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Engine oil contribution to diesel exhaust emissions

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ABSTRACT

The reduction of harmful pollutant emissions as well as CO_2 emissions emanating from motor vehicles will be of considerable interest in the coming decades. Emissions legislation will be the guiding principle in the development of new technologies and vehicles. More attention will have to be paid to off-road vehicles, especially tractors, if the production of healthy food and the maintenance of a cleaner environment are not to be compromised. Therefore, one the biggest challenges facing the automotive industry is to improve fuel economy, both to conserve natural resources and to limit pollutants and CO_2 emissions. Better fuel efficiency and consequently lower emissions will require new materials, new lubricants and low-emission fuel. Engine lubricants help to improve vehicle efficiency but contribute engine exhaust emissions. This paper deals with the influence of engine lubricants on diesel exhaust emissions. Investigations have shown a clear effect of lubricant oil on emissions, which depends on lube oil characteristics, especially sulfur content, metal content, volatility and density. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: engine oil, diesel engine, emissions

INTRODUCTION

Emissions regulations are by far the most prominent driver in the automotive industry and have been so for over a decade. The amount of emissions by automobile engines is also very strongly related to their fuel economy. In general, the higher the fuel economy, the lower the emission of pollutant and carbon dioxide. One way to decrease emissions is to improve the fuel economy of vehicles.

Rising fuel costs and the need to conserve fossil fuel have led to increased interest in the role of lubricants in improving fuel economy. Appropriate lubricant formulations can bring about a beneficial reduction in engine friction, thus improving fuel economy. Friction losses in a car engine may account for more than 10% of the total fuel energy [1]. The fuel consumption of gasoline and heavy-duty diesel engines is of great importance, since it accounts for up to 30% of operating costs. New

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Table I. Emission regulations (g/kWh).

Regulation	Year	NOx	PM
Euro 3	2000	5.0	0.1
Euro 4	2005	3.5	0.02
Euro 5	2008	2.0	0.02
US 02	2002	3.4	0.14
US 07	2007	1.6	0.014
US 10	2010	0.2	0.014
JLT[a]	1999	4.5	0.25
JNST[b]	2003	3.38	0.18[d]
JNLT[c]	2006	2.0	0.027

[a] Japanese Long Term.
[b] Japanese New Short Term.
[c] Japanese New Long Term.
[d] Tokyo city limits at 0.027 g/kWh (JNLT).

regulations, especially for heavy-duty diesel engines, with ever stricter emission limits notably for particulate matter (PM) and nitrogen oxides (NOx), are being introduced in Europe (Euro 4, 5), the USA (US 02, US 07, US 10) and Japan (JNST, JNLT) [2]. As shown in Table I, it is intended that in these regions NOx and PM limits for diesel vehicles will be more than 80% lower than today's levels by 2007–2010.

A specific focus is emissions legislation which continues to increase in severity in the automotive industry and will in the future be applied to an even greater degree to vehicles in the off-highway market.

More attention will have to be paid to non-road diesel mobile machinery emissions, especially tractors (Figure 1), if the production of healthy food and the maintenance of a cleaner environment are not to be compromised. Non-road diesel engines account for about 47% of diesel PM and about 25% of total NOx emissions from mobile sources. Figure 1 shows that Stages IIIB and IV of the non-road emission regulations are equivalent to Euro 4 and Euro 5.

Engine design changes required to meet the latest emission regulations greatly impact on the engine oil degradation process and, consequently, for each new emission regulation, a new engine oil specification is released.

It is known that petroleum-based lubricant base oil is complex mixture of hydrocarbons with carbon numbers generally in the C-20 to C-40 range, depending on specific viscosity grade. Base oil contains a variety of molecules, such as paraffins, isoparaffins and naphthenes. American Petroleum Institute (API) lubricant base stock categories are shown in Table II.

The chemical composition of base oil directly affects its performance. Compared with lubricant-based mineral oils, synthetic lubricants have greater film thickness at high temperature, and achieve full lubrication more quickly at low temperature [3]. Synthetic lubricants generally have better oxidative stability than comparable mineral-based lubricants [3].

In future, automotive lubricants will need to be able to demonstrate improvements in fuel economy, extended drain intervals and reduced emissions.

