

IMPACT OF ENGINE OIL CONSUMPTION ON PARTICULATE EMISSIONS

Kent Froelund

Southwest Research Institute

Ertan Yilmaz

GE Global Research Center

ABSTRACT

By October 2005, Euro 4 emission limits will be introduced in Europe for on-road trucks, reducing the particulate emissions from 0.10 g/kW-hr to 0.02/0.03 g/kW-hr, as measured over the European ESC/ETC cycles. By 2007, the US EPA 2007 emission limits will be introduced in the States for on-road trucks, reducing the particulate emissions from 0.10 g/bhp-hr to 0.01 g/bhp-hr, as measured over the US FTP transient cycle. These reductions are very aggressive. The US EPA 2007 emissions limits will require the application of a particulate-reducing aftertreatment device, such as diesel particulate filters (DPF).

DPF's experience deterioration in performance with the throughput of additive-metals from the consumption of engine lubricant oil. The DPF is sensitive to organo-metallic ash derived from Calcium- and Magnesium-containing additives in the lubricant oil. The ultimate consequence is filter plugging, which clearly prohibits normal engine operation. Heterogenic catalysts depend on transport of exhaust species to the extended surface with subsequent chemical reactions at the reactive sites. These sites are sensitive to lubricant oil organo-metals, as from Zinc- and Phosphorous-containing ash, and both physical and chemical deactivation mechanisms have been proposed in the literature.

For the sake of protecting the performance of aftertreatment devices over time, it will therefore be instrumental to reduce the additive-metal throughput by reducing the oil consumption and by reducing the additive-metal concentration in the lubricant. A quantification for the target reduction in additive metal engine throughput is provided by Jacob et al. (2001). Current European engines emit approximately 1.5 to 3.0 mg/kW-hr oil ash (corresponding to 8 to 15% of total particulate for Euro IV/V), and the proclaimed target is a maximum value on 0.5 mg/kW-hr (corresponding to 2.5% of total particulate for Euro IV/V). Thereby, the particulate filter will not have to be over-dimensioned due to durability concerns. The implementation of this target will clearly mean that oil consumption as well as lubricant oil ash will have to be simultaneously reduced.

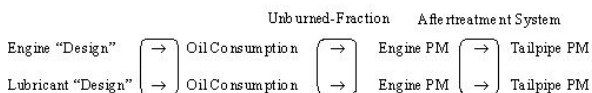
The total engine-out particulate emission is the sum of fuel-contribution and oil-contribution to particulate. Since the fuel-derived particulate is presently the highest contributor, much research effort has been focused on its reduction. The literature is well established in this area. Even though it has been found that engine oil consumption can contribute significantly to particulate matter, little effort can be found in scientific publications on its sources and reduction.

This paper will first summarize what is known about the lubricant oil impact on particulate by introducing sample data. Second, sample data will be shown for the impact of engine design on oil consumption. Third, sample data will illustrate the impact of lubricant design on oil consumption and particulate emissions.

Key-words: Oil Consumption, Particulate, Ash, Diesel

INTRODUCTION

The literature can be divided into two classes: The impact of engine "design" on oil consumption and the impact of lubricant "design" on particulate. The logic cause-effect relationships are as follows:



Both the engine design and the lubricant design impact oil consumption, which through the combustion "transfer function" impacts the engine-out emissions, which through the aftertreatment system "transfer function" ultimately causes the tailpipe emissions.

Clearly, most literature shortcuts this logical cause-effect relationship and only partial data is presented.

OIL IMPACT ON PARTICULATE

The impact of lubricating oil-derived components on particulate emissions is much less understood than the impact of fuel on particulate emissions. The impact will be discussed by introducing sample data from the literature by *Sharp et al.* (2000). The engine-out particulate data are shown in Figure 1 over the US FTP transient cycle for three heavy-duty engines produced in the 90's. The engines model year, power, displacement, application, and emissions certification is shown in Table 1. The test fuel was the 2D certification fuel with a cetane number of 43, a sulfur

concentration of 480 ppm, and 39% aromatics. The test lubricants were all commercial SAE grade 15W40 mineral oils. The Cummins N14 did not apply an oxidation catalyst, whereas both the DDC Series 50 and the Cummins B5.9 did.

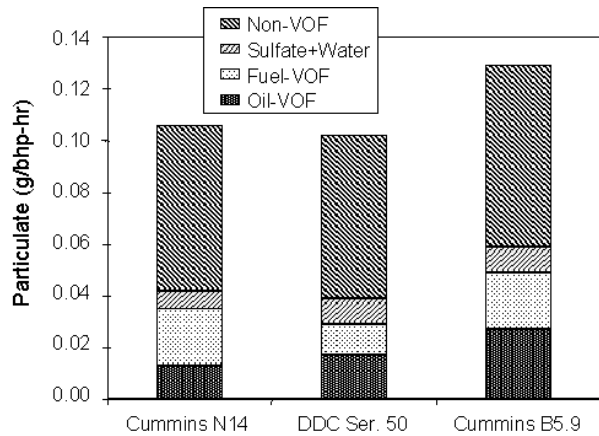


Figure 1: US FTP Transient Engine-Out Particulate Data for Three Contemporary Diesel Engines.

Engine	Power KW	Displ. Liter	Appl.	PM Certif. (g/bhp-hr)
1997 Cummins N14	276	14.0	Highw. Truck	0.10
1997 DDC Series 50	205	8.4	Urban Bus	0.05
1995 Cummins B5.9	119	5.9	Pickup Truck	0.10

Table 1: Test Engines.

In Figure 1, there are four fractions of particulate, which are described in the following:

1. Oil-VOF (Oil volatile-organic-fraction): The oil-VOF is a quantification of the most direct impact of lubricant oil to particulate. Exhaust particulate matter is first collected on a filter media. Then, the volatile organic fraction is distilled from the filter by exposing the filter to a temperature gradient. The volatile compounds of the particulates are divided and quantified into fuel and oil species with the use of a Gas Chromatograph. In another method, the volatile compounds are dissolved from the filter applying a solvent and divided into fuel and oil species using a Liquid Chromatograph. These methods have been used most frequently and have been shown to correlate well by *Newkirk et al. (1992)*. The oil-VOF varied from 0.013 g/bhp-hr for the Cummins N14 to 0.027 g/bhp-hr for the Cummins B5.9 engine. These are typical numbers for current US manufactured heavy-duty diesel engines.

