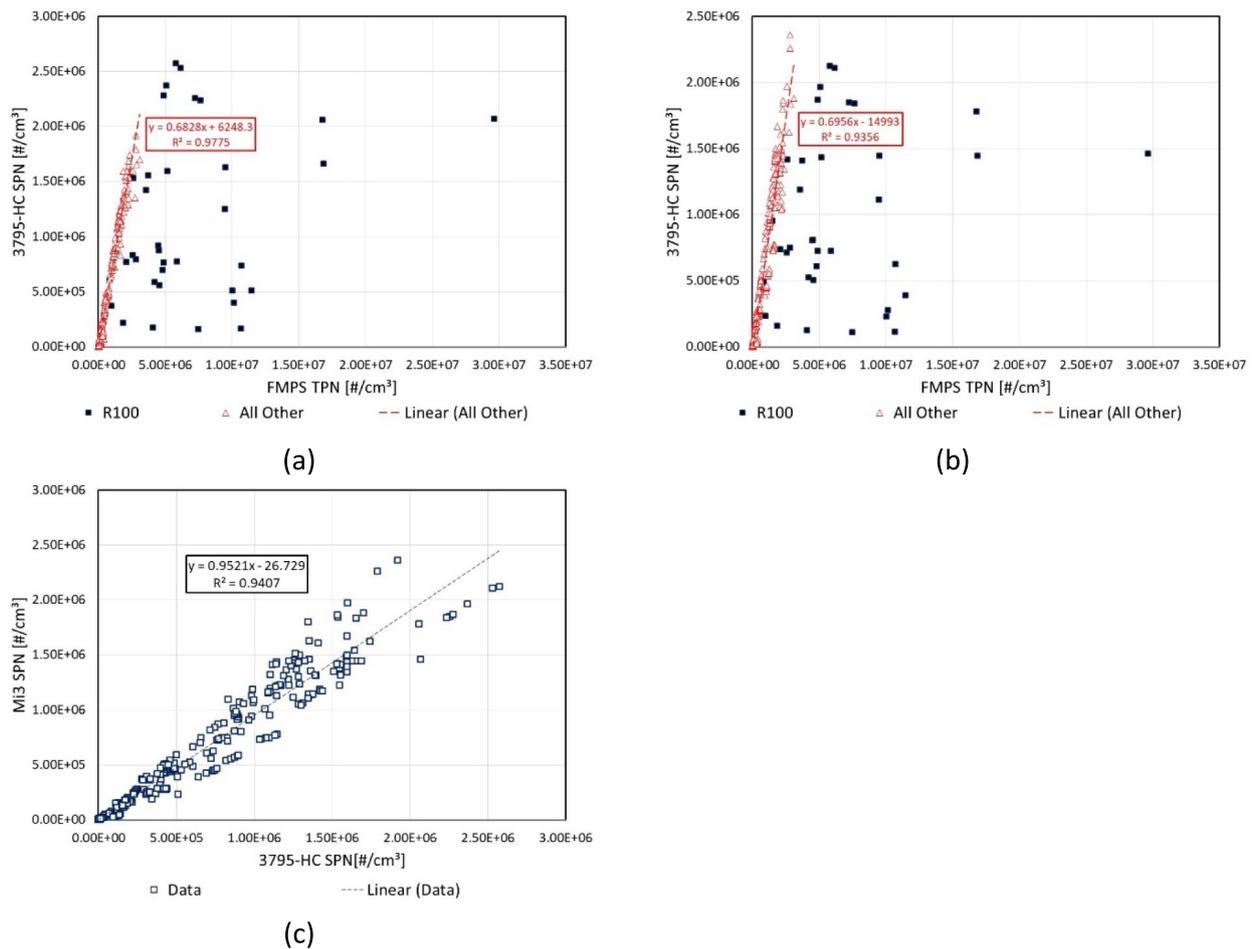
Fig. 12 Relationship between **a** FMPS TPN and 3795-HC SPN concentrations, **b** FMPS TPN and Mi3 SPN concentrations, and **c** 3795-HC SPN and Mi3 SPN concentrations for downstream data (all test modes)

