Role of lubricating oil properties in exhaust particle emissions of an off-road diesel engine

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Role of Lubricating Oil Properties in Exhaust Particle Emissions of an Off-Road Diesel Engine

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Abstract

Particle number emissions from an off-road diesel engine without exhaust after-treatment were studied by using five different heavy-duty lubricating oils in the engine. The study extends understanding on how the properties of lubricating oil affect the nanoparticle emissions from an off-road diesel engine. The lubricants were selected among the performance classes of the European Automobile Manufacturers Association, at least one lubricant from each category intended for heavy-duty diesel engines. Particle size distributions were measured by the means of an engine exhaust particle sizer (EEPS), but soot emissions, gaseous emissions and the basic engine performance were also determined. During the non-road steady state cycle, the most of the differences were detected at the particle size range of 6–15 nm. In most cases, the lowest particle quantities were emitted when the highest performance category lubricant was used. Based on the results of this study, the low contents of Zn, P, and S in lubricating oil contributed to the reduced emission factors for engine-out nucleation mode particles at any load. In addition, the low content of sulfate ash was considered the main influential factor for the low particle number emissions.

Introduction

Diesel engines are a significant source of particulate matter (PM) emissions. By exploiting different engine technologies, gaseous and particle emissions of off-road engines have, however, been considerably reduced over the two last decades. [1]. In several diesel applications (passenger cars, trucks, buses), the breakthrough technology in diesel particle emissions control has been achieved with the commercialization of the diesel particulate filter (DPF). In the European market, the EU Stage V standard comes gradually into effect within 2019–2020. For the first time, this standard also has the limits for the exhaust particle number (PN) emissions of the off-road engines [2] which practically enforces the usage of DPF devices. As the average service life of heavy-duty diesel engines is several years, the diesel engines from off-road applications will be a major source of PM and PN for years to come.

Nonvolatile engine-out diesel exhaust nanoparticles can be divided in terms of formation mechanisms into two distinctive particle modes; soot mode and core (nucleation) mode. [3,4,5,6]. Soot particles are formed in the cylinder, when the fuel-air mixture burns incompletely. Particles can originate from the unburned and partially burned fractions of the fuel and from the lubricating oil. In addition, the core mode is considered to be formed in-side the cylinder due to its nonvolatile nature and electric charge levels of the particles [7]. The nonvolatile core particles are generally smaller than 10 nm, whereas nucleation mode particles are usually smaller than 40 nm. The soot mode mean diameter is generally in the size range of 20–100 nm, which means that soot mode particles can overlap with nucleation particles in a particle size distribution on some occasions.

Particle emissions can be decreased through developing the engine design, after-treatment systems, fuels, and lubricant oils. When a modern diesel engine with very low emissions is developed, more attention has to also be put on the oil-related particle emissions. Selection of lubricant can also affect the emissions of the engines in operation. In addition to the combustion process, fuel, and operating conditions, particle formation depends on the physical and chemical properties of lubricating oil. [8]. A lower oil viscosity means that a thinner film is formed on the cylinder liner during and after expansion stroke. Low viscosity oil also accumulates more easily in the ring gap than oil that has a higher viscosity, and a part of oil ends up into the combustion chamber through the gap. A high oil viscosity is thus favorable when aiming at low lubricating oil consumption through combustion and consequently at low oil-related PM emissions. [9,10]. According to Jung et al. [11], lubricating oil metals also have an effect on particle formation and oxidation.

The most straightforward way of reducing lubricant oil-related particle emissions would be to reduce oil consumption. [12]. Froelund and Yilmaz concluded that the oil-related particle emissions and the oil consumption most likely decrease when the oil viscosity increases and volatility decreases. [9]. Along with engine wear, oil-derived soot may increase, however. [13]. Lubricant oil properties have been found to affect the nanostructure of soot particles, but generally the effects have been associated with nanoparticle and semivolatile particle formation. [14,15]. Especially particle emissions during engine motoring events have been linked with the lubricating oil. [16]. Without a DPF, no correlation between lubricant sulfur and semivolatile nanoparticles was found, but with a DPF, nanoparticles have been detected at high load with positive correlation with the lubricant sulfur level. [17]. In a modern turbocharged gasoline direct injection (DI) passenger car, the PN emissions have shown to correlate positively with the concentrations of the lubricating oil additives (Zn, Mg, P, and S) [18]. In the study of McGeehan et al., [19] inorganic additive elements Ca, P, S, Zn, Mg, and Mo, derived from lubricating oil, were found in the mix of incombustible materials inside the DPF.

Due to the constantly improving combustion process and especially to the very effective particulate filters, the PN emissions of modern diesel engines can be reduced down to a very low level. Nevertheless, incombustible inorganic PM, which originates from the metal additives of lubricant and occurs as ash, may have a detrimental effect on the filters and particularly make their regeneration process more difficult. Ash layers mostly form due to accumulation of lubricating oil residues or additives, which cannot be eliminated during regenerations. DPF ash accumulation increases fuel consumption by increasing the average backpressure levels in the exhaust and by increasing regeneration frequency due to the smaller DPF effective volume. Some of the ash components, like P or Ca are known catalyst poisons hampering the performance of catalytic components in the exhaust system. Despite the high filter effectivity, optimization for engine-out particle reduction is required to avoid increased exhaust backpressure and other problems with DPF ageing. [20,21,22]. In most applications, the initial cost is also a considerable concern, as are the warranty risks, complexity, and the on-board diagnostic burden required by yet another device in the system. [13].