2. Fuel-VOF (Fuel volatile-organic-fraction): The fuel-VOF is a quantification of the fuel impact to particulate. The fuel-VOF is quantified much the same way as the oil-VOF, the only difference being that these are the lighter species.

3. Sulfate + Water: This fraction of the particulate is mostly derived from the fuel. Sulfur originates from the fuel and oil. The 2D diesel fuel contained approximately 500 ppm sulfur and commercial oil contained approximately 5000 ppm sulfur. Since oil consumption for a current US produced heavy-duty diesel engine to a first approximation is about 1:1000 of the fuel consumption, a sulfur balance can be applied to the engine fuel and oil. It can be seen that for this test, 99% of the sulfate originated from the fuel (0.007 to 0.01 g/bhp-hr) and 1% of the sulfate originated from the oil (0.00007 to 0.0001 g/bhp-hr). To a first approximation, the oil sulfur contributed the equivalent of 5 ppm fuel sulfur to the particulate.

4. Non-VOF (Non volatile-organic-fraction): The non-VOF is by definition the residual or balance of all of the above. Often the term “soot” or ‘dry-particulate’ is used for this fraction of the particulate. The non-VOF is considered purely fuel-derived, since most of the non-VOF is carbon C-C chains, which is a fundamental product of a diffusion flame in a diesel engine. However, there exists multiple Non-VOF links to lubricant oil as well. One obvious link is the lubricant ash, from Calcium, Zinc, and Phosphorous additives in the lubricant oil. A quantification of this desired additive metal contribution to particulate is provided by *Jacob et al. (2001)*. Current European engines emit approximately 0.0015 to 0.0030 g/kW-hr oil ash (corresponding to 8 to 15% of total particulate for Euro IV/V). Another possible link is lubricant base-stock, which is pyrolyzed and thus stripped from Hydrogen. Estimates for the lubricant oil impact on the non-VOF of up to 15% have been suggested, which can result in a substantial contribution of oil to particulate emissions.

Having established that oil impacts the various fractions of particulate; the next step is to analyze how much these contributions actually yield. Figure 2 recasts the data from Figure 1, but now with estimates of the oil contribution to each fraction of the particulate. The estimates of oil contribution to each fraction are shown in parenthesis in the legend. Applying these estimates for the “true” oil contribution to particulate, a range from 0.023 to 0.038 g/bhp-hr is obtained. Based on the data in Figure 1 and 2, the impact of lubricant oil to engine-out particulate for contemporary US produced heavy-duty diesel engines range from 20 to 30%. This impact of lubricant oil on engine-out particulate emissions is clearly above both the Euro IV/V and the US EPA 2007 total particulate levels.

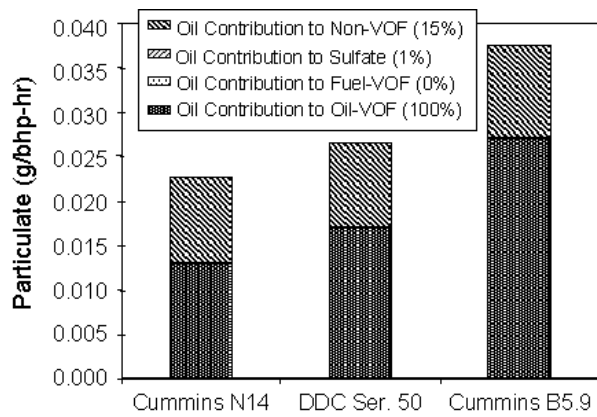


Figure 2: Estimates for Oil Impact on the Fractions of Particulate.

ENGINE DESIGN IMPACT ON OIL CONSUMPTION

In order to understand the impact of engine oil on particulate emissions and to identify proactive actions that can be taken to significantly reduce oil consumption, it is important to generate data and characterize the contribution of different oil consumption sources. Figure 3 schematically illustrates the oil consumption sources in contemporary internal combustion engines, consisting of the piston-ring-liner system, the turbocharger, the valve stem seals, and the crankcase ventilation system.

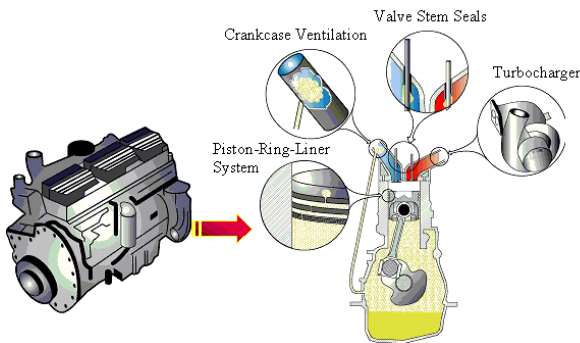


Figure 3: Oil Consumption Sources.

As important as these data are for directing future engine design efforts, little and incomprehensive data is available in the published literature.

SAMPLE DATA 1 - In an attempt to provide some insight into this area, a sample data set has been generated as follows:

- Total oil consumption data have been generated on a Navistar 466-DTA engine, which was applied as test engine for the Clean Diesel I program at *Southwest Research Institute* (1992). Engine details are shown in Table 2. All shown data are for full load conditions.

- Oil consumption from the turbocharger was also measured on the same Navistar engine.
- The valve stem seal oil consumption has been estimated to 6% of the total oil consumption. To put the estimate into perspective, *Mori et al.* measured the oil consumption for valve stem seals in fleet tests (1996). They found that the valve oil consumption amounts to less than 0.10 g/hr per valve seal for mixed driving. This test was over 300,000 km of operation.
- Crankcase ventilation oil consumption data, generated and published on a contemporary heavy-duty diesel engine by *Barris et al.* (2000), was scaled to match the displacement of the Navistar engine.

The oil consumed from various engine components burns to a different degree throughout the engine. The unburned-oil fraction has been estimated based upon a publication by *Inoue et al* (1997). These data have also been smoothed out, so that they trend with speed. This enables the oil consumption data to be linked to particulate data.