challenges associated with using TPN as the metric for monitoring particle number (PN) emissions. The high concentrations of nucleation mode aerosols in the exhaust filtered by fully functional (D-0) and in some cases of compromised filter (D-1 and D-2) for an engine operated at the R100 condition (Fig. 10a) resulted in high uncertainty of the results (Fig. 15a). The elevated uncertainties were also observed for data generated with the engine operated at the I100 condition (Fig. 15a). This uncertainty could be attributed to difficulties in reproducing performance of the DOC + DPF system and associated emissions at the highest torque conditions. The exclusion of aerosols with diameters below 25 nm from those calculations (FMPS$_{25+}$) did not fully eliminate but did reduce the uncertainty of the efficiency calculations based on TPN concentrations (Fig. 15b).

The efficiency determined using SPN data obtained with 3795-HC (Fig. 15c) and Mi3 (Fig. 15d) proved to be associated with substantially lower uncertainties. A strong linear relationship was observed between efficiencies calculated using 3795-HC and Mi3 data for I75, I50, and HI conditions

(Fig. 16). In the case of the LI data, the calculations with the Mi3 data produced substantially higher efficiency numbers than those calculated with 3795-HC data.

4 Discussion

The data generated in this study indicates that the selection of the proper test conditions is critical to the success of the DPF EAM program. The data obtained for I75 and I50 engine operating conditions proved to be the most suitable for assessing effectiveness of the DOC + DPF system on the Kubota D1803-CR-T-E4B engine. These conditions create engine speeds and loads and emission profiles in the range of those that would be generated at TCS and HS conditions.