This study selected the lubricants from the performance classes of the European Automobile Manufacturers Association (ACEA), at least one lubricant from each category intended for heavy-duty diesel engines. ACEA has classified these lubricating oils into four quality categories. Lubricating oils in the category of ACEA E4 or ACEA E7 are not suitable for the engines fitted with particulate filters. Moreover, only some engines equipped with exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) system or both can use these oils. ACEA E6 and ACEA E9 classified lubricating oils are recommended for the modern engines equipped with particulate filter, EGR or SCR catalyst. The highest performance category (ACEA E6) is intended for low-SAPS engine oils which fulfil the most optimized limits of sulfate ash, phosphorus, and sulfur (SAPS). [23].

Many recent observations, thus, indicate that lubricating oil and its formulation may have a significant effect on the particle emissions and exhaust aftertreatment systems of diesel engines. For these reasons, a large amount of new information is required about the effects of lubricant composition on the PN emissions. In this study, five different relevant fresh lubricating oils were studied for their effects on the exhaust emission characteristics when used in a modern diesel engine. The main aim was to investigate how these lubricating oils affect the exhaust PN emissions, but soot, gaseous emissions and the basic engine performance were also determined.

Methodology

Engine laboratory measurements

Experiments were performed with a diesel engine (installed in a test bed and loaded by means of an eddy-current dynamometer and run according to the ISO 8178 C1 cycle. The 4-cylinder test engine was a turbocharged, intercooled (air-to-water) off-road diesel engine (model year 2012), equipped with a common-rail fuel injection system. The displacement of the engine was 4.4 dm^3 (bore 108 mm, stroke 120 mm) and the rated power 101 kW. The engine was not equipped with any exhaust gas after-treatment devices.

Lubricating oils

The effect of the lubricating oil on the exhaust gas particles and gaseous emissions was investigated by using five different heavy-duty diesel engine oils (HDDO), Table 1. Four of the oils were commercial products (A–D) and one was a development product (E).

Table 1. Lubricating oils used in the study.

Oil		A	B	C	D	E
SAE viscosity grade		10W-40	15W-40	10W-40	10W-40	15W-40
ACEA E grade		E9	E7	E4	E6	E9
	ASTM method					
Kinematic viscosity at 100 °C, mm^2/s	D445	14.4	14.1	13.5	13.7	14.3
Kinematic viscosity at 40 °C, mm^2/s	D445	95.5	101	89.0	88.9	100
VI	D2270	155	142	154	156	145
Density at 15 °C, kg/m^3	D4052	868	886	869	863	861
Calcium, mg/kg	D5185	2042	2917	4088	1630	2051
Phosphorus, mg/kg	D5185	918	1056	997	681	940
Zinc, mg/kg	D5185	1073	1220	1168	809	1093
Sulfur, mg/kg	D5185	3797	8585	3176	2450	3399
Boron, mg/kg	D5185	17	0	235	91	0
Magnesium, mg/kg	D5185	2	2	24	609	1
Sum of additives, mg/kg		7849	13780	9688	6270	7484

The lubricant A was used as the reference. The engine was run with commercial low-sulfur diesel fuel oil, completely fulfilling the fuel standard EN590. [24].

Analytical procedures

When starting the experiments, fresh oil was changed into the engine. The old lubricant was drained, and new oil was added at an amount of six liters to the oil sump. The oil filter was changed.

After the oil change, the engine was run for 10 minutes to remove the remnants of previous lubricant as thoroughly as possible. Thereafter, the oil was drained, and filter changed again. Eight liters of fresh test lubricating oil was added to the oil sump. After the oil change, the engine was warmed up. The warmup time varied between 30 and 60 minutes.

Each day before the measurements, the analyzers were calibrated manually once a day according to the instructions of the instrument manufacturers. The experimental setup is in Figure 1. During the measurements, the particles from a size range of 5.6 to 560 nm were measured by using the engine exhaust particle sizer (EEPS, model 3090, TSI Inc.), for which the sample flow rate was adjusted at 5.0 L/min. The “SOOT” inversion algorithm was applied in the EEPS data processing [25].

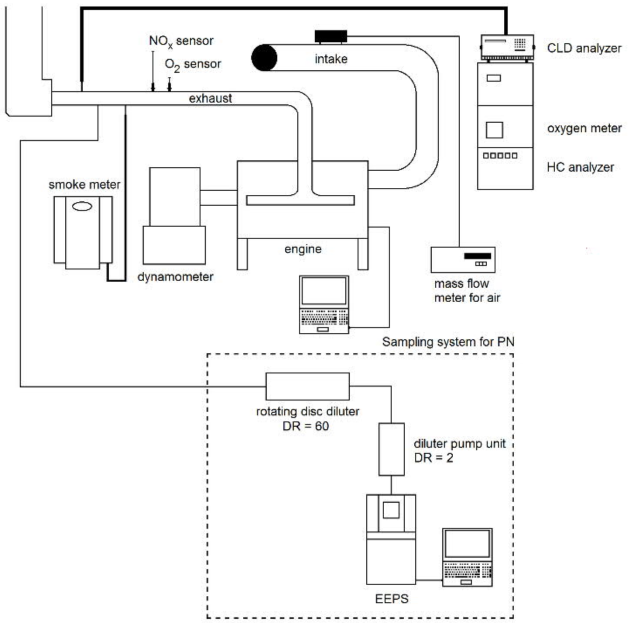

Figure 1. Experimental setup.