Make	Navistar
Model	466-DTA
Displacement	7.6 L
Cylinder Configuration	Inline-6
Aspiration	Turbocharged and Intercooled
Injection	Direct
Valve	2V
Rated Power	250 hp @ 2400 rpm
Load	100% (950 Nm @ 1600 rpm)
Emission Certification	0.25 g/bhp-hr Particulate

Table 2: Navistar Engine Specifications.

Figure 4 shows the resulting oil consumption rates of the different sources with engine speed. The same data was used to determine the relative importance of each source as illustrated in Figure 5. At low-speed and full-load conditions, the non-powercylinder oil consumption dominates the powercylinder oil consumption, yielding 80%+ of the total. With increasing speed, the powercylinder oil consumption increases sharply. At high-speed, full-load operation, the powercylinder oil consumption dominates all other sources, yielding 80%+ of the total. It can thus be concluded that the contribution of different oil consumption sources and total oil consumption show a strong variation with engine speed.

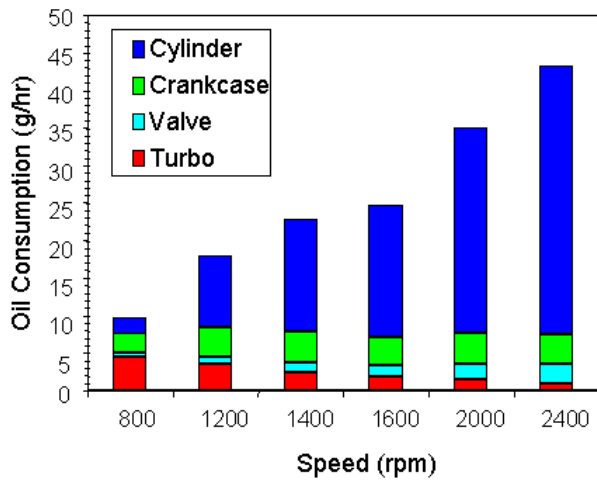


Figure 4: Design Group Oil Consumption (under 100% load).

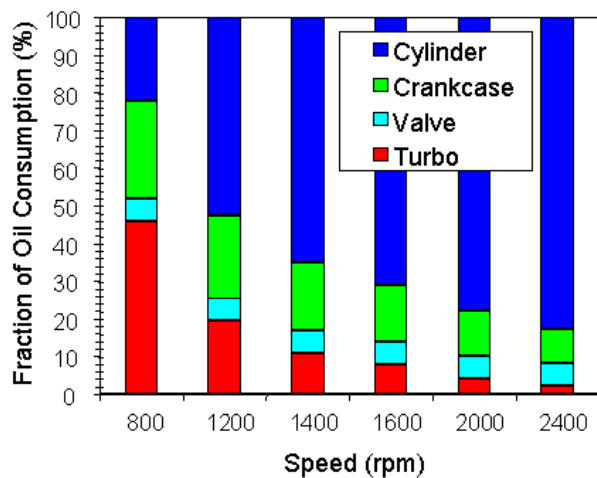


Figure 5: Design Group Oil Consumption Split.

As mentioned above engine oil consumption can contribute significantly to particulate emissions. It is generally believed that most of the oil contribution is in the VOF fraction of the total particulate. All the oil consumption sources in Figure 3 may contribute to the oil-VOF. However, little is known about the relative importance of each source. It is speculated that the oil passing the valve guides and turbocharger are major contributors, since large portions of the oil from these sources may not enter the cylinder and escape the combustion event through the exhaust manifold. In particular, oil leaking through the turbocharger seal is expected to exhibit the highest unburned oil fraction, since it is located, downstream of the exhaust valve.

On the other hand, as shown in Figure 5, the major contributor to total oil consumption is the piston-ring-liner system. The unburned oil fraction of this source depends on the timing within the cycle when the oil is transported into the cylinder. Oil transport into the combustion chamber during late expansion and exhaust strokes is exposed to lower temperatures. This oil may therefore escape the combustion event, and may

contribute to unburned oil consumption and the particulate VOF. Therefore, it is critical to understand and model oil consumption mechanisms and its impact to particulate oil VOF to minimize particulates.

Three potential oil consumption mechanisms have been suggested to contribute to the oil consumption from the piston-ring-liner system. These mechanisms are schematically illustrated in Figure 6. A hypothesis is the mechanical transport of liquid oil into the combustion chamber due to inertia forces caused by acceleration and deceleration of the piston assembly (Figure 6a). Another mechanism is the direct oil transport with the reverse gas flow from the second land into the combustion chamber (Figure 6b). During some periods of the cycle when the second land pressure becomes greater than the combustion chamber pressure, reverse gases flow into the combustion chamber through the top ring gap and around the top ring groove if the top ring loses its stability in the groove. Oil evaporation (Figure 6c) was also found to contribute significantly to the oil consumption from the piston-ring-liner system, especially during severe operation conditions when the thermal loading of engine components is high.

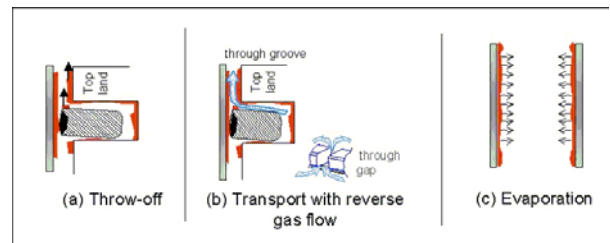


Figure 6: Oil consumption mechanisms from piston-ring-liner system.

All of these consumption mechanisms contribute to total oil consumption from the piston-ring-liner system during engine operation. Whether one or the other mechanism dominates depends mostly on the engine design specific oil transport rates, engine operating parameters, and lubricant properties. The oil must traverse a complex course before being transported into the combustion chamber, as indicated in Figure 7, refer also to *Yilmaz* (2003). The difficulty in modeling oil consumption lies in predicting oil transport, and the amount of oil present in the clearances of the partially flooded piston-ring-liner system. Therefore, the key to understand oil consumption and its sources is oil transport in the piston-ring-liner system to the consumption regions. The oil transport rate to the upper piston regions is governed by different mechanisms in different regions, such as gas flow, inertia forces due to piston movement, and interactions between the rings and grooves as well as between rings and liner. Next, sample data is presented from recent studies that have analyzed and characterized some of these oil consumption sources and mechanisms at different operating conditions.