The duration of the TCS and HS EAM tests is limited due to potential issues with overheating of the torque converter or hydraulic system [5, 11]. In the case of the common engines installed in diesel-powered underground mining vehicles, the TCS and HS tests typically could not be
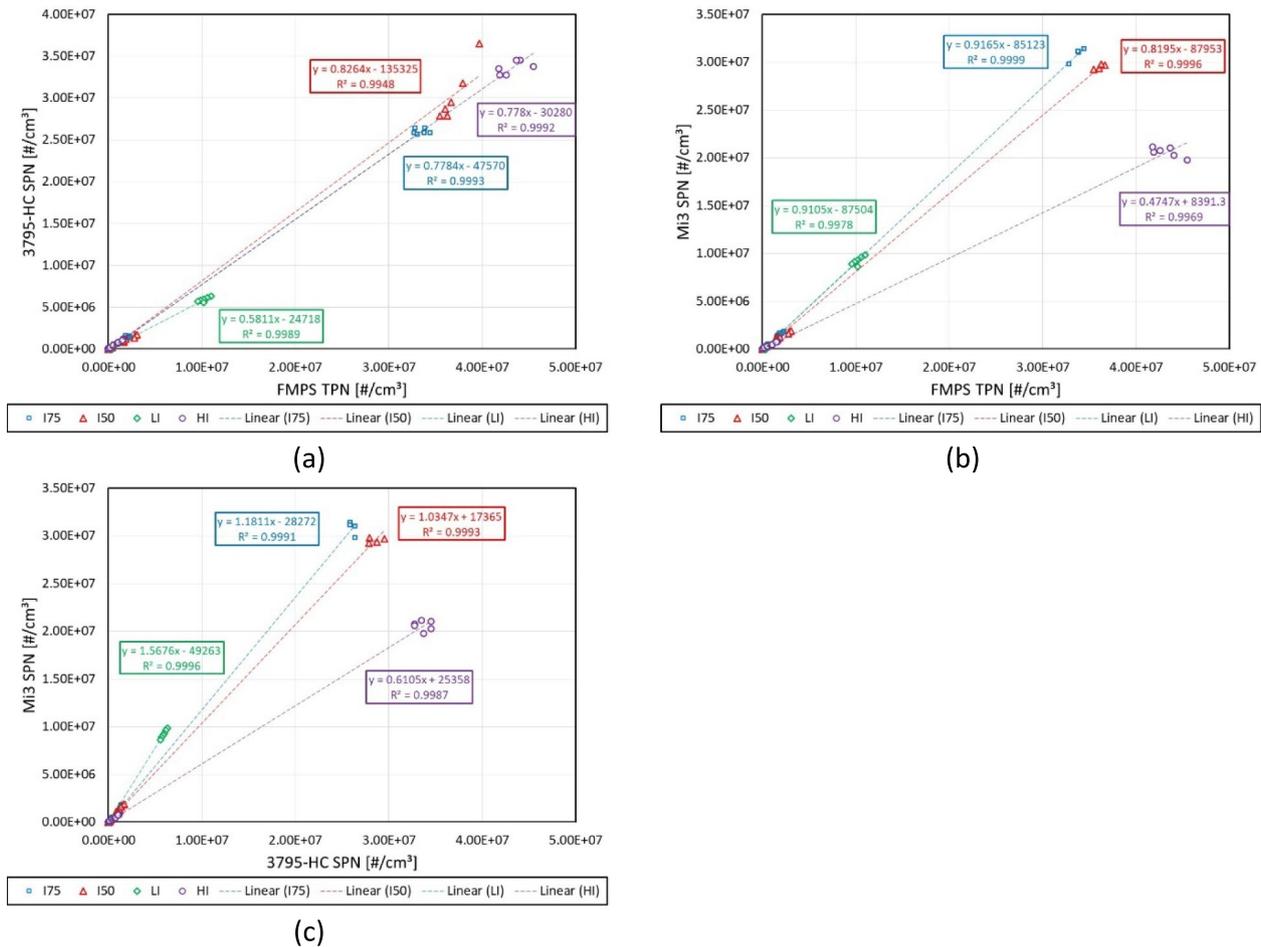
Fig. 13 Relationship between **a** $FMPS_{25+}$ TPN and 3795-HC SPN concentrations, **b** $FMPS_{25+}$ TPN and Mi3 SPN concentrations, and **c** 3795-HC SPN and Mi3 SPN concentrations for I75, I50, LI, and HI conditions (upstream and downstream data)

conducted for more than 60 to 90 s without jeopardizing the integrity of power train systems [13]. The data from the six consecutive repetitions of the 240-s SPN concentration measurements performed with 3795-HC (Fig. 17) illustrates the challenges with obtaining repeatable in situ EAM emissions measurements using TCS and HS conditions. The average 240 s data showed lower average SPN concentrations and lower uncertainties than average 90 s data (initial 90 s of the run). However, it appears that the quality of 90 s data would be acceptable for EAM purposes.

Since the particle emissions from the DPF systems could be strongly affected by the DPF element condition [32, 70, 71], special attention needs to be given to the preconditioning of the engine and exhaust aftertreatment systems prior to each test [32]. The common practice used to improve accuracy and repeatability in EAM testing is to bring the temperature of engine and exhaust components to level characteristic of the used test condition. The data (Fig. 17) indicates that in the case of tests conducted at I50 engine operating conditions, following that criteria

would not be sufficient to secure the terminal state of the SPN emissions. Obtaining data for the multiple consecutive repetitions of EAM TCS and HS tests conducted after adequate preconditioning would help to obtain more reliable and repeatable data (Fig. 17).