The exhaust sample measured by the EEPS was first diluted with ambient air by means of a rotating disc diluter (RDD) (model MD19-E3, Matter Engineering AG).The dilution ratio used in the RDD was constant 60 during the measurements. The exhaust aerosol sample was conducted to the RDD and a dilution air was kept at 150 °C. In this way, mainly the nonvolatile particle fraction at 150 °C is measured by the EEPS. The diluted sample (5 L/min) was further diluted by purified air with a dilution ratio of 2 in order to fit the sample volume flow to suitable for the EEPS. Thus, the total dilution ratio used in particle size distribution measurements was 120.

Three-minute stable time intervals were chosen for the results recordings of the particle number (PN) and particle size distributions. The averages of the normalized PN concentrations ($dN/d\log D_p$, where N is particle concentration and D_p the mobility diameter of a particle) were calculated from each bin in order to illustrate the particle size distributions. The calculated averages of the normalized PN concentrations were multiplied by the total dilution ratio of the exhaust sample to present the corresponding concentrations in the raw exhaust.

As known, lognormal bimodal size distribution consist of two lognormal modes. Thus, the emission factors for nucleation mode PN and soot mode PN were calculated from the lognormal fittings of both modes. The lognormal fit functions were calculated for all measured particle size distributions in order to evaluate the PN shares of nucleation and soot mode particles (see Appendix). The additional emission factors were calculated by taking into account the normalized PN concentrations in the corresponding EEPS spectrometer size bins: for PN (< 23 nm), the bins representing the particle geometric mean sizes from 6.0 to 22.1 nm, and for PN (> 23 nm), from 25.5 to 523.3 nm.

The recorded smoke value was the average of three consecutively measured smoke numbers (model 415S, AVL). Nitrogen oxides (NO_x) and hydrocarbon (HC) emissions of exhaust were measured by using appropriate analyzers (Eco Physics CLD 822 M h for NO_x and J.U.M. VE7 for HC). The emission factors for HC and NO_x were calculated according to the ISO 8178 standard.

The sensor data were collected by means of software, made in the LabVIEW system-design platform. In addition to the gaseous emissions, the systems recorded the temperatures of cooling water, intake air and exhaust gas plus the pressures of the intake air and exhaust gas. The engine control parameters were followed via WinEEM4 engine management software.

Experimental matrix and running procedure

The measurements were conducted according to the test cycle C1 of the ISO 8178-4 standard, known as the non-road steady state cycle (NRSC) [2]. The rated speed was 2200 rpm and the intermediate speed 1500 rpm. At 100% load, the maximum torque was 410 Nm at rated speed and 525 Nm at intermediate speed. An eddy-current dynamometer of model Horiba WT300 was employed to load the engine.

Each day before the measurements, the intake air temperature was adjusted at 50 °C downstream the charge air cooler when the engine was run at 100% load at rated speed. The temperature was controlled manually by regulating cooling water flow to the heat exchanger. After this initial adjustment, the temperature was allowed to change with engine load and speed.

Before the recordings at each load point, it was waited that the engine had stabilized, the criteria being that the temperatures of coolant water, intake air and exhaust were stable.

All measurement values were recorded once at each load point of the cycle. For each lubricant, the oil change procedure, engine warm up and measurements were performed in an exactly similar way.

Results

Particle size distributions and smoke

Figure 2 shows the particle size distributions, calculated from TSI EEPS 3090 recordings, at 100%, 75%, 50%, and 10% load at rated speed and Figure 3 at 100%, 75%, and 50% load at intermediate speed, and at idle. In both Figures, the normalized particle numbers are presented as a function of the particle mobility diameter.

At rated speed (Figure 2), the distributions were usually bimodal, one peak being detected at a particle size of approx. 10 nm and the other within a size range of 30–50 nm. At 100% load (Figure 2a), at the size of approx. 10 nm, significantly fewer particles were observed with lubricant D than with the others. At 50% load (Figure 2c) with all lubricants, there was again one peak within a particle size range of 30–50 nm. Contrary to 100% load, however, the other peak at 10 nm was observed only with lubricants B and E. With B, the peak was rather low, though.

At intermediate speed, at 100% (Figure 3a) and 75% (Figure 3b) loads, there was one peak at a particle size of approx. 10 nm and the other within a size range of 30–50 nm. At rated speed within the size range of 10–20 nm, clearly the lowest quantity of particles was detected with lubricant D while lubricant E resulted in the highest particle number. Above the particle size of 50 nm, PN did not differ as widely. Between 50–100 nm, lubricant B led to the largest amount of particles.

