

Towards a Model for Engine Oil Hydrocarbon Particulate Matter

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ABSTRACT

The drive to reduce particle emissions from heavy-duty diesel engines has reached the stage where the contribution from the lubricant can have a major impact on the total amount of particulate matter (PM).

This paper proposes a model to predict the survival rate (unburnt oil divided by oil consumption) of the hydrocarbons from the lubricant consumed in the cylinder. The input data are oil consumption and cylinder temperature versus crank angle.

The proposed model was tuned to correlate well with data from a six-cylinder heavy-duty diesel engine that meets the Euro 5 legislation without exhaust gas aftertreatment.

The measured (and modelled) oil survival shows a strong correlation with engine power. The maximum oil survival rate measured (19%) was at motoring conditions at high speed. For this engine, loads above 100 kW yielded an oil survival rate of nearly zero.

INTRODUCTION

Over the last few decades, particulate matter (PM) in exhaust gases from heavy-duty diesel engines has been heavily reduced. For example, in Europe the maximum allowed PM was reduced from 0.36 g/kWh in 1992 (Euro 1) [1] to 0.02 g/kWh in 2005 (Euro 4) [2]. The European Commission [3] proposes a further reduction to 10 mg/kWh for the Euro 6 legislation (2013), as well as measuring the number of particles in addition to particle mass measurements.

The reduction of particle emissions from heavy-duty diesel engines has reached the stage where the lubrication oil can be a significant source of particulate matter.

PARTICLE DEFINITION

Within the automotive industry, particle emissions are defined by the measuring methods. Particulate mass is today measured by collecting liquid and solid PM on a filter. Particle numbers are determined in accordance with the UN/ECE Particulate Measurement Program (PMP) [4]. The PMP procedure involves heating and dilution of the exhaust gases and is intended to measure solid particles.

The content on the filter used for measuring particulate mass can be divided into a solid fraction consisting of carbon and ash; a liquid fraction that is often referred to as SOF (soluble organic fraction) or VOF (volatile organic fraction); and sulphates with water. The solid carbon is formed during rich combustion; the ash is formed from additives in the lubricant or fuel. The liquid fraction is fuel or oil that is not fully oxidized. Oxidation of sulphur to SO₃ leads to sulphuric acid/sulphates [5].

The relative composition of the particulate matter from an American mid-1990s heavy-duty engine is shown in [Figure 1](#). The reduction of particulate matter since the 1990s has to a large extent been done by reducing the carbon particles (formed during rich combustion), sulphates, and unburnt fuel, and thus the relative contribution of the unburnt oil has tended to increase.

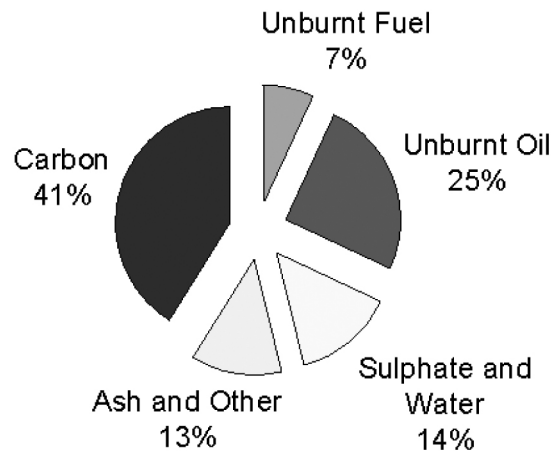


Figure 1. Typical PM composition, data according to Kittelson [5], from Johansson [6]