The engine operating conditions that generate exhaust temperatures that can promote a regeneration of the DPF element and those that can lead to the pronounced generation of nucleation mode aerosols should not be used to generate EAM data (Fig. 12). The data for those conditions could be associated with high uncertainty and difficult to reproduce. The DPF regeneration can be detected by the increase in CO emissions. The no-load conditions, LI and HI, are not ideal for EAM testing and generally should be used only when TCS and HS conditions are not an option. In the case of data generated this study, the higher uncertainty and poor repeatability of HI and LI data can be traced to very low DPF-out SPN and TPN concentrations, potentially below the lower detection limit of the evaluated instruments (Fig. 14).
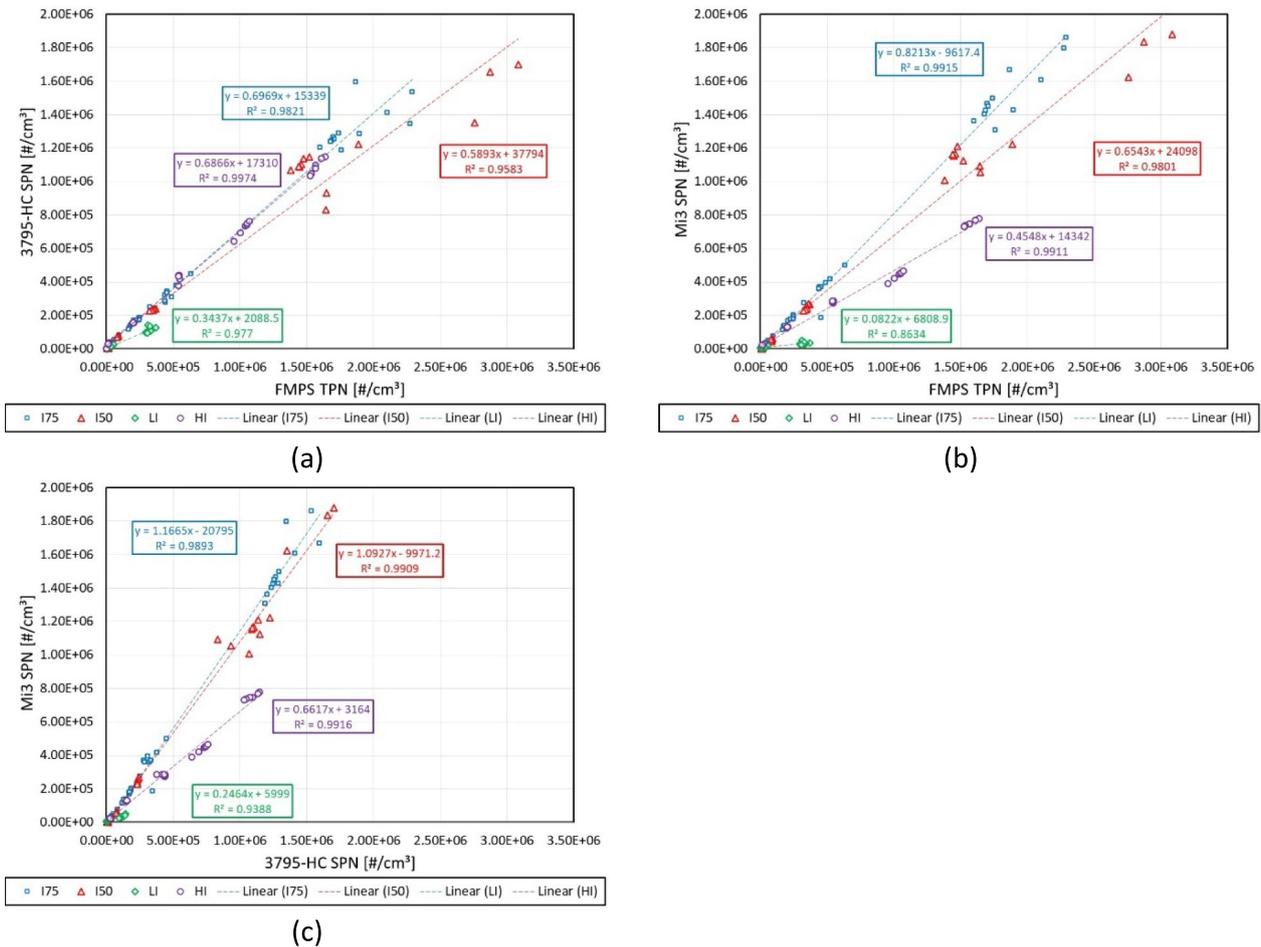
Fig. 14 Relationships between **a** $FMPS_{25+}$ TPN and 3795-HC SPN concentrations, **b** $FMPS_{25+}$ TPN and Mi3 SPN concentrations, and **c** 3795-HC SPN and Mi3 SPN concentrations for I75, I50, LI, and HI conditions (downstream data)