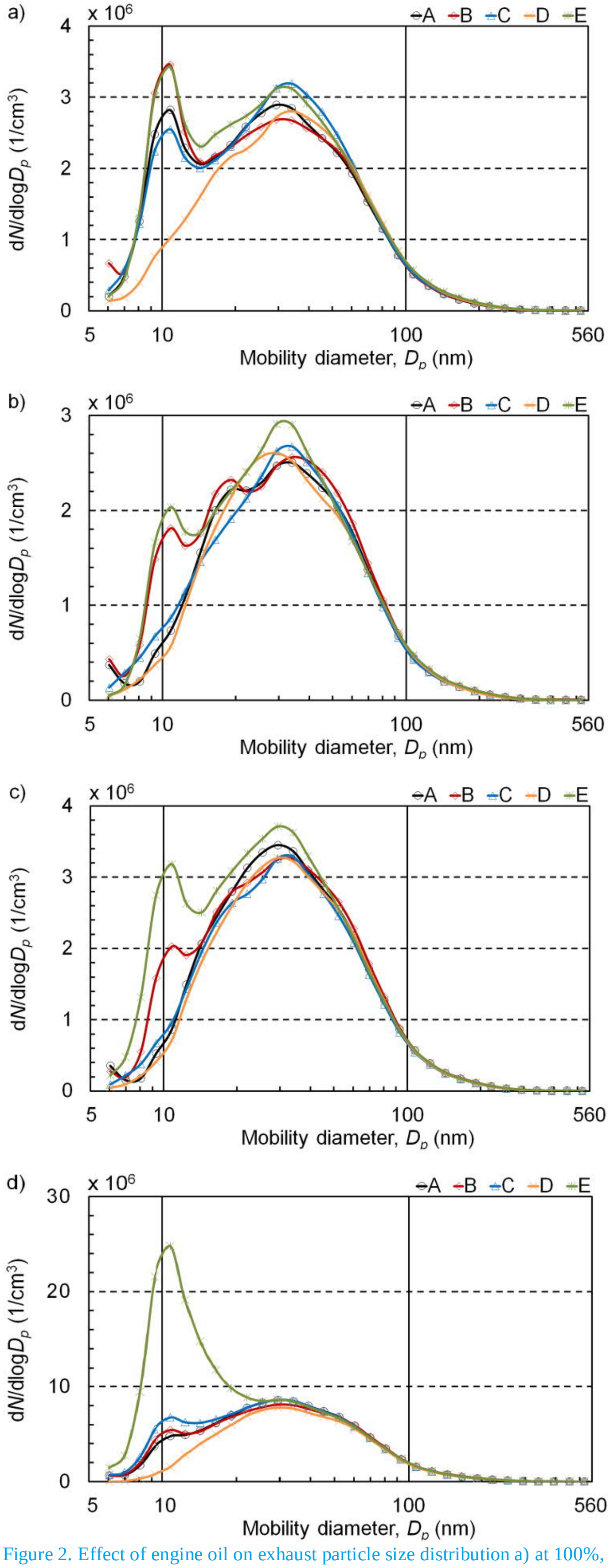

Figure 2. Effect of engine oil on exhaust particle size distribution a) at 100%, b) 75%, c) 50%, and d) 10% load at rated speed.

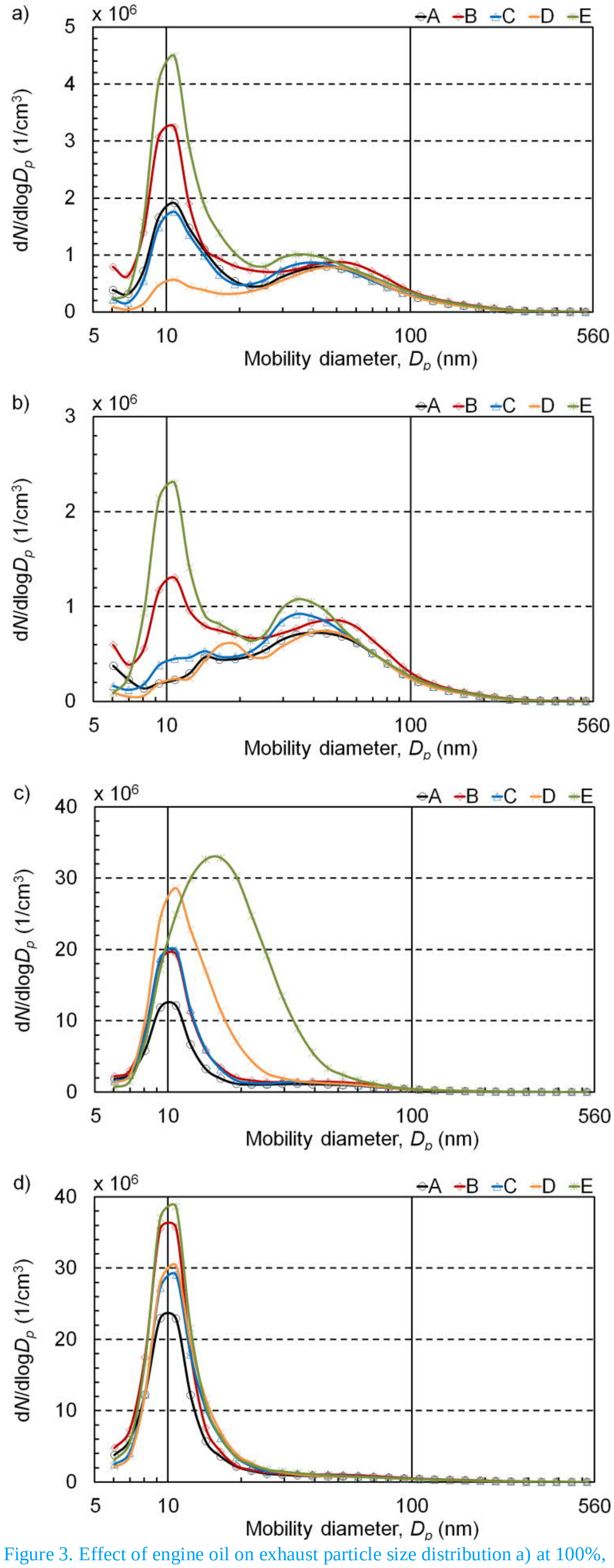

Figure 3. Effect of engine oil on exhaust particle size distribution a) at 100%, b) 75%, and c) 50% at intermediate speed, and d) at idle.

