The Contribution of Oil to Carbon Particle Emissions from Diesel Engines

Technical Report

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Abstract
Reducing particle emissions from diesel engines has been an important issue in recent decades. This study assesses the contribution of oil to carbon particle emissions by reviewing the literature and theory on fuel soot formation, and combining it with estimates based on a maximum and minimum approach.

The study shows that the minimum oil contribution to carbon particle emissions for a Euro 5 heavy-duty diesel without exhaust aftertreatment is around 0.4 mg/kWh. The corresponding maximum estimate is 1.1 mg/kWh.
1 Introduction

Particle emissions from heavy-duty diesel engines have been greatly reduced in the last few decades. For example, in Europe the allowable emissions were reduced from 0.36 g/kWh in 1992 (Euro 1) [1] to 0.02 g/kWh in 2005 (Euro 4) [2]. They will be reduced to 0.01 g/kWh for 2013 (Euro 6) [3]. The Euro 6 legislation will probably also include particle number legislation.

Traditionally, particle emissions have been reduced by reducing the particles arising from the fuel, for example by improving the fuel injection system and air management, and by reducing fuel sulphur content. However, as the fuel-related particles have been effectively reduced, the role of oil-related particles has become more and more prominent.

The author is currently working in a project to increase understanding of oil-related particles. The project has shown that when best practices are used, the cylinder system is normally the largest contributor of oil-related particles [4]. Other contributors are the turbocharger bearings, valve stem seals, and crank case ventilation.

In-cylinder oil consumption can be categorized as follows [4]:

- **Throw-off**, when oil is driven towards the combustion chamber by inertia forces (Figure 1a)
- **Reverse blow-by**, when gas containing oil is driven by pressure to flow towards the combustion chamber (Figure 1b)
- **Evaporation** from hot surfaces (Figure 1c)
- **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 1d).

![In-cylinder oil consumption](image)

**Figure 1. In-cylinder oil consumption, from Johansson and Andersson [5]**

This categorization of oil consumption is derived from Yilmaz et al. [6] and Herbst and Priebisch [7]. Yilmaz et al. use the terms *throw-off, transport with reverse gas flow* and *evaporation*. Herbst and Priebisch [7] divide in-cylinder oil consumption into *evaporation, oil throw-off, reverse oil blow* and *oil scraping by piston top land*. An alternative categorization by Mihara et al. [8] depends on the state of the oil when it is consumed. They divide the in-cylinder oil consumption into *vapour oil consumption* (VOC) and *liquid oil consumption*.
(LOC). The SAE Piston and Rings Standards Committee [9] uses the categories liquid oil that is scraped, flowing or being squeezed around the ring; vaporization of oil; and oil in a mist. The inter-ring pressure is often a concern when oil consumption occurs, and has previously been addressed by Johansson and Andersson [5].

The definition of a particle can differ from field to field, but within the automotive industry, particle emissions are defined by the measuring methods and how the particles are collected on a filter. Particle emissions from diesel engines are often 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 (and is often referred to as soot); ash is formed from additives in the lubricant or fuel. The liquid fraction is fuel or oil (hydrocarbons) that is not fully oxidized. Oxidation of sulphur to SO₃ leads to sulphuric acid/sulphates [10].

The contribution of oil to particle emissions is modelled using transfer functions (Figure 2). The transfer functions for the oil hydrocarbons, ash, and sulphur-associated particles are described in [11], [12] and [13].

![Transfer function model from oil consumption to particle emission, from Tornehed and Olofsson [11]](image)

This study aims to assess the contribution of oil to carbon particle emission. It is done by using maximum and minimum estimates based on a literature review of theory and measurements within the field. The influence of the increasing use of exhaust aftertreatment devices is left outside of this study. Thus the current (Euro 5) legislation is used as reference for calculating examples of emissions, since these requirements can be met without exhaust aftertreatment [14].