Despite using different measurement principles, both instruments produced comparable results for the DPF-out SPN concentrations in the targeted range between 2×10^3 and 3×10^6 #/cm^3 (Fig. 14) and for efficiencies of the DOC+DPF system for the I75, I50, and HI conditions. The Mi3 SPN data was found to be more affected than 3795-HC data by the variability in properties of diesel aerosols generated for the different test conditions and potentially by the differences in properties of those and aerosols used to calibrate the instruments [56, 72].

In absence of the SPN emissions and DPF performance criteria pertinent to underground mining diesel-powered vehicles, the operations would have to establish own criteria and threshold values for selection and EAM inspection of DPF systems. Two types of criteria can be used to define performance of the DPF systems: (1) the SPN concentration standard based on the results of measurements performed downstream of the system or (2) the efficiency standard based on the results of measurements of SPN upstream and downstream of the system and subsequent calculations of DPF efficiency. The

example of the former one is the Switzerland standard [15]. The Switzerland authorities require annual assessment of DPF systems on non-road diesel-powered machinery using results of the measurement of solid particles with a diameter greater than 23 nm at HI engine operating conditions. The upper concentration limit for hot DPF systems is set to 2.5×10^5 #/cm^3. Similarly, in Netherlands, Belgium, and Germany, the DPF systems on light-duty diesel-powered vehicles were assessed at the