At intermediate speed (Figure 3), the largest differences in the PN concentrations were detected at the particle size of approx. 10 nm, the lubricant E generating far the highest PN and lubricant D the lowest. At this speed, the distribution shapes differed from those at rated speed since the accumulation mode peaks were relatively much lower compared to those at approx. 10 nm.

With all lubricating oils at all loads, the measured smoke values were generally so close to each other that the conclusions were hard to draw, Table 2.

Table 2. Measured exhaust smoke emission for lubricants.

Speed, rpm	Load, %	Smoke, FSN				
		Oil A	Oil B	Oil C	Oil D	Oil E
2200	100	0.025	0.029	0.031	0.022	0.042
2200	75	0.022	0.014	0.016	0.029	0.029
2200	50	0.025	0.028	0.019	0.019	0.030
2200	10	0.063	0.067	0.064	0.070	0.068
1500	100	0.014	0.018	0.022	0.013	0.019
1500	75	0.017	0.016	0.008	0.013	0.015
1500	50	0.026	0.017	0.019	0.024	0.027
860	0	0.041	0.058	0.054	0.033	0.040

Bimodal particle size distributions have also been measured both in on-road and laboratory conditions from heavy-duty diesel truck engines [26], light-duty diesel engines [5], natural gas buses [27], direct-injected gasoline vehicle [18,28] and off-road diesel engines [29,30]. Compared to this study, the peaks of the bimodal size distribution were at around 10 nm and 40 nm during the NRSC when Pirjola et al. [30] investigated the similarly fueled, identical off-road engine model. At the particle size range of 10 nm, nonvolatile particle mode was distinctive when two low-ash, low-sulfur lubricants were studied in an off-road engine at idling and low-load conditions. [7]. In the study of Lähde et al. [7], the difference in the core PN in nucleation mode was about 40% between two lubricants. The difference between lubricant Ca concentrations (36%) and the difference between detected core PN (40%) were reported to be similar.

Regulated emissions

The HC, NO_x, and particle number emission factors over the NRSC cycle are given in Table 3. Regarding the particle number, the emission factors are also shown separately for particles smaller and larger than 23 nm (particle size used in European particle number emission standards) and for nucleation mode and soot mode, analyzed detailed below.

The cycle-weighted NO_x emissions remained almost constant (7.6–7.7 g/kWh), independent of which lubricant was used, Table 2. The specific HC emission also remained almost constant at 0.16 to 0.17 g/kWh regardless of the lubricant.

The cycle-weighted total PN sum during the NRSC cycle was the lowest with lubricant A and highest with lubricant E. The PN sum was 1.8 times higher with lubricant E compared to lubricant A. In addition, the PN sums of either smaller or greater than 23.7 nm particles during the cycle were the lowest with lubricant A and the highest with lubricant E since it often generated very high nucleation-mode particle numbers.

Table 3. The HC, NO_x, and particle number emission factors and exhaust particle number concentrations for the off-road diesel engine with different lubricating oils over the NRSC cycle. Particle number concentrations and emission factors have been determined for specified particle size ranges from the particle number size distribution measurements.

Oil	A	B	C	D	E
HC, g/kWh	0.17	0.17	0.18	0.17	0.16
NO_x, g/kWh	7.6	7.6	7.6	7.8	7.7
PN > 23 nm, $x10^{13}$ 1/kWh	1.0	1.1	1.1	1.0	1.3
PN < 23 nm, $x10^{13}$ 1/kWh	1.0	1.3	1.1	1.2	2.2
PN, nucleation, $x10^{13}$ 1/kWh	0.4	0.7	0.6	0.6	1.7
PN, soot, $x10^{13}$ 1/kWh	1.6	1.7	1.6	1.5	1.8
PN, all, $x10^{13}$ 1/kWh	2.0	2.3	2.2	2.1	3.5

The mode resolved particle emissions are seen in Table 3. For the nucleation mode, lubricant A showed the lowest share, 19%, of all particles, throughout the whole cycle. The corresponding share with lubricant E was 49%, being the highest of all lubricating oils.

For the lubricating oils B, C and D, the shares of nucleation mode particles were 29%, 27% and 28%, respectively. The exhaust temperatures upstream the turbocharger turbine was very similar with all lubricating oils. The difference in the temperature was below 4 °C irrespective of the engine speed or load.

Effect of lubricating oil metals and kinematic viscosity

Table 4 contains the values of squared correlation factors for either positive (+) or negative (-) linear interdependences between the total PN of the particle modes (nucleation mode are abbreviated to NM and soot mode to SM), and the lubricant additive concentrations, total additive concentration, and kinematic viscosity at 100 °C.

Positive correlations with nucleation mode PN and elemental composition was observed with Zn and P. The correlations were negative with Mg and B. At lower loads like 10% (rated speed) and 50% (intermediate speed) the correlation of nucleation PN and sum of additives was negative, but for the points of higher power, the correlation was positive. The clearest observation, however, was the positive correlation between the total PN of nucleation mode particles and lubricating oil kinematic viscosity at 100 °C at illustrated load points. In the case of soot mode particle emission factors at the same load points, the correlations were also negative with the exception of 100% load at rated speed.

Discussion

In particular, the number of nanoparticles can increase if the lubricating oil ends up in the cylinder and burns. Additionally, the primary particle diameters may increase when the load is low. [31].

Table 4. The values of squared correlation factors for either positive (+) or negative (-) linear interdependences between the total PN of the particle modes (NM, SM), and the lubricant additive concentrations, total additive concentration, and kinematic viscosity at 100 °C.