### 2 Review of results from engine tests

Buchholz et al. [15] report a study in which they used ¹⁴C to distinguish between oil and fuel carbon particle emissions. They used a 100% biodiesel with a known ¹⁴C content and a ¹⁴C-free lubrication oil. The lubricant contributed 4% of the carbon particles, with a standard deviation of 1%. The engine used was a 1993 Cummins B5.9, a six-cylinder diesel engine with the total capacity of 5.9 L and a maximum power of 175 hp at 2500 rpm. The test was run at 1600 rpm and 285 Nm (50% of maximum torque). The engine was equipped with a Bosch B7100 PE inline fuel injection pump capable of pressures up to 115 MPa.

Hilden and Mayer [16] studied the contribution of the oil to total particulate matter and to SOF. Their data can be used to assess the oil’s contribution to non-SOF particles. They used ¹⁴C to label the oil in 5 diesel engines with displacements between 1.8 L and 5.7 L.
manufactured between 1978 and 1983. The vast majority of the oil particulates were found in the SOF; 2% of the non-SOF (soot) was from the oil, with a standard deviation of 2%.

Schneider at al. [17] studied oil deposits in the exhaust system and particles in the exhaust stream of a gasoline engine by labelling the oil with $^{14}$C. The engine was a 1997 4.6 L V8 engine. The oil’s contribution to the soot deposits in the exhaust manifold was 2%, in the exhaust port 6%, and on the oxygen sensor 3%. The results from the sample filtered out from the exhaust gas stream showed a clear influence of engine speed. The oil’s contribution to soot was ~3% at 750 rpm and ~20% at 2500 rpm. The average calculated from all measuring points tabled by Schneider at al. [17] is 6% with a standard deviation of 5%. For the samples taken in the exhaust stream, the corresponding values were 11% with a standard deviation of 7%.

Mayer et al. [18] studied a 5.7 L diesel engine from 1978. The engine oil was labelled with $^{14}$C. The recovery rate, defined as radioactivity in the SOF particles in relation to radioactivity in the total particulates, was found to be 101% with a standard deviation of 4%. Hence the oil’s contribution to non-SOF particles is very low (on average negative) in this study.

3 Soot particle formation

Studies by Haynes and Wagner [19] and Frenklach [20] indicate that soot particle formation originating from diesel fuel combustion can be summarized as:

- Particle inception, when the first soot particles arise from condensed material, typically with a diameter < 20 Å.
- Surface growth, when gas phase species adhere to the surface and increases particle mass. This is where most of the solid phase is generated; the number of particles is constant but the mass increases.
- Particle coagulation, when the size of the particles increases either by coalescence or agglomeration. The sum of the particle mass is constant and the number of particles decreases.
- Soot oxidation.

Several principles for soot inception have been discussed, including polyacetylene, ionic species, or polycyclic aromatic hydrocarbons as a gaseous precursor of soot. The present majority opinion is that soot particles form via PAH (polycyclic aromatic hydrocarbons) [20]. The small size of the initial soot particles, often referred to as soot nuclei, makes the soot loading from the initial particles negligible. The bulk of the (solid) soot particles are formed during the surface growth phase [19]. The end product of soot leaving the cylinder will be dependant on the balance between the formation and subsequent oxidation of soot particles.

Akihama et al. [21] studied the influence of the local temperature and equivalence ratio ($1/\lambda$) on the soot formation rate for n-hexane. A rich mixture is not enough to promote soot production, as the right temperature is also needed (Figure 3). They found that the maximum soot production for n-hexane occurred at 2000 K and that soot formation is suppressed at temperatures below ~1700 K. Other authors using the same approach as Akihama et al. [21] with temperature and equivalence ratio maps have shown very similar maps, but the soot formation region is often displaced towards lower temperatures. For example, Charlton [22] published a map in which the maximum soot formation region is around 1500 K.
Figure 3. Soot formation rate dependency on local temperature and equivalence ratio, principle after Akihama et al. [21]

The clear connection between local temperature and soot in diesel diffusion combustion has been shown by, for example, Lindström and Ångström [23] (see Figure 4.