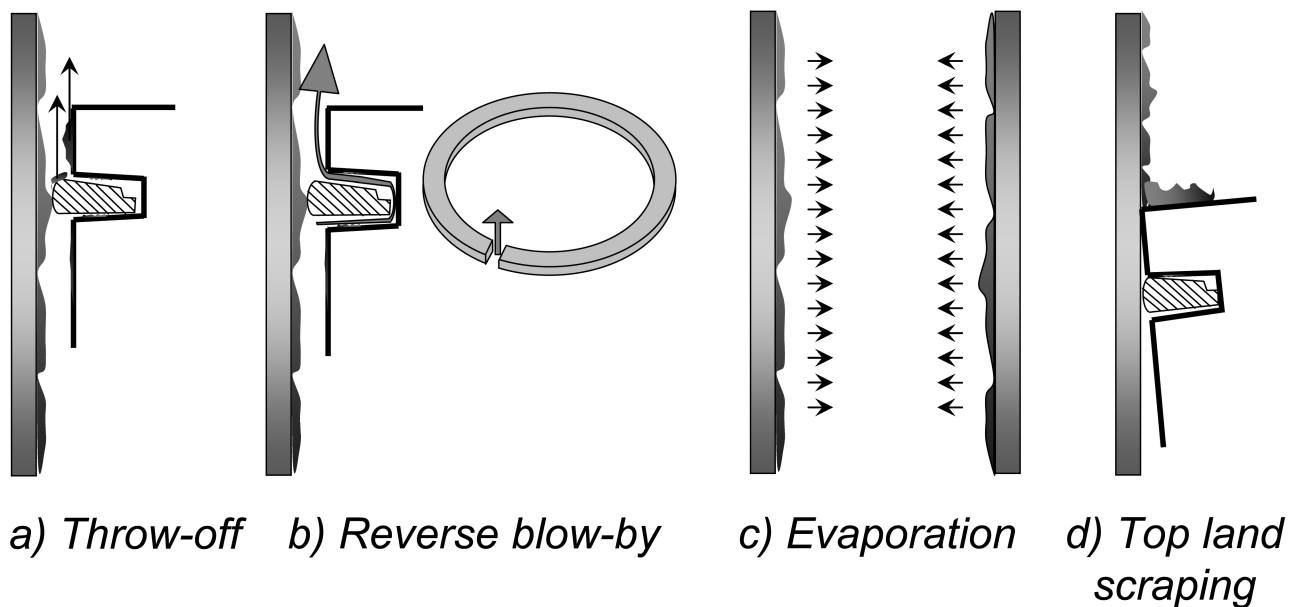


Figure 2. In-cylinder oil consumption, from Johansson and Andersson [7]

OIL-DERIVED PM

A condition for the creation of oil-related PM is oil consumption. Oil can be consumed via the cylinder, turbocharger, valve stem seals and crankcase ventilation. If best practices are used, the cylinder system is the largest contributor of oil-related particles [6].

OIL CONSUMPTION VERSUS OIL-RELATED PARTICLES

Some of the oil consumed in an engine ends up as particle emissions. The authors propose the following terminology for categorizing in-cylinder oil consumption: [6]

- Throw-off, when oil is driven towards the combustion chamber by inertia forces (Figure 2a)
- Reverse blow-by, when gas containing oil is driven by pressure to flow towards the combustion chamber (Figure 2b)
- Evaporation from hot surfaces (Figure 2c)
- Top land scraping, when oil is scraped from the cylinder liner by the top land of the piston, or more likely, by carbon deposits on the top land (Figure 2d).

This categorization of oil consumption is derived from Yilmaz et al. [8] and Herbst and Pribsch [9]. Yilmaz et al. use the terms *throw-off*, *transport with reverse gas flow* and *evaporation*. Herbst and Pribsch [9] divide in-cylinder oil

consumption into *evaporation*, *oil throw-off* reverse oil blow and *oil scraping by piston top land*.

An alternative categorization depends on the state of the oil when it is consumed. Mihara et al. [10] divide the in-cylinder oil consumption into *vapour oil consumption* (VOC) and *liquid oil consumption* (LOC). The SAE Piston and Rings Standards Committee [11] uses the categories liquid; oil that is scraped, flowing or being squeezed around the ring; vaporization of oil; and oil in a mist.

The authors are currently developing a model to describe the relation between oil consumption and oil-related particle emissions (Figure 3). In the model presented in this paper, oil consumption is divided into a liquid/droplet part and an evaporation part. The liquid part is defined as the sum of throw-off, reverse blow-by and top land scraping.

Kittelson [5] divides the particle constituents into hydrocarbons, ash, sulphates plus water, and carbon. Each constituent is given a transfer function describing its relationship to oil consumption. The transfer function for the sulphur-associated particles is described by Johansson in [12].

The inter-ring pressure is often a concern when oil consumption occurs, and has previously been addressed by Johansson and Andersson [7].

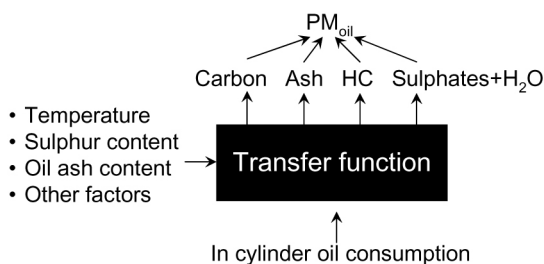


Figure 3. Transfer model from oil consumption to particle emission

PURPOSE AND LIMITATIONS

This paper describe a model that can predict the survival rate for lubrication oil consumed in the cylinder system in diesel engines. The survival rate is defined as oil-related hydrocarbon particle emissions divided by oil consumption. The survival rate for oil has previously been measured by numerous authors but models predicting the survival rate are rare.

The proposed model is tuned with data from measurements. The model is limited to in-cylinder conditions; the effect of any aftertreatment devices is not included.