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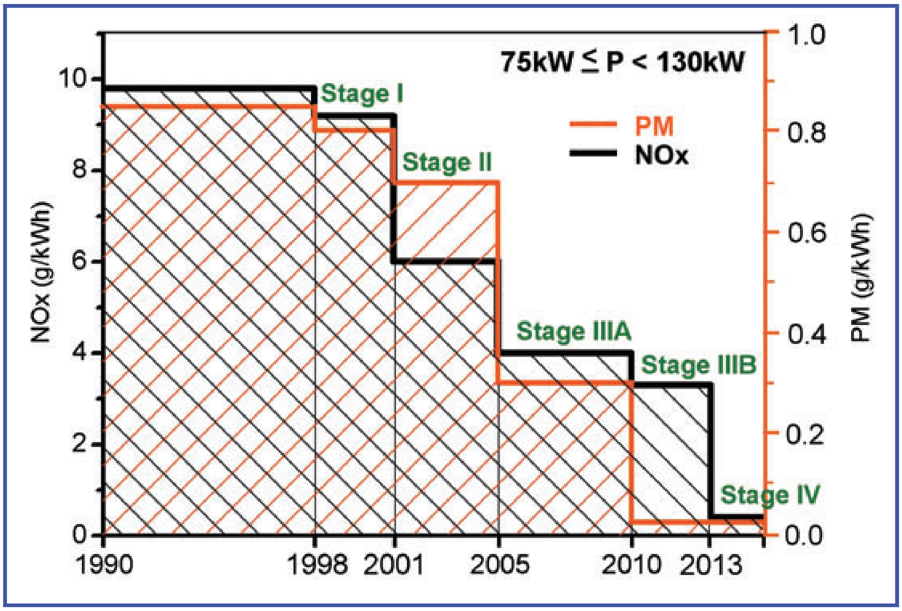

Figure 1. Non-road mobile machinery diesel engine emissions (NOx and PM) trends (Dir. 2004/26/EC).

Table II. API lubricant base stock categories.

API group	% Saturates	% Aromatics	% Sulfur	Viscosity index	Noack %
I	<90	>10	>0.03	<120	30
II	≥90	<10	≤0.03	80–120	25
III	>90	<10	<0.03	>120	11
IV			All polyalphaolefins		11
V			All stock not included in group I–IV		<11

Extended Drain Intervals

Against the background of maintaining vehicle performance there has also been a strong trend towards extended drain intervals. Table III demonstrates the significant changes in typical drain intervals in the recent past.

Extending oil drains increases soot levels. If soot is not adequately dispersed by the engine oil, it can cause sludge to form on rocker and front engine covers, bearings to fail, valve bridges and fuel injection links to wear, and filters to plug.

The durability of the lubricant and additive system in relation to the ability to disperse soot and maintain a regime of reduced wear has led to significant changes in additive formulation.

Extending oil drains allows maximum up-time for hauling freight and reduces costs for fresh oil, filters, mechanics' labor, and used oil and filter disposal.

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Table III. Typical drain intervals over the recent past (km).

Typical oil drain	1995	2003
Passenger car	10 000	30 000
Heavy-duty	40 000	100 000

Fuel Economy

Original equipment manufacturers are under intense pressure to provide the most fuel-efficient vehicles to respond to both the emission regulations and Kyoto protocol. For example, in Japan, by 2010, the fuel consumption of automobiles must be reduced by an average of 22.8% compared to 1995 [4].

In Japan, several automobile manufacturers have applied very low viscosity 0W20 oils to their factory fills. These low-viscosit,y fuel-efficient oils are usually formulated with organic molybdenum compounds. They can provide a fuel economy benefit of as much as 2–3%.

In addition to the to the molybdenum friction-reducing additives, high-quality group III base oils also play a crucial role in the 0W20 oils. It has been pointed out that the use of low-viscosity oils could raise concerns about viscosity increases and oil consumption, which could negatively affect fuel efficiency and catalyst performance. From this viewpoint, the International Lubricant Standardization and Approval Committee (ILSAC) GF-3 standard requires that oil volatility must be reduced to 15% Noack, which is substantially lower than the previous 22% in GF-2. This change not only minimizes the viscosity increase but also is expected to significantly reduce oil consumption. For low-viscosity 0W20 oils, this can be achieved only through the use of very high viscosity index group III base oils (Figure 2).