Figure 4. Visual spectrum, temperature analysis, and soot intensity during combustion in an optical diesel engine, from Lindström and Ångström [23]

Heywood [24] describes three paths for carbon particle formation:

- Low temperature path, below 1700 K. Only the aromatics and highly unsaturated aliphatic particles with high molar weight are prone to form solid carbon; this occurs by pyrolysis.
- Medium temperature path, above about 1800 K (typical diesel temperatures). If the combustion is rich enough, all hydrocarbons normally appearing in diesel fuel produce soot.
- High temperature path, above typical diesel temperatures. Nucleation of carbon vapour occurs.
4 Estimation of oil-related carbon particles

The data presented earlier in this paper were used to estimate the oil’s contribution to carbon particle emissions. The following assumptions were used:

- Oil consumption, 0.2 g/kWh (0.1 % of the fuel consumption)
- Fuel consumption, 200 g/kWh
- Hydrogen to carbon relationship, 2 for the lubrication oil
- Hydrogen to carbon relationship, 1.85 for fuel
- The lubrication oil consists only of hydrocarbons. Ash and other species are disregarded.

1. A maximum limit for the specific oil-related carbon particle emissions was calculated by assuming that all carbon in the oil consumed creates carbon particles. The calculations indicate maximum carbon particle emissions of 0.17 g/kWh.

2. The assumption that all carbon in the consumed oil ends up as carbon particles is not plausible, since the oil carbon particles alone would clearly exceed the Euro 5 particle emission limit (0.02 g/kWh [2]). However, experience has shown that the rules can be met without exhaust aftertreatment [14].

3. Another approach is to assume the same ratio for carbon particle formation for the oil as for the fuel. The current Euro 5 emission legislation allows particle emissions of up to 0.02 g/kWh [2]. On this basis one could assume that carbon particles arising from the fuel produce emissions of 0.01 g/kWh. This leads to a fuel carbon transfer rate of $5.8 \cdot 10^{-5}$. The transfer rate is defined as the carbon particle mass divided by the consumed amount of carbon. Applying this transfer rate to the maximum limit estimate for the oil carbon particles yields a specific oil-carbon particle emission of $9.9 \cdot 10^{-6}$ g/kWh. This is considerably lower than 0.02 g/kWh.

4. Buchholz et al. [15] showed that 4% of the carbon particles from a 1993 diesel engine were oil-related. Applying the 4% factor to a modern Euro 4/5 engine leads to oil-related carbon particle emissions of 0.4 mg/kWh, using an assumed total carbon particle emission of 0.01 g/kWh (50% of the Euro 4/5 limit).

5. The engine tested by Buchholz et al. [15] was produced in 1993. The US emission standard at that time allowed PM emissions of up to 0.34 g/kWh (0.25 g/bHPPh) [25]. Applying the 4% value and assuming that 50% of the particles are carbon leads to oil-carbon particulate emissions of 6.7 mg/kWh.

6. Schneider at al. [17] studied oil’s contribution to soot particles on a port injected petrol engine. They showed an 11% oil contribution to soot in the exhaust. Applying 11% in the same manner as the 4% from Buchholz et al. [15], together with the current emission legislation, leads to an estimate of 1.1 mg/kWh.
5 Discussion

The quantity of oil-related carbon particles has been estimated in a number of ways in this study and the results are summarized in Figure 5. The oil’s contribution to soot particles derived from the measurements reviewed is shown in Figure 6.