PTI intervals using SPN emission measurements at LI operating conditions [15, 73]. The Netherlands/Belgium and Germany standards are 1×10^6 #/cm^3 (cold engine condition) and 2.5×10^5 #/cm^3 (hot engine condition), respectively [73]. The SPN emissions for the light-duty vehicles operated at LI conditions were found to correlate well with the SPN emission measured for those vehicles operated over the New European Driving Cycle (NEDC) test using chassis dynamometer [73]. Alternatively, the operations can define their own efficiency standards. The SPN emissions and DPF performance criteria should take into account the type of the evaluated engine and exhaust aftertreatment system. Potentially, developments in
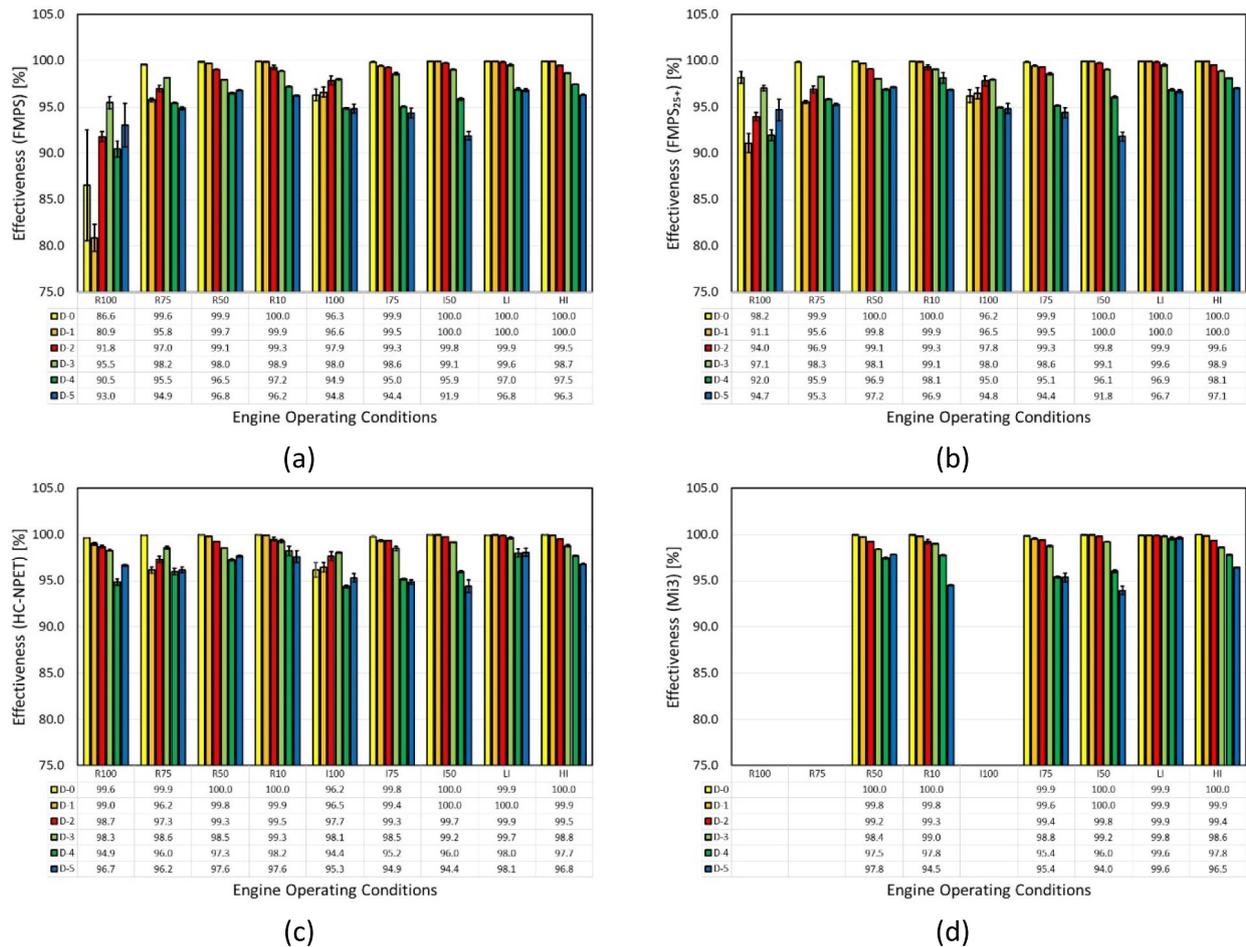
Fig. 15 The effectiveness of the fully functional and compromised DOC + DPF system in removal of **a** TPN (FMPS), **b** TPN (FMPS$_{25+}$), **c** SPN (3795-HC), and **d** SPN (Mi3)

(a)

	R100	R75	R50	R10	I100	I75	I50	LI	HI
D-0	86.6	99.6	99.9	100.0	96.3	99.9	100.0	100.0	100.0
D-1	80.9	95.8	99.7	99.9	96.6	99.5	100.0	100.0	100.0
D-2	91.8	97.0	99.1	99.3	97.9	99.3	99.8	99.9	99.5
D-3	95.5	98.2	98.0	98.9	98.0	98.6	99.1	99.6	98.7
D-4	90.5	95.5	96.5	97.2	94.9	95.0	95.9	97.0	97.5
D-5	93.0	94.9	96.8	96.2	94.8	94.4	91.9	96.8	96.3

(b)

	R100	R75	R50	R10	I100	I75	I50	LI	HI
D-0	98.2	99.9	100.0	100.0	96.2	99.9	100.0	100.0	100.0
D-1	91.1	95.6	99.8	99.9	96.5	99.5	100.0	100.0	100.0
D-2	94.0	96.9	99.1	99.3	97.8	99.3	99.8	99.9	99.6
D-3	97.1	98.3	98.1	99.1	98.0	98.6	99.1	99.6	98.9
D-4	92.0	95.9	96.0	98.1	95.0	95.1	96.1	96.9	98.1
D-5	94.7	95.3	97.2	96.9	94.8	94.4	91.8	96.7	97.1