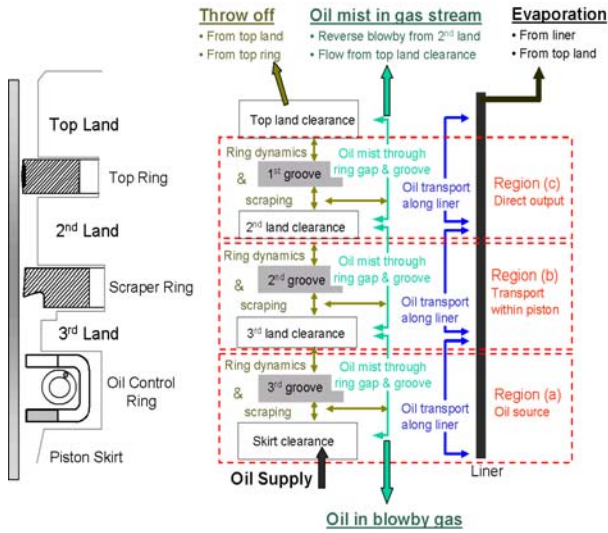


Figure 7: Oil transport in the clearances of the piston-ring-liner system.

SAMPLE DATA 2 - In a study by *Yilmaz et al.* (2003), a combined experimental and theoretical approach was used to separate and quantify different oil consumption sources and mechanisms of a European, four-cylinder production spark ignition engine. The contributions of oil evaporation, oil flow into the combustion chamber passing by the piston system and blowby oil consumption to total engine oil consumption was determined at different steady state speed and load conditions. The engine characteristics are listed in Table 3.

A four-cylinder production spark ignition engine with an extensive diagnostic system was used as test engine to identify and quantify key oil consumption sources at different steady state speed and load conditions.

Engine Type	Port injected spark ignition engine
Displacement	2 liter
Bore	~ 86 mm
No. of cylinders	4
Compression ratio	10.4 : 1

Table 3: Test Engine Specifications.

Figure 8 quantifies the relative contribution of each of the separated oil consumption sources to total engine oil consumption for different speeds at 100% load. The values displayed are the oil consumption rates due to each source, normalized by the total engine oil consumption at each operating condition. The importance of each oil consumption source does not change significantly as engine speed is increased from 2500 rpm to 4200 rpm. The major contribution in this range is from the oil transport, which varies between 40 to 50 percent. Oil evaporation, also a significant

contributor to oil consumption at high load, exhibits a consistent trend as its relative importance increases gradually from 30 percent at 2500 rpm to 40 percent at 4200 rpm. The blowby contribution varies between 10 to 15 percent as the engine speed is increased.

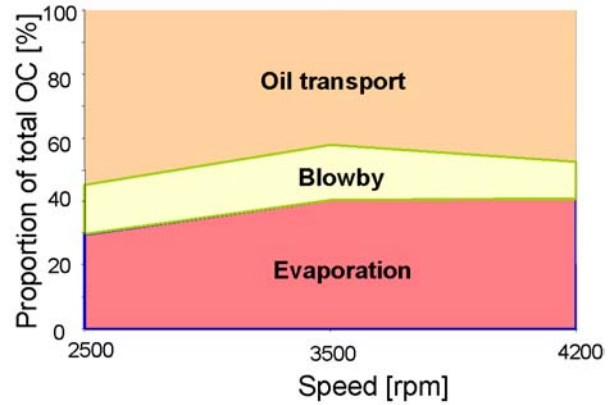


Figure 8: Effect of engine speed on the relative importance of oil consumption mechanisms to total oil consumption at 100% load.

Figure 9 quantifies the relative contribution of each of the three separate oil consumption sources to total engine oil consumption for different load conditions at 3500 rpm. At 0% load, oil transport into the cylinder contributes substantially to total oil consumption (~90%). As engine load increases, the contributions of oil evaporation and blowby oil consumption rise continuously, while the contribution of oil transport decreases. At 100% load the relative importance of oil transport decreases to 40 percent, oil evaporation was found to increase to about 45 percent, and roughly 15 percent of oil consumption is due the oil entrainment in the blowby gas flow. The data presented above confirms the dominant contribution of the piston-ring liner system to total oil consumption.

Oil evaporation from the liner was found to be the major contributor to total evaporation. In the following, results of a validated multi-species liner evaporation are presented. The cumulative total evaporation and the cumulative evaporation of the modeled four lightest species (represents the first 6 percent of the oil distillation curve) are shown in Figure 10. The results are normalized by the total evaporation rate during one cycle. This illustration of the evaporation process during the cycle shows that approximately 30 % of the total evaporation is during late expansion and exhaust strokes. The evaporated oil during this period will most likely not oxidize and can contribute to the oil-VOF fraction of the total particulate.

In addition to oil evaporation, oil transport with the reverse gas flow may be a likely contributor to the particulate oil-VOF, especially when the top ring loses its stability. For example, in another study by *Yilmaz et al.* (2001), an increase of oil consumption

during load transients was observed. Figure 11 shows the oil consumption measurements from no load (0%) to full load (100%) at two different engine speeds (2500 and 4200 rpm). During these transients, oil consumption reaches a peak that is significantly higher than the steady state values, before decreasing to the steady state level of the final operating condition. This increase of oil consumption was caused by top ring instability during late expansion and early exhaust strokes. During this period of the cycle, when the inertia force is downward, higher second land pressures cause the top ring to lose its sealing ability and to flutter during the transient at full load. During top flutter, reverse gas flows not only locally through the gap, but also through the groove, entraining the oil accumulated in the groove during low load conditions and driving it into the combustion chamber. Figure 12 shows the gas flow rates through the different paths at full load. It is evident that the gas flow through the top ring gap is negligible compared to the flow through the groove. More importantly, the reverse gases flow into the combustion chamber mainly during the exhaust stroke, when the combustion is completed and in-cylinder temperatures are low. Therefore, this oil consumption mechanism may also contribute significantly to the oil-VOF of particulate emissions.