LITERATURE SURVEY OF THE RELATION BETWEEN OIL CONSUMPTION AND OIL-RELATED HYDROCARBON PARTICLES

A number of authors have measured oil consumption and oil-related particles simultaneously. The results are summarized in Table 1. Note that the data in Table 1 are extracted by the authors from the figures in the respective publications.

Essig et al. [13] define a survival rate as unburnt oil (measured by gas chromatography) divided by oil consumption (measured by a tritium radio tracer technique). They found that reducing oil consumption by modifying the cylinder system gave a proportional decrease in oil-related particles. The oil survival rate was found to be high (up to 100%) at high speed and low load, and low (almost zero) at low speed and high load. Essig et al. [13] explain the difference in survival rate by the different post-reactions possible for hydrocarbons, depending on the engine temperature.

Andrews et al. [14] studied four different engines and use the term “lube oil combustion efficiency”. The combustion efficiency is equal to one minus the survival rate. Hence 75% lube oil combustion efficiency corresponds to a 25% survival rate. The oil consumption was measured by a calcium tracer technique and the oil-related particles were assessed by thermal gravimetric analysis (TGA) combined with flame ionization detection (FID).

Test results from their Perkins DI-4-236 show “that lube oil emissions were highest at the low exhaust temperatures of low load power operations” [14]. Analysis of the data (Figure 4) shows an r^2 correlation of 0.77 between lube oil combustion efficiency and engine power. An even better correlation is found when comparing with engine torque ($r^2 = 0.98$). The r^2 correlation was 0.83 between lube oil combustion efficiency and exhaust temperature. It was also noted in the paper that the Perkins DI-4-236 suffered from high oil consumption via the exhaust valves.

Inoue et al. [15] use the term “conversion ratio into lube oil particles” to define the ratio between oil related particles and oil consumption. The oil consumption for the cylinder system was measured separately by having a separate oil system with oil labelled with ^{35}S radio tracer. The oil-related particles were assessed by SOF extraction followed by use of the ^{35}S tracer.

Inoue et al. also [15] shows that conversion rate from oil consumed via the cylinder system decreases with increased engine load. Furthermore they point out that “oil consumed upstream of the combustion chamber is easily burned, while

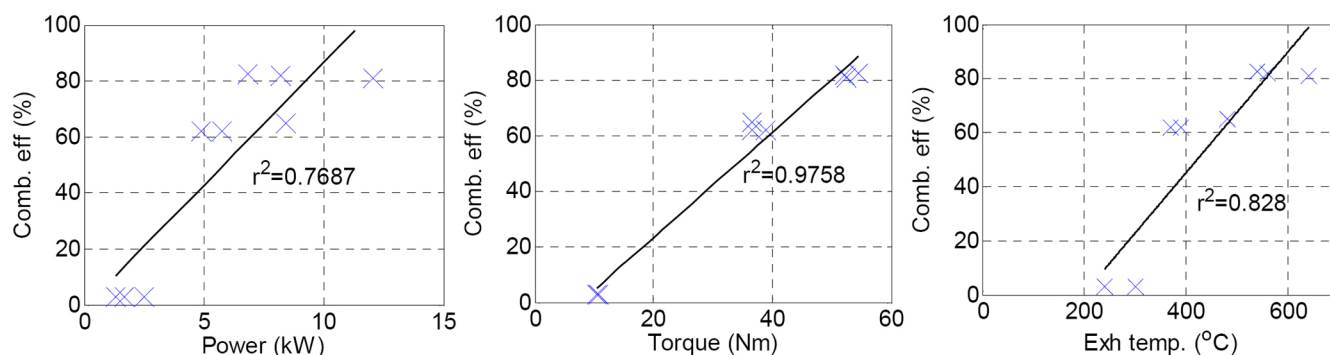


Figure 4. Lube oil combustion efficiency as a function of engine power, load and exhaust temperature, data from Andrews et al. [14]

oil consumed in the exhaust regions is largely converted to PM.”

Shore [16] measured the oil survival rate by measuring oil consumption using a tritium tracer, and the oil-related particles by analyzing measurement filters using gas chromatography. The oil survival rate was at its maximum at light load.

Kawatani et al. [17] used a test setup with different piston ring tensions to create different oil consumption levels and particle levels. The reduction/increase of particle emissions (collected with a TEOM) divided by the reduction/increase in oil consumption (sulphur trace method) is used to define the conversion rate into oil related particles. Kawatani et al. [17] indicate the importance of a high combustion temperature to reduce the conversion rate/survival rate.