(c)

	R100	R75	R50	R10	I100	I75	I50	LI	HI
D-0	99.6	99.9	100.0	100.0	96.2	99.8	100.0	99.9	100.0
D-1	99.0	96.2	99.8	99.9	96.5	99.4	100.0	100.0	99.9
D-2	98.7	97.3	99.3	99.5	97.7	99.3	99.7	99.9	99.5
D-3	98.3	98.6	98.5	99.3	98.1	98.5	99.2	99.7	98.8
D-4	94.9	96.0	97.3	98.2	94.4	95.2	96.0	98.0	97.7
D-5	96.7	96.2	97.6	97.6	95.3	94.9	94.4	98.1	96.8

(d)

	R100	R75	R50	R10	I100	I75	I50	LI	HI
D-0			100.0	100.0		99.9	100.0	99.9	100.0
D-1			99.8	99.8		99.6	100.0	99.9	99.9
D-2			99.2	99.3		99.4	99.8	99.9	99.4
D-3			98.4	99.0		98.8	99.2	99.8	98.6
D-4			97.5	97.8		95.4	96.0	99.6	97.8
D-5			97.8	94.5		95.4	94.0	99.6	96.5

SPN and other emissions monitoring technologies should in the near future allow for real-time monitoring of the in-use performance of exhaust particulate filters and assessment of real-world SPN emissions [74, 75].

It is important to note that the results of emission tests conducted as a part of EAM programs are only indicative of the magnitude of those sources. The SPN emissions defined by sample conditioning procedures to strip the volatile aerosols and established for a limited number of available test conditions have a limited relationship with the actual particulate number and mass emissions [41]. Therefore, those could not be used reliably to estimate the exposures of workers to DPM.

5 Conclusions and Future Work

Assuring effectiveness of DPF systems in removal of particulates through viable EAM programs is of critical importance to the success of the overall underground mining DPM control strategies. This study focused on evaluation of EAM practices and instrumentation needed to support operation of contemporary engines equipped with DPF systems and traditional engines retrofitted with DPF systems in the underground mining industry. The study indicated that out of the several test conditions currently used in EAM programs for underground mining vehicles fitted with automatic transmissions and hydraulic systems, the torque converter stall and hydraulic stall could be the most appropriate for assessing the effectiveness of the DPF-based advanced aftertreatment systems. The study also showed that low idle and high idle might not be suitable for producing reliable and reproducible EAM data. Both direct reading instruments evaluated in this study proved to be viable tools for real-time monitoring of solid particle number concentrations in diesel exhaust. In combination with the viable data-driven SPN emissions and DPF performance criteria, these methodologies can help operators to detect and subsequently remove faulty DPF systems from the equipment and minimize unnecessary release of diesel aerosol in the underground environment.