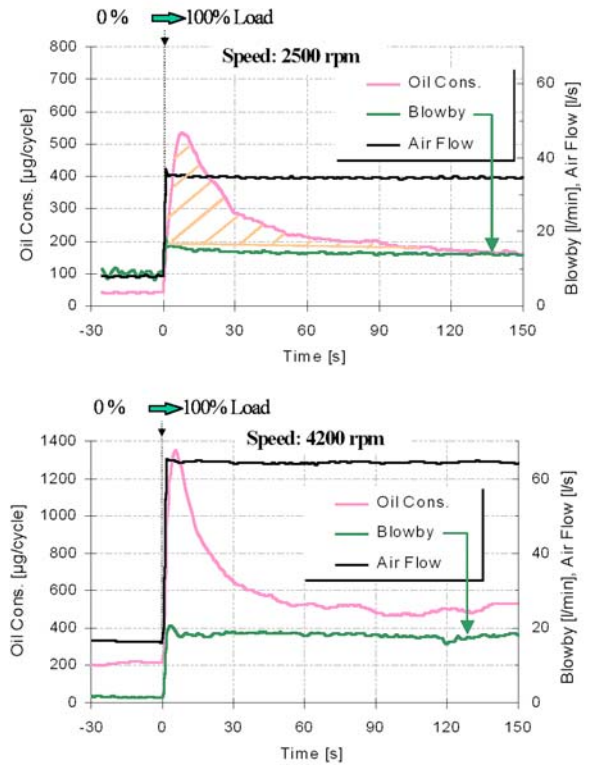


Figure 11: Oil consumption during transient in load (0% to 100%) at different speeds.

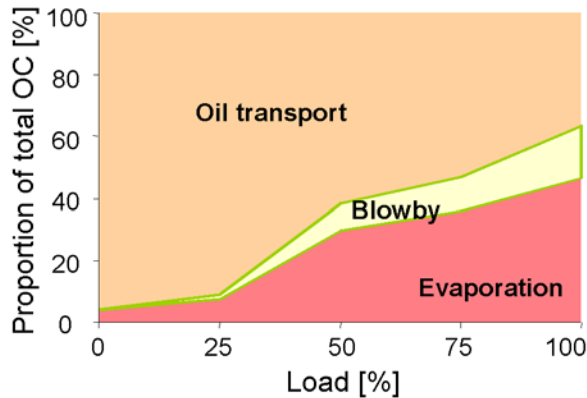


Figure 9: Effect of engine load on the relative importance of oil consumption mechanisms to total oil consumption at 3500 rpm.

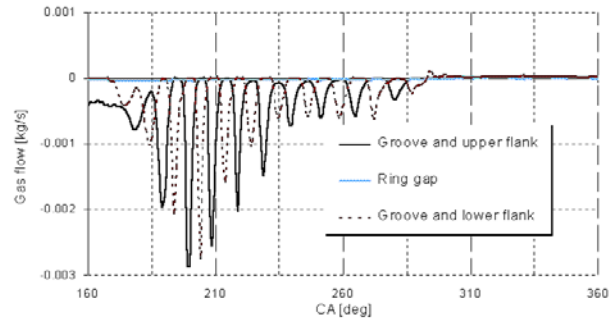


Figure 12: Gas flows through top ring groove and gap during reverse flutter at full load (100%), 4200 rpm.

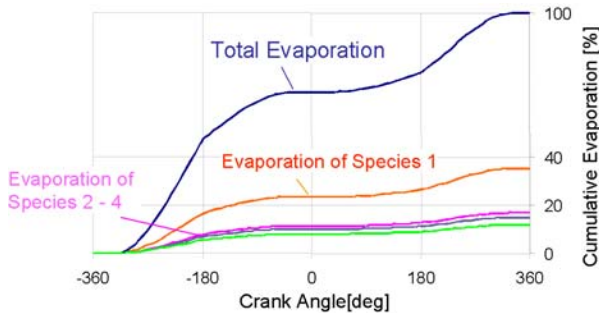


Figure 10: Cumulative total oil evaporation and proportions of the lightest four species during one engine cycle at 100% load, 3500 rpm.

LUBRICANT DESIGN IMPACT ON OIL CONSUMPTION AND PARTICULATE

In the previous section, the contribution of oil consumption sources to total oil consumption was characterized and quantified for 2 different test engines. It was emphasized that there is only a limited knowledge on oil consumption sources and mechanisms, and on their impact on oil-VOF of particulate. This section focuses on the impact of lubricant design on oil consumption and particulate emissions. Generally, oil viscosity and volatility are believed to be the significant physical oil properties that affect oil consumption and particulate emissions. While the viscosity affects complicated oil transport mechanisms on the liner and piston, the volatility directly governs the oil evaporation rate from hot surfaces during the engine cycle. However, other oil

properties and parameters such as additive composition can have an impact on oil consumption as well. In general, there is a lack of studies that investigate the effects of these oil properties and parameters on oil consumption and particulates. In a recent combined experimental and theoretical study by *Yilmaz et al.* (2002), oil evaporation was found to be sensitive to oil volatility, engine thermal loading and oil transport rates to regions of high evaporation. Two oils with different volatility (Noack volatilities of 13.5% and 16.8%) and similar viscosity characteristics were used to analyze oil evaporation at different steady state speed and load conditions. These oils operate in the piston-ring-liner system over a broad range of temperatures. Analysis results showed a similar low-shear-rate viscosity-temperature relation for both oils at temperatures above 100 °C.

Figure 13 shows the measured improvement of oil consumption at different speed and load conditions by using lower volatility synthetic oil (Noack 13.5%) instead of the baseline oil (Noack 16.8%) - as a percent of the baseline oil consumption. As oil volatility was reduced, oil consumption decreased at several engine speed and load conditions. At low load, there is little difference between the two test lubricants due to lower component temperatures. It is clear that the impact of oil volatility on oil consumption increases with engine speed and load. For example at 4200 rpm and full load (100%), oil consumption was improved by approximately 30 percent due to the reduction in oil volatility, implying a substantial contribution of oil evaporation to total oil consumption at high speed and load conditions. This has also an impact on particulate emissions because a significant portion of the evaporated oil may escape the combustion event and contribute to oil VOF of particulates.