Figure 3 shows fuel economy benefits as result of the lower elastohydrodynamic lubrication (EHL) friction of the very high viscosity index (VHVI) group III base oils in comparison with group I. Typically, polyalphaolefin (PAO) based engine oils have a fuel consumption benefit of up to 3.4% relative to comparable mineral oils. In automotive transmissions the benefit is of the order of 10% of the power transmitted through the unit, resulting in a fuel economy benefit of up to 2% in the driveline of a vehicle. This results in on overall benefit of up to 5.4% in a vehicle [5]. In industrial transmissions, it is a possible to achieve a 10% reduction in energy consumption by replacing mineral oil with equiviscous PAO based oils.

This trend toward improved fuel economy has led to the introduction of lower oil viscosity grades such as 5W30 and 10W30 that are now commonplace in the heavy-duty engines. Analogous changes are also apparent for passenger car engine lubrications where there is a move toward 10W30 and 5W30. Lower oil consumption reduces the soluble organic fraction in the exhaust [6] but lowers the amount of fresh oil and additives to be added to the crankcase.

The demands on automotive lubricants have never been greater in terms of their technical requirements. The base oils of the future will need to posses the following characteristics: thermal oxidation stability, low evaporation, higher natural viscosity index, lower aromatic content, low or no sulfur, low viscosity, and a lower proportion of environmentally damaging materials (metals, sulfur, phosphors and halogens) [7]. Low-viscosity synthetic motor oil is thus expected to dominate in vehicles in the coming decades.

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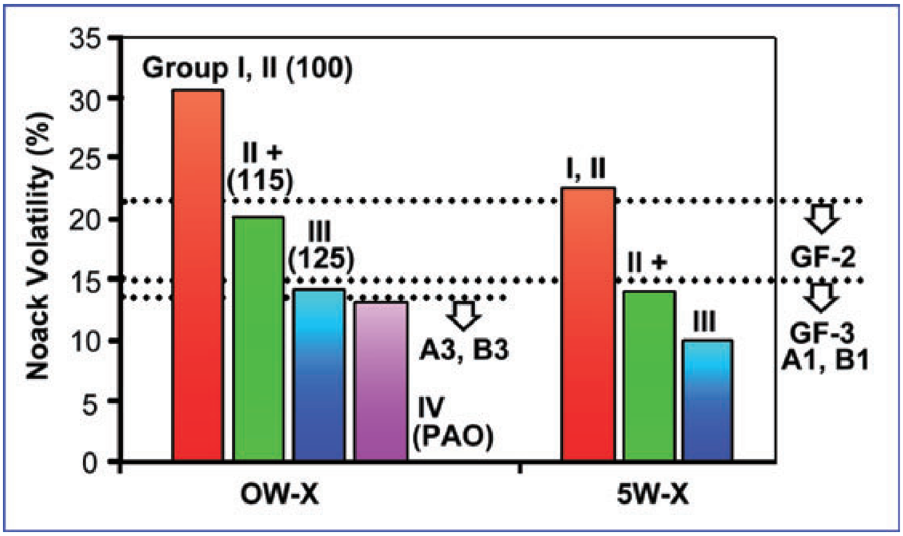

Figure 2. Noack volatilities of different base oil types vs. specification limits.

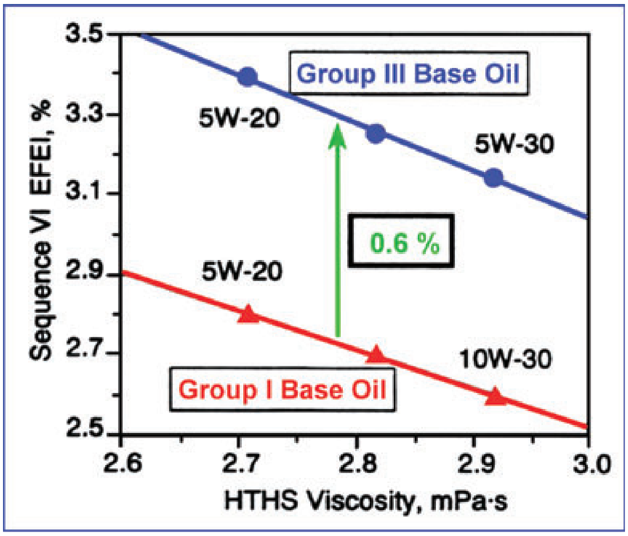

Figure 3. Fuel economy benefits obtained from VHVI group III base oil.