Speed			Rated				Intermediate			Idle
Load			100%	75%	50%	10%	100%	75%	50%	
Ca	NM	+/-	+	+	-	-	+	+	-	+
		R^2	0.58	0.02	0.01	0.03	<0.01	<0.01	0.13	0.17
	SM	+/-	+	-	-	+	+	+	-	-
		R^2	<0.01	0.02	0.14	0.19	0.03	0.09	0.05	0.22
Mg	NM	+/-	-	-	-	-	-	-	-	+
		R^2	0.86	0.13	0.18	0.12	0.56	0.24	<0.01	<0.01
	SM	+/-	-	+	-	-	-	-	+	-
		R^2	0.67	0.01	0.16	0.87	0.35	0.81	0.26	0.03
B	NM	+/-	+	-	-	-	-	-	-	+
		R^2	0.04	0.27	0.38	0.11	0.28	0.20	0.09	0.15
	SM	+/-	-	+	-	-	-	-	-	-
		R^2	0.25	0.09	0.26	0.00	0.19	0.14	0.05	0.83
Zn	NM	+/-	+	+	+	+	+	+	-	+
		R^2	0.85	0.31	0.19	0.03	0.44	0.25	0.02	0.02
	SM	+/-	+	-	+	+	+	+	-	+
		R^2	0.44	0.11	0.01	0.63	0.41	0.69	0.07	0.03
P	NM	+/-	+	+	+	+	+	+	-	+
		R^2	0.84	0.34	0.21	0.03	0.46	0.27	0.02	0.02
	SM	+/-	+	-	+	+	+	+	-	+
		R^2	0.46	0.12	0.01	0.62	0.44	0.70	0.06	0.04
S	NM	+/-	+	+	+	-	+	+	-	-
		R^2	0.09	0.89	0.28	0.03	0.18	0.17	0.10	<0.01
	SM	+/-	+	-	-	+	+	+	+	+
		R^2	0.09	0.75	0.05	0.02	0.33	0.21	0.14	0.42
Sum of additives	NM	+/-	+	+	+	-	+	+	-	+
		R^2	0.27	0.70	0.15	0.05	0.13	0.13	0.16	0.01
	SM	+/-	+	-	-	+	+	+	+	+
		R^2	0.06	0.61	0.13	0.07	0.29	0.23	0.06	0.13
Kinematic viscosity at 100°C	NM	+/-	+	+	+	+	+	+	+	-
		R^2	0.01	0.09	0.24	0.17	0.39	0.14	0.07	0.27
	SM	+/-	+	-	+	+	+	+	-	+
		R^2	0.48	0.01	0.46	0.16	0.15	0.30	0.05	0.47

Lähde et al. [7] suggested the connection between the lubricant Ca concentration and the particle core concentration based on their result where the core number concentration increased approx. 40% when the lubricant with 36% higher Ca concentration was used.

The lubricant D of the present study would seem to have fulfilled several features that promote low PN emissions. It was the only low-SAPS engine oil to meet the ACEA E6 2012 specification. [23]. Therefore, the lowest amount of residual sulfate ash might have transferred into the exhaust when the lubricant D was used, assuming that all the lubricants ended up in the cylinder and combusted in an equal way. Froelund and Yilmaz concluded that the oil-related particle emissions and the oil consumption most likely decrease when the oil viscosity increases and volatility decreases. [9]. In this study, however, the least number of particles were emitted with Lubricant D apart from a quite low kinematic viscosity at 100 °C.

With regard to the particle size distributions in general, rather slight differences were detected in the shapes of the distributions at a certain load when different lubricants were used. The distributions were commonly bimodal and the peak PN located usually within the same size ranges. The biggest differences were seen in nucleation mode particles with a diameter of approx. 10 nm. The generally low-SAPS, but high-Mg lubricant D was observed to have the lowest PN emissions when considering the whole engine operation range. The PN of approx. 10 nm particles was usually the lowest when lubricant D was used. For comparison, Pirjola et al. [18] also detected bimodal PN distributions in the exhaust of gasoline direct injection engine with all studied lubricating oils that supports the results of the present study. All lubricating oils tested in [18] were modern European light duty engine oils with either ACEA A3/B4 or ACEA C3 approvals. [23]. Hence, all these engine oils were approved in use also in diesel engines.

The lowest elemental concentrations of Zn, P, and S in the lubricant D contributed to the reduced total PN for nucleation mode particles at any load. The results of Pirjola et al. [18] indicated that decreased concentrations of Mg, Zn, P, and S in the lubrication oil decreased nonvolatile particle emission factors. Contrary to Pirjola et al. [18], the decreased Mg concentration was associated with increased PN emission factors in this study. Lubricant D had also the lowest concentration of Ca. However, consistent correlation was not found between Ca concentration and PN emission factor due to varying trend of the correlation along with the engine operating point.

The PN averages calculated from the EEPS scans were found to remain fairly constant, mostly, and be repetitious in this study. As an example, the variation of the PN during the three-minute time intervals can be seen in Figure 4. The three-minute intervals were subdivided into one-minute intervals by utilizing the values from the recordings of those two EEPS measurement channel, where the PN peaked with different lubricants at 100% load at intermediate speed.