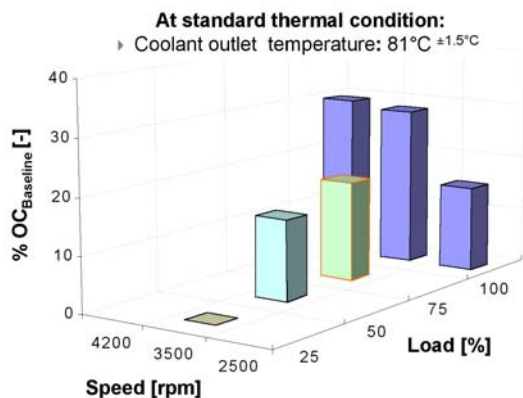


Figure 13: Decrease of oil consumption (as percent of the baseline oil consumption) due to reduction of volatility at different speed and load.

In a different study, *Kiovsky et al.* (1993) demonstrated that the viscosity and volatility are interdependent within each chemical group of base-stocks, refer Figure 14. For any given base stock, the Noack volatility increases as the kinematic viscosity

decreases. This is an important effect, since fuel efficiency generally increases from a lower viscosity level of the base stock. To decrease the base stock viscosity under the constraint of a maximum allowed volatility, it is needed to shift to a lower volatility base stock. This is typically associated with increased cost.

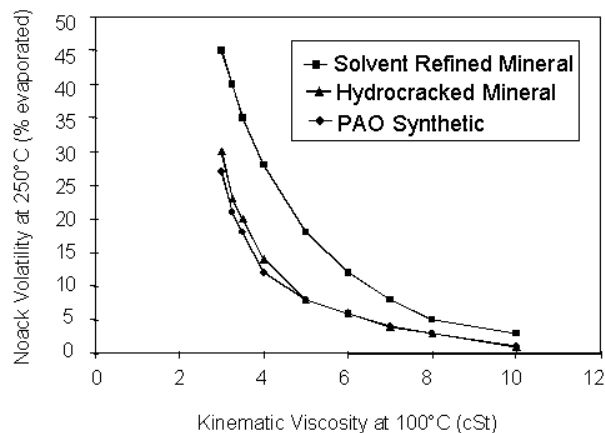


Figure 14: Correlation Between Kinematic Viscosity and Noack Volatility.

In the following is a list of other studies that relate particulate emissions to oil properties and parameters:

Mayer et al. (1980) applied the radioactive Carbon-14 technique to estimate the oil-fraction of particulate matter for a 5.7L IDI-diesel engine. The oil-fraction of the particulate matter ranged from 2 to 28%. These results are important for this publication, since this technique supposedly represent the “true” oil impact on particulate.

Manni et al. (1997) investigated the emissions response of a single-cylinder DI-diesel engine using different lubricants. The baseline oil was mineral 15W40 oil and the candidate was synthetic 5W30 oil. For an operating condition close to maximum torque, the particulates were reduced by 22% by applying the prototype synthetic oil as compared to the baseline oil.

Manni et al. (2000) later investigated the emissions response of a multiple-cylinder IDI-diesel engine using different lubricants. The baseline oil was a mineral SAE 15W40 and the candidate oil was a synthetic SAE 0W40. For the ECE15 and EUDC MVEG test cycle, the synthetic oil reduced the average particulate emissions by 11% and reduced the average nitrogen oxides by 5%.

Casserino et al. (2000) measured the particulate emissions of a 6-liter truck diesel engine certifying to Euro-II emissions level. The effect of various lubricant oil viscosity and volatility levels on particulate emissions was investigated. The reference oil was a 15W40 mineral oil with a kinematic viscosity of 14.5 cSt at 100°C and a Noack volatility of 15%. For a 0W40 synthetic oil with a kinematic viscosity of 14.3 cSt at 100°C and a Noack volatility of 11%, the

particulate emissions could be decreased by 5.5% for the cold start and by 2% for the warm start of the US FTP transient cycle.

Jefferd *et al.* (2000) found that by applying different oils on a heavy-duty DI-diesel engine, a 20% increase in particulate and a 7 to 9% decrease in nitric oxides were found when applying the synthetic SAE 5W40 oil as compared to the baseline mineral SAE 15W40 oil.

A recent SwRI study by Froelund (2001) provided a significant contribution to the knowledge database in this area of research. The purpose of this study was to investigate the impact of fuels and oils on the emissions. The test engine was the Mercedes-Benz OM611 2.2 liter common-rail direct-injected diesel engine, which is used in the Mercedes C-class vehicles in Europe. At the time of the project, the Partnership for a New Generation Vehicle (PNGV) had identified the direct-injected diesel engine as a promising technology in meeting the PNGV goal of 80 miles per gallon (33 km/l or 3 l per 100 km) for a prototype sedan by 2004.

Two test fuels were selected:

1. A “California Air Resource Board” fuel, abbreviated CARB, with low-aromatic (~19%) and low-sulfur (~170 ppm) content
2. An “Oxygenate” fuel, abbreviated ADMM15, with ultra-low-aromatic (~8%), ultra-low sulfur (<10 ppm), and 5 % oxygen content.

Three test lubricants were selected, with viscosity and volatility properties as shown in Table 4.

SAE Grade	Base Stock	Kin. Viscosity @100°C [cSt]	Volatility Noack [%]
5W30	Mineral	9.6	20.9
5W30	Synthetic	10.4	7.2
15W50	Synthetic	18.5	4.9

Table 4: Test Oil Specifications.

The total particulate, nitric oxide, and other gaseous emissions were measured. The particulate composition was investigated by a gas chromatograph technique applied at SwRI deemed the DFI-GC technique by Newkirk *et al.* (1992). The steady-state operating modes can be seen in Table 5. The emissions were also measured during the US FTP Transient cycle. Other details found in the publications by Froelund *et al.* (2001). Based on the discussions under Case 1, it is important to mention that the techniques applied in this work provides a lower estimate of the oil contribution to the particulate. Figures 15 through 17 presents some results of relevance for this discussion of the oil impact on particulate emissions.