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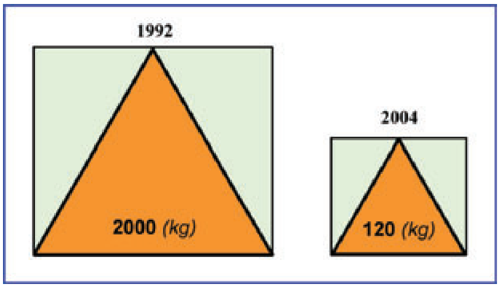

Figure 4. Typical truck particulate emissions.

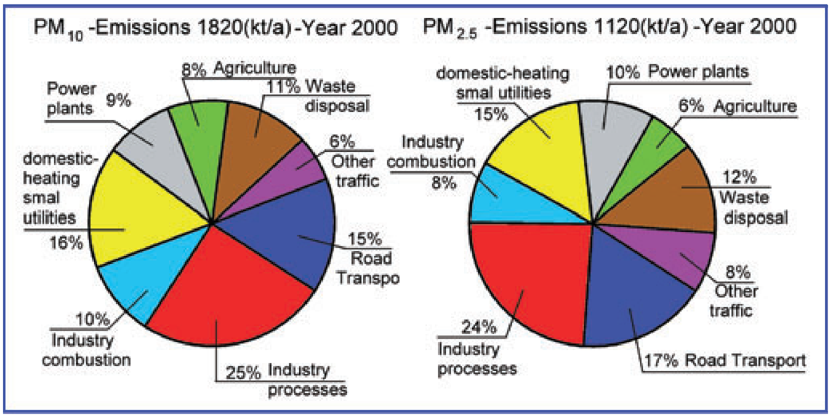

Figure 5. Contributions of different sources to PM_{10} and $PM_{2.5}$ in Europe, 2000.*

Emissions Reduction

Reducing the exhaust and CO_2 emissions of cars and trucks constitutes a major challenge for automotive industry. In the current industry climate emissions reduction has been the most significant driver of lubricant quality and the concept of lifetime reduction of emissions is of fundamental importance. Enormous steps have been made in, for example, PM reduction in the last decade or so (Figure 4).

Diesel soot was regarded in the past as carcinogenic due to the adsorption of polycyclic aromatic hydrocarbons (PAH, including nitro and *n*-PAH) [8]. It was concluded that the care of the particle is the main reason [9]. Diesel soot aggregate particles are between 90 nm and 130 nm in size and aggregated from about 50 primary particles with geometrical diameters between 15 nm and 30 nm. Spherical primary particulates alone do not occur. Adsorbed on the soot particles are soluble organic as well

*Diesel engine, emissions were measured in accordance with ECE E 96 Regulations, 8-mode cycle. The temperature of tested engine oil was 75°C.

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as gaseous hydrocarbons and sulfates of smaller size. Diesel particulates are included in the group of PM_{10} (particle with smaller than 10 µm aerodinamic diameter –D), $PM_{2.5}$ (D < 2.5 µm), PM 0.1 (D < 0.1 µm), and PM 0.05 (D < 0.05 µm). Different emission sources for PM_{10} and $PM_{2.5}$. summarized for Europe [10] in 2000. are shown in Figure 5.

It will be seen that the difference between PM_{10} and $PM_{2.5}$ in Europe is almost 40% (1820:1120); note also that road transport's share of regarding $PM_{2.5}$ in comparison with PM_{10} has increased slightly from 15% to 17%. Within the Auto-Oil-Program II it is estimated that PM_{10} emissions for Europe have declined from 1820 kt to 1600 kt in 2005. Taking the Euro 4 emission standards of 2005 into account, a further decline to 1200 kt in 2020 can be expected. The share of road transport with regard to PM_{10} emissions, will also be smaller still in the future. Besides the particulate mass the size of the particulate is a further important parameter to consider in terms of health effects. Particles below 2.5 µm can penetrate into the terminal bronchi and below 1 µm into alveolar regions.

Heavy-duty diesel engines need low emission lubricants if they are to contribute to the lowering of NOx and PM emissions. The key elements used in lubricant formulation are sulfur, sulfated ash and phosphorus. These elements will cause compliance problems as emission limits fall.