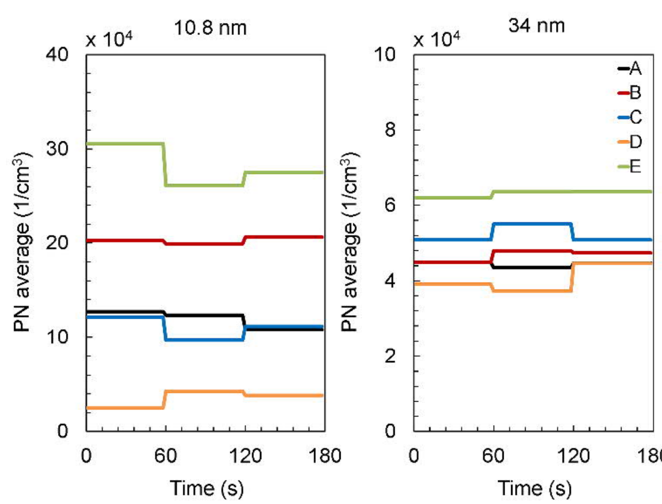

Figure 4. The variation of the average PN during the three-minute time intervals selected for the results at the two EEPS channels (10.8 nm, 34 nm).

Summary

To summarize, with all studied lubricants, the engine performance, gaseous emissions and smoke were almost equal. Some differences between the oils were, however, detected especially in the particle number (PN). The most of the PN emissions differences were detected for the nonvolatile nucleation mode particles. Notably at this size category, the lowest particle quantities were at almost all loads emitted when lubricant D was used. Lubricant D was the only low-SAPS oil to meet the ACEA E6 2012 specification. It had the highest Mg concentration and the lowest concentrations of Ca, Zn, P, and S. The total additive content of D was 6270 ppm. The low contents of Zn, P, and S correlated with the reduced emission factors for nucleation mode particles at any load. Within the range of accumulation mode particles, no significant differences between the oils were recorded. In the future, more research will be needed to obtain deeper understanding how the elemental concentrations of the lubricating oils affect the PN emissions in diesel engines. It would be favorable to only vary the lubricating oil composition additive by additive both in terms of the additive amount and quality.

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Abbreviations

ACEA	European Automobile Manufacturers Association
ASTM	American Society for Testing and Materials
BC	black carbon
CLD	chemiluminescence detector
DPF	diesel particulate filter
EEPS	engine exhaust particle sizer
EGR	exhaust gas recirculation
EN	European norm
EU	European Union
HC	hydrocarbon
HDDO	heavy-duty diesel engine oil
ISO	International Standard Organization
NM	nucleation mode
NO_x	nitrogen oxides
NRSC	non-road steady state cycle
PM	particulate matter
$PM_{2.5}$	atmospheric particulate matter with a diameter of less than 2.5 µm
PM_{10}	atmospheric particulate matter with a diameter of less than 10 µm
PN	particle number
RDD	rotating disc diluter
SAPS	content of sulfated ash, phosphorus and sulfur in lubricating oil
SCR	selective catalytic reduction
SM	soot mode

APPENDIX

Lognormal fit functions were calculated for all measured particle size distributions in order to evaluate the PN shares of nucleation and soot mode particles (Table A1). Separate lognormal distribution functions were fitted for both modes of a bimodal distribution. Both fit functions were characterized by a peak width and mean particle size (Table A2), and the total particle number in each mode was integrated. The quality of fittings was evaluated by minimizing the least sum of squares for the difference between the measured and calculated distribution (Figure A1).

Table A1. Calculated fitting values and total fit for the measured particle numbers when Lubricant A was used at 100% load at rated speed. Fits for modes 1 and 2 were calculated by using the function for fittings.

	Mode 1	Mode 2
σ_g	1.30	2.92
D_g	10.1	30.3
Factor	0.1926	1.1637
N_{tot}	557239	3365934

* Function for fittings:

$$\frac{dN}{d\ln D_p} = \frac{N_{tot}}{\ln\sigma_g\sqrt{2\pi}} \cdot e^{\left[-\frac{(\ln D_p - \ln D_g)^2}{2\ln^2\sigma_g}\right]}$$

EEPS D_p (nm)	Measured $dN/d\log D_p$	A fit for mode 1(*	A fit for mode 2(*	Total fit for $dN/d\log D_p$
6.04	203057	1.94E+04	212986	
6.98	478760	1.79E+05	332782	511479
8.06	1259053	7.97E+05	497597	1294232
9.31	2477857	1.74E+06	714361	2457975
10.8	2820820	1.85E+06	992508	2842111
12.4	2284055	9.89E+05	1295450	2284055
14.3	2062123	2.60E+05	1638337	1898473
16.5	2155023	3.37E+04	1990664	2024369
19.1	2330575	2.01E+03	2328559	2330571
22.1	2588780	5.82E+01	2608781	2608839
25.5	2776099	8.83E-01	2798113	2798114
29.4	2892530	6.82E-03	2880487	2880487
34	2845476	2.31E-05	2845476	2845476
39.2	2634936	4.36E-08	2698705	2698705
45.3	2427982	3.64E-11	2453231	2453231
52.3	2224614	1.56E-14	2140815	2140815
60.4	1925575	3.22E-18	1791782	1791782
69.8	1530867	3.12E-22	1437109	1437109
80.6	1149248	1.56E-26	1107045	1107045
93.1	780719	3.72E-31	817600	817600
107.5	514420	4.48E-36	579745	579745
124.1	350351	2.69E-41	394655	394655
143.3	231996	7.79E-47	257586	257586
165.5	159354	1.09E-52	161202	161202
191.1	103321	7.57E-59	96852	96852
220.7	63895	2.54E-65	55789	55789
254.8	36097	4.33E-72	30872	30872
294.3	19927	3.44E-79	16359	16359
339.8	10618	1.40E-86	8330	8330
392.4	8173	2.74E-94	4066	4066
453.2	6662	2.58E-102	1903	1903
523.3	5962	1.23E-110	855	855

Table A2. Parameters for the nucleation mode and soot mode fits of the measured particle size distributions.