Mode	Speed rpm	Load Nm
M20	1,000	102
M10	2,000	34
M5	2,600	150
M17	2,600	310
M14	4,200	206

M20	1,000	102
M10	2,000	34
M5	2,600	150
M17	2,600	310
M14	4,200	206

Table 5: Operating Steady-State Modes.

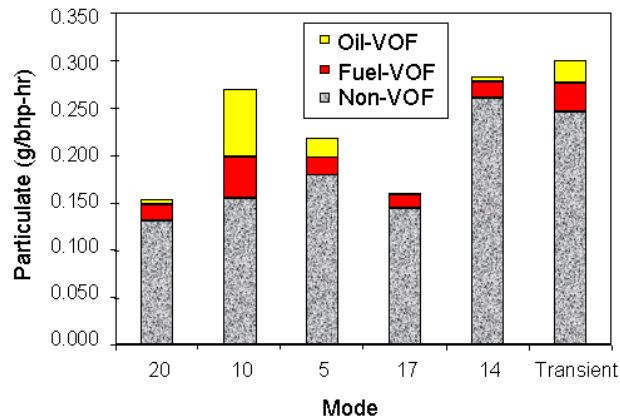


Figure 15: Particulate Split (CARB Fuel and Mineral 5W30 Oil).

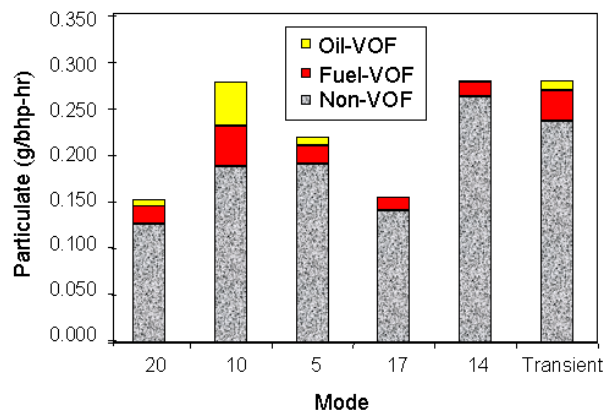


Figure 16: Particulate Split (CARB Fuel and Synthetic 5W30 Oil).

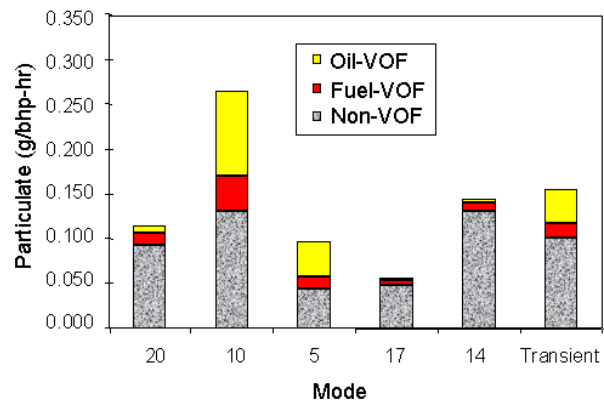


Figure 17: Particulate Split (ADMM15 Fuel and Mineral 5W30 Oil).

The following are some findings from this work:

- Applying the mineral SAE 5W30 oil grade and the CARB fuel, the highest oil-contribution to particulate occurred at Mode 10 and it was 25% (Figure 15).
- Applying the mineral SAE 5W30 oil grade and the ADMM15 oxygenate fuel, the highest oil-contribution to particulate occurred at Mode 10, and it was 37% (Figure 17).
- The reduction in total particulate emissions by selecting the synthetic 15W50 oil was found primarily to originate from a reduction in oil-VOF. The fuel-VOF and non-VOF remained practically constant.
- Applying the synthetic 15W50 oil, the NOx emissions over the US FTP transient cycle increased by approximately 10% by, as compared to the 5W30 oils. For mode 10, the increase was 33%. This effect is explained through a friction increase (FMEP), which for constant torque operation (BMEP) is offset by a load increase (IMEP).
- The data suggest a trade off between particulates and nitric oxides emissions with the selection of lubricant oil. This effect is novel in the published literature.
- Statistical analysis showed no interaction between the fuels and oils in almost all cases.

Clearly, this sample of references to the literature suggests that the crankcase oil impact on emissions yielded mixed results for different researchers. Compared to fuel-effect, the oil-effect have overall a weaker impact on particulate emissions, and it is thus more difficult to measure at a statistically significant level. Most researchers found that a lower volatility decreases particulate emissions slightly, and lower friction (through the combined effect of viscosity and friction modifiers) decreases the nitrogen oxide emissions substantially.

CONCLUSION

1. The impact of lubricant oil consumption on particulate emission has been established by means of one sample data set. This data set is for three contemporary US-certified engines operated under the US FTP transient cycle. It is estimated that the “true” impact for contemporary US certified engines is about 0.023 to 0.038 g/bhp-hr. This impact of lubricant oil to engine-out particulate for contemporary US produced heavy-duty diesel engines range from 20 to 30% of the total engine-out particulate, and it is clearly above both the Euro IV/V and the US EPA 2007 total particulate levels.
2. Different oil consumption sources have been characterized and quantified on 2 different test engines. Based on this data, the following conclusions were made:
 - At high-speed, full-load operation, the piston-ring-liner system is often the major contributor to total oil consumption.
 - At low-speed, low-load operation, other component may yield significant contribution to total oil consumption.
 - Transient engine operation leads to increasing oil consumption above and beyond any steady-state engine operation.
3. The impact of lubricant design on particulate emissions has been documented through one sample data set. Based on this data, the following conclusions were made:
 - Higher oil viscosity reduces most likely the oil consumption and the oil-derived particulate emissions.
 - Lower oil volatility reduces the oil consumption and the oil-derived particulate emissions.
 - Oil evaporation increases strongly with engine load.
 - Viscosity and volatility are connected properties through a trade-off curve for a given base stock.
 - Constraints on either the viscosity or the volatility may necessitate a substitution to a more refined base stock.
 - The impact of auxiliary lubricant additives on oil consumption is poorly documented in the literature.
 - Oil friction characteristics have shown a strong effect on nitrogen oxide emissions.
4. In looking forward towards future particulate emission targets such as Euro IV/V or US EPA 2007, the following approach is recommended for a given engine development program:

- a) Establish the oil impact on particulate
- b) Establish the engine design impact on particulate
- c) Establish the lubricant design impact on particulate
- d) Establish the impact of the engine-out emissions on aftertreatment systems
- e) Decide upon a combination of measures, which will guarantee a satisfactory low particulate level for meeting the particular emission limit:
 - Oil contribution to particulate
 - Oil contribution to ash deposits in particulate filter
 - Oil contribution to ash deactivation on catalytic surfaces
- f) Investigate cost, production, durability, packaging issues, etc.