Fuel sulfur level is a major factor for future lubricants because as fuel sulfur levels drop, the contribution of sulfur originating from the lubricant becomes greater. As an example, with a fuel of 10 ppm S, and with a typical mineral-based engine oil with a sulfur level of 0.5%, an engine with an oil consumption of 0.1% of the fuel consumption — all numbers quite plausible in the marketplace today — the equivalent lubricant contribution to sulfur in the exhaust gas in 5 ppm, which is quite comparable to the fuel contribution. Typical sulfur contents (0.1–0.5%wt) of commercial European car lubricants are shown in Figure 6.

The recently proposed GF-4 specification proposes a lubricant sulfur limit of 0.5%wt. By avoiding the use of group I base oils, sulfur levels can be reduced to 0.3–0.4% without further changes to formulations, the only consequence being a substantial increase in cost. Lube S (sulphur) and fuel S emissions are the same order of magnitude when using 3 ppm S fuel with lube ranging in S concentration from 0.15 to 0.34 wt.%.

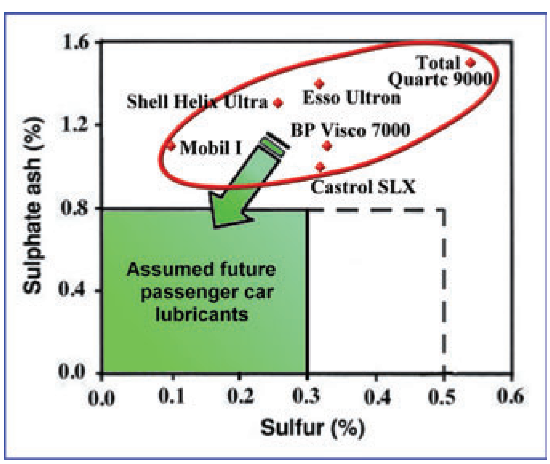

Figure 6. Composition of current commercial lubricants versus the assumed future limits.

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Phosphorus is indicated to impact the activity of gasoline catalytic converters, mainly due to the formation of glassy deposits. Typical phosphorus content of European lubricants is 0.1%wt. A future phosphorus limit of 0.05%wt is suggested in the draft ILSAC GF-4 specification.

The sulfated ash sources in a lubricant are the metallic detergent zink dialkyl dithiophosphate (ZnDTP). Diesel particulate filters are impacted by sulfated ash built-up. This can lead to a build-up of inert material in after treatment installations, causing a rise in back pressure which upsets programmed air–fuel mixture levels. In extreme cases, accumulation of ash could result in the cracking of ceramic substrates. The typical ash content of European car lubricants is 1.0–1.5%wt (Figure 6), and 1.0–1.9% for heavy-duty diesel.

Current European engines emit approximately 1.5–3.0 mg/kWh oil ash (corresponding to 8–15% of total PM for Euro 4/5), and the proclaimed target is a maximum value of 0.5 mg/kWh (corresponding to 2.5% of total PM for Euro 4/5).

Figure 6 shows the composition of current commercial lubricants in terms of sulfated ash and sulfur content in comparison to the assumed future limits. The future proposed limit for sulfur and ash is 0.2wt S (passenger cars) and 0.2–0.3%wt S (heavy-duty diesel) and 0.5–0.8%wt ash (passenger cars) and 1.0%wt (heavy-duty diesel).

EXPERIMENTAL

Tests of the contribution of lubricant properties to diesel exhaust emissions have been performed on a three-cylinder direct injection (DI) engine (THDM 33/T-TD.3.152 Perkins) of rated power 40.5 kW at 2250 rpm and swept volume 2.5 dm^3, turbocharged with intercooler. This engine is an older design with an open combustion chamber in the piston, while nozzles have four holes, each 0.28 mm in diameter. Injection pressure is 210 bar and the injection angle is 12°.

For those investigated were used two mineral-based motor oils (grade 15W40), and full synthetic (PAO) base oil (grade 5W40). Irrespective of the extent to which these two oils have different viscosity index improvers and lubricity additives, these grades have been chosen for tests because, above all, they are widely used in the market. The aim is to show whether the use of synthetic oils rather than mineral ones results in reduction of emissions. Low-sulfur (0.030%) diesel fuel has been used for testing purposes. The physico-chemical characteristics of the oils tested are shown in Table IV. The temperature of tested engine oil was 75°C.

Table IV. Physico-chemical characteristics of oils tested.