![Figure 5. Oil carbon particle emission estimates](image)

![Figure 6. Oil contribution, with one standard deviation, to carbon particle emission depending on engine build year and fuel](image)

The maximum estimate, by assuming all carbon in the lubrication oil produces carbon particles, TR=100%, indicates a maximum emission level of 0.17 g/kWh. This is a gross overestimation since the oil-carbon particles alone would clearly exceed the Euro 5 particle emission limit (0.02 g/kWh [2]), which can be met without exhaust aftertreatment [14]. Although this maximum estimate is far from the real value, it can be used for comparative purposes and to determine how large fraction of the available carbon finally produced carbon particles.

Using the assumption that oil has the same transfer rate into carbon particles (TR = 5.8 \cdot 10^{-8}) as fuel would give oil carbon particle emissions of approximately 10 μg/kWh for a Euro 5 engine. This is likely to be an underestimate since all the studies summarised in Figure 6 [15, 16, 17] show an oil contribution to carbon particles above reasonable levels of oil to fuel consumption. The lowest average oil contribution was 2% (Hilden and Mayer [16]). The oil consumption was not stated, but normal oil consumption is well below 1% of the fuel consumption.

The Buchholz et al. [15] study showed that the oil contributed 4% oil of the carbon particles. For a modern engine (Euro 4/5) this would correspond to 0.4 mg/kWh. This is 2% of the Euro 4/5 particulate limit. For a US diesel engine from 1993, the corresponding value is 6.7 mg/kWh, which is 34% of the Euro 4/5 limit.

The total soot particulates could be assumed to be low in the Schneider at al. [17] study, because the engine was a port-injected gasoline engine. Port-injected gasoline engines are generally assumed to be soot free, and Heywood [26] states “In properly adjusted spark-ignited engines, soot in the exhaust is not a significant problem”. The absence of soot is generally due to the pre-cylinder mixing of the gasoline and air prior to combustion, making the equivalence (1/λ) approximately 1. This to a large extent avoids the local soot-rich island
in Figure 3. Remarkably, even though the fuel is considered to burn almost soot-free, the fuel clearly dominated as soot source.

The reason why the majority of the soot particles are caused by the fuel even in engines considered not to have soot problems might be found in the soot creation/oxidation process. According to Akihama et al. [21], soot formation is promoted not only by a rich mixture, but also by the right local temperature (maximum soot formation rate at 2000 K [21] or 1500 K [22]). Fuel consumption is in the range of 1000 times the oil consumption, and the cylinder temperature will therefore be dominated by the fuel heat release. Thus the conditions to create soot are dominated by the fuel, and reducing the soot from the fuel automatically reduces the soot from the oil. It is likely not only the creation process, but also the burnout of the particles that are affected. Since the fuel governs the soot emissions, the continuing reduction of fuel soot from a 1993 vintage engine (Buchholz et al. [15]) up to today would also reduce the oil soot particles. Therefore the 4% reported by Buchholz et al. [15] is likely to be the oil’s contribution to soot particles even for modern diesel engines. This figure should be seen as a minimum estimate, and the 11% extracted from Schneider at al. [17] could be used as a maximum estimate.

The fact that the standard deviations of the oil’s contribution to soot (Figure 6) range from 29–90 % of the average values ought also to be kept in mind. Perhaps more studies containing a range of engine speed and load combinations could help to explain the variations in data. For example, Schneider et al. [17] found that the oil’s contribution to soot particles increased with higher engine speeds. It would be interesting to repeat the $^{14}$C measurements to see how much the oil contributes to soot in a modern diesel engine. Another alternative to improve our understanding of oil soot particle formation could be to introduce lubrication oil into a model originally designed for fuel soot formation and oxidation. An example of such a model is the one presented by Westlund et al. [27].

6 Conclusions
Oil-related carbon particle emissions may be estimated by multiplying total carbon particle emissions by a factor of 4 % as a minimum and 11 % as a maximum.

This study indicates that the contribution of the oil to carbon particles for a Euro 5 heavy-duty diesel without exhaust aftertreatment can be estimated to be between 0.4 mg/kWh and 1.1 mg/kWh.

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8 References