REFERENCES

Barris, M., Donaldson Company, “Crankcase Emissions & Closed Crankcase Filtration”, 2000 SAE TOPTEC “Diesel Engine TOPTEC: Emission Challenges for the Future”, 2000

Casserion, M., Benda, R., Plomer, A., Reboul, P., BP Amoco Chemical Co., “Improved Fuel Economy and Reduced Heavy-Duty Diesel Engine Particulate Emissions with PAO Based Lubricants”, Presented at the National Petrochemical & Refiners Association 2000 Lubricants and Waxes Meeting, Houston, Texas, Nov. 2000

Froelund, K. Owens, E., Southwest Research Institute, Private Communication, 2000

Froelund, K., Owens, E., Frame, E., Buckingham, J., Southwest Research Institute, Garbak, J., DOE, Tseregounis, S., General Motors, Jackson, A., Exxonmobil, “Impact of Lubricant Oil on Regulated Emissions of a Light-Duty Mercedes-Benz OM611 CIDI-Engine”, SAE paper 2001-01-1901

Froelund, K., Menezes, L., Johnson, H., Rein, W., “Real-Time Transient and Steady-State Measurement of Oil Consumption for Several Production SI-Engines”, SAE paper 2001-01-1902

Froelund, K., Owens, E., Frame, E., Buckingham, J., Southwest Research Institute, “Impact of Lube Oil on Advanced Light-Duty CIDI-Engine Emissions”, Final Report, Released January 2001, Distribution Unlimited, Defense Technical Information Center, Att:DTIC-OCC, 8725 John J. Kingman Road, Suite 0944, Fort Belvoir, Virginia 22060-6218

Inoue, T., Masuda, Y., Yamamoto, M., Toyota Motor Corp., “Reduction of Diesel Particulate Matter by Oil Consumption Improvement Utilizing Radioisotope Tracer Techniques”, SAE paper 971630

Jacob, E., Gotre, W., Rothe, D., MAN Nutzfahrzeuge AG, Rammer, F., Richter, K., both SNF Nutzfahrzeuge, “The Influence of Lubricating Oil on the Emissions of Diesel Engines with Exhaust Aftertreatment”, 2001

Jefferd, K., Rogerson, J., Copp, D., Brundle, R., Huntly, M., BP Amoco, “The Impact of Lubricants on Heavy-Duty Diesel Engine Fuel Economy and Exhaust Emissions”, SAE paper 2000-01-1983

Kioovsky, T., Yates, N., Bales, J., “Fuel Efficient Lubricants and the Effect of the Special Base Oils”, Journal of the Society of Tribologists and Lubrication Engineers, 48th Annual Meeting, Calgary, Canada, May 1993

Manni, M., Florio, S., Euron, Gommellini, C., Agip, “An Investigation on the Reduction of Lubricating Oil Impact on Vehicle Exhaust Emissions”, SAE paper 972956

Manni, M., Florio, S., Euron, Gommellini, C., Agip, “Impact of Fuel and Oil Quality on Deposits, Wear, and Emissions from a Light-Duty Diesel Engine with High EGR”, SAE paper 2000-01-1913

Mayer, W., Lechman, D., Hilden, D., General Motors, “The Contribution of Engine Oil to Diesel Exhaust Particulate Emissions”, SAE paper 800256

Mori, G., Umeki, T., Ueno, Y., Ohishi, T., Arai Seisakusho Co., “Engine Valve Stem Seal, Oil Leakage Control Technology and Performance”, SAE paper 960208

Newkirk, M., Southwest Research Institute, “Application of Methods for Determining Total Organic Contribution to Diesel Particulates”, ASME Paper 92-ICE-16 Presented at the ASME Energy Source Technology Conference and Exhibition, January 1992, Houston, Texas

Sharp, C., Southwest Research Institute, Howell, S., MARC IV, Jobe, J., National Biodiesel Board, “The Effect of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part I: Regulated Emissions and Performance”, SAE paper 2000-01-1967

Yilmaz, E., Thirouard, B., Tian, T., Wong, V. W., Heywood, J. B., and Lee, N., “Analysis of Oil Consumption Behavior during Ramp Transients in a Production Spark Ignition Engine”, SAE paper 2001-01-3544, 2001.

Yilmaz, E., Tian, T., Wong, V. W., and Heywood, J. B., “An Experimental and Theoretical Study of the Contribution of Oil Evaporation to Oil Consumption”, SAE paper 2002-01-2684, 2002.

Yilmaz, E., “Sources and Characteristics of Oil Consumption in a Spark Ignition Engine”, Ph.D. Thesis, Department of Mechanical Engineering, MIT, September 2003.

CONTACT

Dr. Kent Froelund is a Principal Engineer in the Engine Research Department at Southwest Research Institute, where he specialises in applying the SwRI Real-Time Oil Consumption measurement system. He has represented the institute on two worldwide Consulting Service travels and is the author of about 15 publications. He can be contacted as follows:

Dr. Kent Froelund
Engine Research Department
Southwest Research Institute
San Antonio, Texas 78228
USA
Tel: +1 (210) 522 3664
Fax: +1 (210) 522 2019
Email: kfroelund@swri.org

Dr. Ertan Yilmaz is a Research Engineer in the Combustion Laboratory of the Energy and Propulsion Technologies organization at the General Electric Company/Global Research Center. He focuses on in-cylinder combustion processes for low emission and efficient reciprocating power technologies for railroads and distributed electricity production.

Dr. Ertan Yilmaz
GE Global Research Center
Energy and Propulsion Technologies
Niskayuna, New York 12309
USA
Tel: +1 (518) 387 4584
Fax: +1 (518) 387 7258
E-mail: yilmaz@research.ge.com