	Speed, rpm	Load, %	Oil A NM	Oil A SM	Oil B NM	Oil B SM	Oil C NM	Oil C SM	Oil D NM	Oil D SM	Oil E NM	Oil E SM
			557239	3365934	622900	3428215	848961	3200675	0	3364811	629434	3732581
	2200	100	10.1	30.3	10.2	29.8	10.8	34.0	13.5	31.8	10.2	29.8
			1.3	2.9	1.3	3.2	1.5	2.5	1.7	3.0	1.3	3.0
			0	2880974	811001	2493973	0	3070210	0	2993274	265730	3256505
	2200	75	9.3	31.8	13.3	37.2	9.3	30.8	9.3	30.5	10.3	29.6
			4.2	2.8	1.7	2.4	1.7	2.9	1.7	2.8	1.2	2.9
			0	3902092	390244	3679162	0	3679376	0	3656333	489624	4262024
	2200	50	9.3	30.1	11.1	32.4	15.7	30.9	12.4	31.2	10.2	28.7
			1.1	2.8	1.3	2.8	1.8	2.8	3.0	2.8	1.3	2.9
			469321	10155896	598705	10017773	986347	10322518	0	8993907	7658133	10600876
	2200	10	10.5	30.5	10.3	30.5	10.5	30.1	10.8	32.8	10.8	29.3
N_{tot}			1.3	3.0	1.3	3.1	1.3	3.0	1.3	2.8	1.4	3.1
GMD, nm			687245	791970	1025953	1170904	602484	894847	193399	733687	1360185	1216295
GSD	1500	100	11.0	42.9	10.1	36.4	10.8	39.2	11.1	45.4	10.7	34.1
			1.4	2.5	1.4	3.3	1.4	2.7	1.4	2.4	1.3	3.1
			0	906263	483093	995818	152588	901074	0	909992	700698	1069654
	1500	75	14.3	34.9	10.3	39.3	10.7	37.2	14.9	34.9	10.2	34.5
			1.3	3.2	1.5	2.9	1.5	2.6	1.6	3.1	1.3	2.7
			4040359	1537654	5449757	3012580	6041336	1914019	9947468	2854977	23722284	2280942
	1500	50	10.1	31.3	10.1	19.4	10.4	28.4	11.5	21.7	15.4	32.5
			1.3	3.4	1.3	4.4	1.3	3.3	1.5	3.6	2.0	2.7
			6972228	3894316	9599519	10102795	10682304	1212139	9542550	3202410	10770443	7596050
	860	0	10.0	10.3	10.0	3.8	10.8	45.3	10.7	14.2	10.1	5.1
			1.3	8.0	1.3	11.8	1.4	3.2	1.4	5.9	1.3	9.1

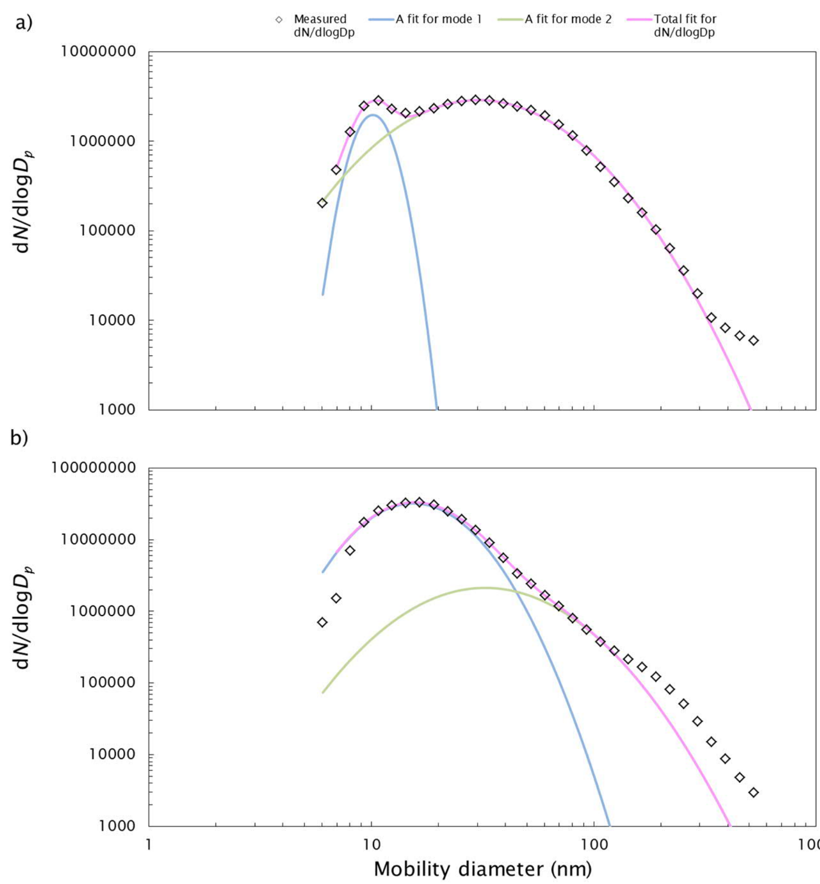

Figure A1. Calculated fits and total fit for the measured particle numbers when a) Lubricant A was used at 100% load at rated speed, and b) Lubricant E was used at 50% load at intermediate speed.