Fig. 16 The relationship between efficiencies of the DOC + DPF system calculated using 3795-HC and Mi3 data
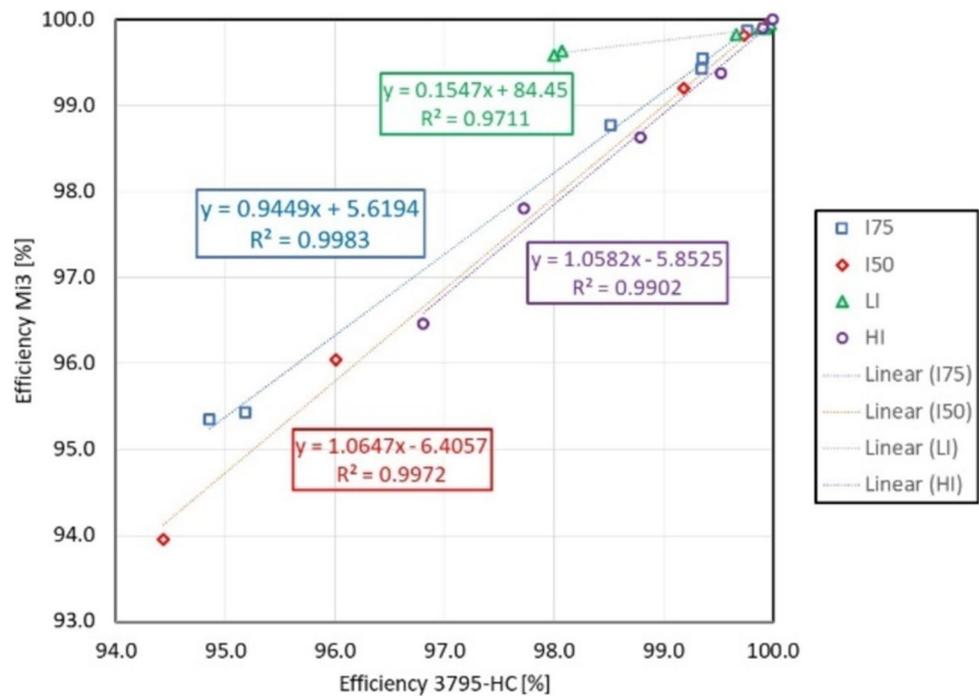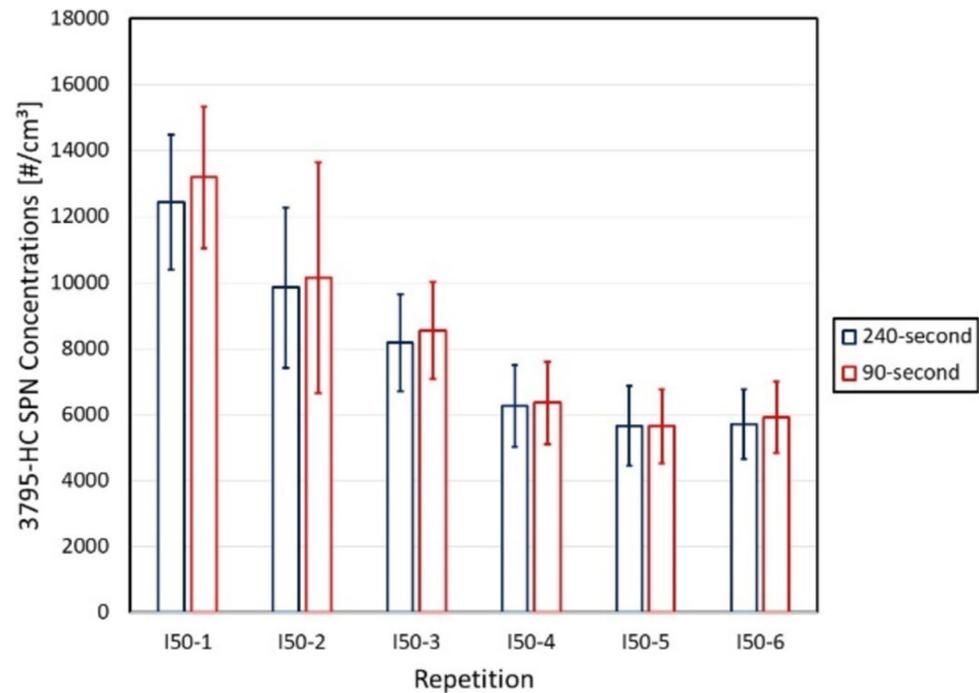

Fig. 17 Six repetitions of the I50 4-min runs

It is important to note that this study was limited in scope and warrants the use of complementary studies conducted for the larger fleets of underground mining vehicles powered by engines equipped with DPF-based exhaust aftertreatment systems. In addition, these methodologies and instrumentation, as well as performance criteria, need to be evaluated for monitoring performance and potential deterioration of the emissions from engines equipped with non-DPF exhaust aftertreatment systems.

Declarations

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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