Knoll et al. [18] measured oil emissions in the cylinder on a 2L spark ignition Volkswagen engine. They found that the amount of unburnt oil in the cylinder is low during the intake stroke and rapidly increases after firing top dead centre (FTDC). The rate of unburnt oil then decreases until bottom dead centre (BDC) and then increases to reach its maximum at the end of the exhaust stroke.

TEST SETUP

The oil survival rate was obtained by measuring the oil-related hydrocarbon particulate matter and comparing it with the oil consumption. The study was conducted using a Scania 6 cylinder engine developed to meet the Euro 5 legislation. The engine has a total capacity of 12.7 L, a maximum power output of 353 kW at 1900 rpm and a maximum torque of 2500 Nm between 1000 and 1300 rpm. The engine fulfils the Euro 5 legislation without aftertreatment, making it suitable for studies in which in-engine effects are studied. Exhaust aftertreatment devices would most likely influence the oil survival rate.

The measurements were done by keeping the engine at steady state conditions for 20 minutes. Oil consumption and particulate matter were measured simultaneously for the last 15 minutes of each load point. In total three test matrices were run (Figure 5, Figure 6, Figure 7).

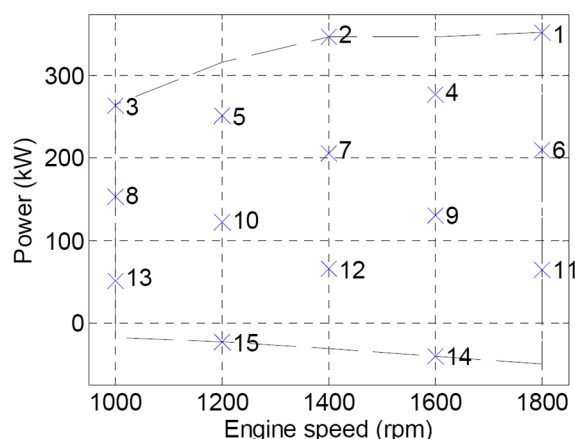


Figure 5. Test load points, test matrix 1

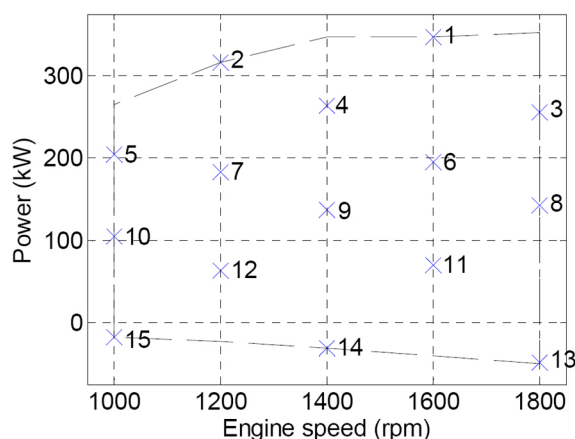


Figure 6. Test load points, test matrix 2

Table 1. Summary of oil survival rate test results

Author	Publ. year	Engine description	Engine speed (rpm)	Engine load (%) or BMEP (bar)	Survival rate	Comments
Essig et al. [13]	1990	11 L diesel truck engine, typical of 1988 technology	800–2000	0–17 bar	0–100%	High survival rate at high speed and low load.
Andrews et al. [14]	1998	Perkins 4-236 NA diesel engine modified to single cylinder engine. Displacement 965 cc per cylinder	1200, 1500 and 2200	1.4–7.1 bar	0–83%	Good correlation between increased engine load and reduced oil survival rate.
		Ford 1.6 L indirect diesel injection	2200	3.8 bar	22%	
		Perkins 6 cylinder prototype turbocharged diesel engine. Displacement 1 L/cylinder	US HD transient test cycle		62%	The test cycles include considerable periods with low load and motoring conditions.
		Ford 1.8 L indirect diesel injection	1500	2.2 bar	Average 7.5%	Single load points, but variations in cold start/steady state, with or without EGR.
			2500	3.2 bar	Average 7.2%	
Inoue et al. [15]	1997	Experimental turbocharged diesel engine, 4.2 litre inline 6 cylinder, 110 kW/3600 rpm	2160	0–100%	0–43%	Oil consumed upstream of the combustion chamber is easily burned, while oil consumed in the exhaust regions is largely converted to PM.
Shore [16]	1988	Direct injected truck diesel engine	850–2200	Light load to 100%	0–40%	Light load gave the highest oil survival rate. Higher load presumably oxidizes the oil during the combustion process.
Kawatani et al. [17]	1993	Heavy-duty diesel engine, 7.5 L inline 6 cylinder, “Engine B”	600–3000	0–100%	6–65%	High speed and low load gave the highest oil survival rate. Decreasing speed or increasing the load reduced the oil survival rate.