Lubricating oil	Mineral		Synthetic
	I	II	III
Grade	15W40		5W40
Density (kg/m3), 15°C	880	860	845
Flash temperature	228	226	230
Kinematic viscosity (mm^2/s), 100°C	15.06	14.6	12.2
Viscosity index	135	141	160
Noack	10.3	10.1	8.6

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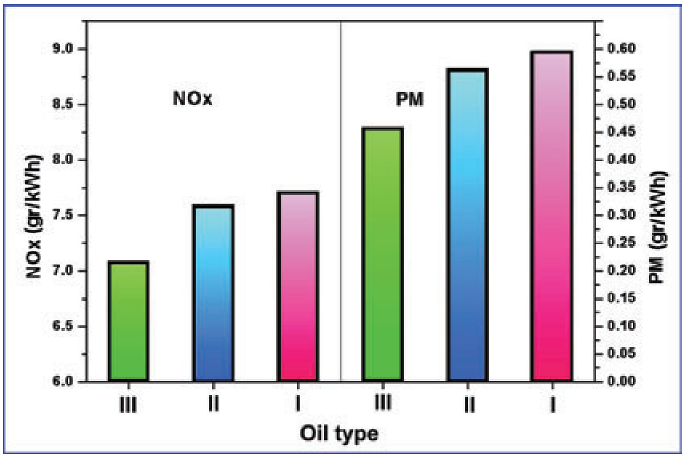

Figure 7. Specific emissions of the mineral and synthetic engine oils.

RESULTS AND DISCUSSION

The values of specific emissions of NOx and PM (g/kWh) for mineral and synthetic engine oils are shown in Figure 7. It will be seen that NOx and PM emissions are lower with synthetic oil than with mineral oils.

Test results show that mineral oils produce by 8% higher NOx emission than the synthetic oil (Figure 7). This is possibly a consequence of the different additives and aromatic contents of the oils, because there is good correlation between aromatic content and density. At the same time mineral oil has a higher sulfur content (0.8%) than synthetic oil (0.6%).

NOx emission is affected by aromatic content. An increase in aromatic content has been shown to increase NOx and PAH emissions as a consequence of increasing the flame temperature during combustion. Investigations [11–13] have demonstrated a decrease in NOx emissions of between 5% and 9% when using synthetic SAE 5W40 oil as compared to mineral SAE 15W40 oil.

On the other hand, decreasing the aromatic and increasing the saturate level provide very thermally stable base oils.

The effect of oil density on NOx emissions is shown in Figure 8: increasing the density results in an increase in NOx emissions.

As for PM, it can be noted from Figure 7 that particulate emissions are lower with synthetic oil than with mineral oils. The specific particulate emissions of synthetic oil are 19–24% smaller than those of the mineral oils. These results are in good compliance with results recently presented by Goodier [13]. According to him, switching an older engine from mineral to synthetic lube oil could bring significant benefits in terms of lower emission and fuel economy. Tests carried out by BP in Germany have shown that PAO synthetic oil in some cases reduces particulate emissions by nearly a third and visible smoke by 10%.

At its UK research laboratory, BP Chemicals carried out emissions measurements on a Euro 2.12 litre truck diesel engine which was run first on regular 15W40 mineral lube oil, then on a VHVI 5W40,

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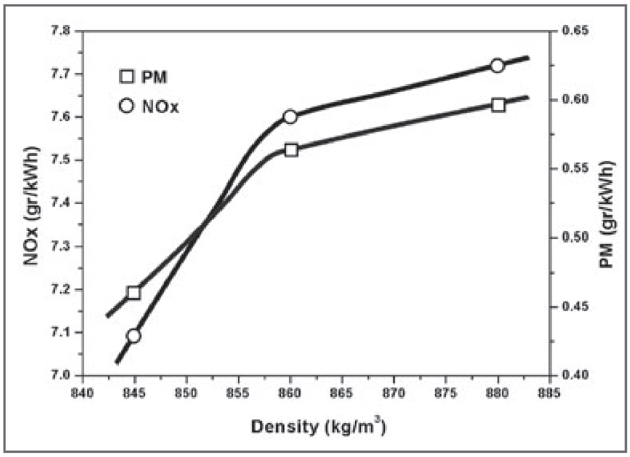

Figure 8. Dependence of NOx and PM emissions on oil density.

and finally on a fully synthetic 5W40 [13]. It was concluded that PAO oil could reduce PM emissions by 35–55%. Interestingly, it was mostly the solid particle element of the PM emissions that was reduced by switching from mineral oil to PAO. The other element, the soluble organic fraction, was found to be reduced by only 13% under cold start and 7% under warm start conditions.

Some investigations [11–17] demonstrated decreases of between 5% and 22% in particulate emissions when using synthetic oil as compared to mineral oil. For example, Manni *et al*. [11] investigated the emissions response of a single-cylinder DI diesel engine using different lubricants. The baseline engine (lubricant) oil was mineral 15W40 oil and the candidate was synthetic 5W30 oil. For operating conditions close to maximum torque, particulate emissions were reduced by 22%.

Earlier work [14] shows (Figure 9) the composition of particulate as a function of engine operating conditions. At low speed and load (torque) a high percentage of the oil is found in the particulate. This is because combustion temperature is relatively cool for the oil to burn. As load increases, the oil is less evident. At the high load condition, the predominant change is the non-soluble portion. This means, that under all conditions, the fuel-derived portion of the SOF changed to some degree with the lubricant parameters.

Manni *et al*. [16] later investigated the emissions response of a multiple-cylinder indirect injection diesel engine using different lubricants. The baseline oil was a mineral SAE 15W40 and the synthetic oil was SAE 0W40. For the ECE 15 (European Cycle Emission) and EUDC MVEG (European Urban Drive Cycle Motor Vehicle Emission Group) test cycle, the synthetic oil reduced the average particulate emissions by 11%.

Casserino *et al*. [18] measured particulate emissions of a 6-liter truck diesel engine certified to Euro 2 emissions level using a 15W40 mineral oil and 0W40 synthetic oil. They showed that synthetic oil reduced particulate emissions by 5. 5% for the cold start and by 2% for the warm start of the US Federal Test Procedure)transient cycle.

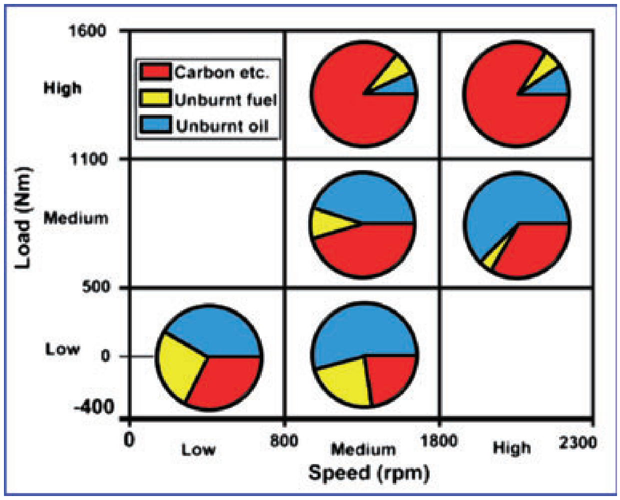

Figure 9. Impact of engine operating conditions on particulate composition.

Jefferd *et al*. [17] published an unexpected result. With a heavy-duty DI diesel engine, they found a 20% increase in particulates and a 7–9% decrease in nitric oxides when using synthetic 15W40 oil as compared to mineral 15W40 oil.

The dependence of particulate emissions on oil density is shown in Figure 8. It can be seen that there is good correlation between oil density and particulate emissions. Particulate emissions increase with increasing density, because of the increase in the thickness of the layer left on the surface of the cylinder liner after piston ring passage. On the other hand, synthetic oils have lower volatility then mineral oils. Their basis is different that of mineral oils.

Particulate emissions may vary by 30–40% with the aging of lubricating oil, mainly due to carbon emissions [19]. The age of the lubricating oil has a significant influence on the particulate SOF, and this influence increases with time.

CONCLUSIONS

Based on the results obtained, the following conclusions may be drawn:

(1) The contribution of engine lubricant oil to diesel engine particulate emissions is evident.
(2) Mineral engine oil produces higher PM and NOx emissions than synthetic oil.
(3) The NOx emissions of synthetic engine oil are 8% lower than those of mineral oil.
(4) Particulate emissions of synthetic oil are 19–24% lower than those of mineral oils.
(5) There are good correlations between lubricant oil density and emission, the latter increasing with the former.

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