Particulate Emissions Associated with Diesel Engine Oil Consumption

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Abstract

Particulate emissions from diesel engines have been a key issue for diesel engine developers in recent decades. Their work has succeeded in reducing the exhaust particles from the combustion of fuel, which has led to increasing interest in the contribution of particulates from lubrication oil.

When discussing oil-related particulate emissions, hydrocarbon particles are customarily referred to. This thesis uses a broader definition, in which oil-related particulate emissions are modelled not only by the hydrocarbons, but also include the ash, carbons, and sulphate oil particulate emissions.

The model developed in the project uses input data as oil consumption and oil ash content combined with tuning parameters, such as the oil ash transfer rate (ash emissions divided by oil consumption and oil ash content). Controlled engine tests have been performed to verify assumptions and fill knowledge gaps. The model can be applied to a variety of diesel engines, although the tuning factors might have to be reset. For example, introducing diesel particulate filters would dramatically reduce the oil ash emissions, since oil ash would accumulate in the filter.

Oil consumption has played a central role in the present research. The modelling results indicate that special attention should be paid to oil consumption under running conditions with a low in-cylinder temperature, since the oil survival rate is high there.

Under low-load and motoring conditions, hydrocarbons proved to be the main contributor to oil-related particulate emissions. At high engine load, oil ash emissions were the largest contributor to oil-related particulate emissions.

Keywords: Lubrication oil; Particulate emission; Particulate matter (PM); Oil consumption; Diesel engine
Preface

The research presented here was performed at the Department of Machine Design at the Royal Institute of Technology (KTH), Stockholm, Sweden and at Scania CV AB in Södertälje, Sweden. The project began in 2005 and many colleagues at both Scania and KTH have contributed to the results. I would like to take the opportunity to thank all my colleagues who made this project possible. In particular, I owe special gratitude to:

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Scania CV AB for funding the project, with support from Programrådet för fordonsforskning (PFF) and the Swedish Energy Agency.

Finally, I would like to thank Charlotte for all her cheerful comments over the years and for becoming my wife (hence, the changed surname on the publications).

Stockholm, September 2010

Petter Tornehed
List of appended papers

This thesis consists of a summary and the following six appended papers:

Paper A

Paper B

Paper C

Paper D

Paper E
Tornehed, P. The contribution of oil to carbon particle emissions from diesel engines. Royal Institute of Technology, KTH, Trita-MMK 2010:04, ISSN 1400-1179, ISRN/KTH/MMK/R-10/04-SE.

Paper F
Johansson, P. Impact of sulphur on particulate matter, paying special attention to the lubricant: Based on a literature review. Royal Institute of Technology, KTH, Trita-MMK 2009:14, ISSN 1400-1179, ISRN/KTH/MMK/R-09/14-SE.
Division of work between authors

The research presented here was initiated by Henrik Willstrand (Scania) and supervised by professors Sören Andersson (KTH) and Ulf Olofsson (KTH) with assistance from professor Hans-Erik Ångström (KTH).

The research presented in the appended papers was performed by Tornehed under the supervision of Andersson or Olofsson. Andersson, Olofsson, and Ångström guided me through the research process.
List of publications not included in this thesis

Licentiate thesis


Papers appended to licentiate thesis


Other publications


Abbreviations and nomenclature

PM = particulate matter
PM$_{10}$ = particulate matter with an aerodynamic diameter below 10 µm
PM$_{2.5}$ = particulate matter with an aerodynamic diameter below 2.5 µm
NOx = nitrous oxides
SOF = soluble organic fraction
VOF = volatile organic fraction
VOC = vapour oil consumption
LOC = liquid oil consumption
EPR = AVL EXCITE Piston and Rings
DPF = diesel particulate filter

The piston rings and piston ring area are referred to according to Figure 1.

![Diagram](image-url)

*Figure 1. Nomenclature of the ring area of the piston*
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Appended papers

A. Variations in piston second land pressure as a function of ring gap position
B. Modelling lubrication oil particulate emissions from heavy-duty diesel engines
C. Towards a model for engine oil hydrocarbon particulate matter
D. Modelling of lubricant ash particles in diesel engine exhaust
E. The contribution of oil to carbon particle emissions from diesel engines
F. Impact of sulphur on particulate matter, paying special attention to the lubricant
1 Introduction

The work presented here represents the results of the project “Oil-related particle emissions”. The participating partners have been Scania CV AB and the Department of Machine Design at the Royal Institute of Technology (KTH). The project was funded by Scania CV AB with support from Programrådet för fordonsforskning (PFF) and the Swedish Energy Agency.

The main purpose of the project was to improve our knowledge of how lubrication oil contributes to particulate emission from diesel engines.

1.1 Background

Particulate matter (PM) consists of tiny solid and liquid particles originating from both natural (e.g., volcanoes, forest fires, and dust storms) and anthropogenic sources (e.g., burning fuels in vehicles and power plants). The impact of on-road transportation on particle mass and particle number concentration in urban areas is well acknowledged, Charron [1]. On-road PM emissions come not only from engine exhaust, but also originate from brakes, tires, and road surfaces (including the resuspension of road dust); an additional contribution comes from secondary particles formed in the atmosphere.

Abu-Allaban et al. [2] have demonstrated that the largest amount of vehicle-derived PM$_{10}$ (particles with an aerodynamic diameter below 10 μm) comes from road dust, while for PM$_{2.5}$ (particles with an aerodynamic diameter below 2.5 μm), tailpipe emissions were the largest contributor. Gehring et al. [3], studying PM$_{10}$, found the levels of abrasion particles (wear particles from, e.g., brakes, tires, and road) and resuspension particles to be in the same range as exhaust particles; at locations with disturbed traffic (e.g., traffic lights), the abrasion and resuspension particles were even more prominent than the exhaust particles. Furusjö et al. [4], analysing PM$_{10}$, found that roadside PM was dominated by long-range transported particles. In urban street “canyons”, resuspended, vehicle-derived, and long-range transported particles dominated. Querol et al. [5] found the traffic (including from exhaust and abrasion) contribution to PM at kerbside to be 35–55% for PM$_{10}$ and 40–60% for PM$_{2.5}$. The industry contribution was 15–25% for PM$_{10}$ and approximately 20% for PM$_{2.5}$ [5].

Exhaust particulate emissions can be modelled at many levels, and the choice of model should depend on the purpose of the study. For example, the exhaust particulate emissions from vehicles on a certain road have been assessed by Sjödin et al. [6] using the ARTEMIS road model (Assessment and Reliability of Transport Emission Models and Inventory System) developed by the EU [7, 8]. This model assesses the particulate emissions from traffic by analysing driving patterns for a wide range of vehicles. From an engine development perspective, soot particle formation is often a concern. Hiroyasy et al. [9] presented a two-step model in which the change in soot particle mass is the difference between soot production and oxidation. Such a model can be incorporated into computational fluid dynamics (CFD) calculations. The Hiroyasy et al. [9] two-step
model has been expanded into a multi-step model, for example, by Kitamura et al. [10] and Tao et al. [11], to better explain the soot kinetics. Generally, CFD modelling is time consuming and the results depend greatly on the tuning of the model. One way to reduce the computational time is not to use CFD, but instead use a multi-zone model, as done by Westlund et al. [12].

1.2 Diesel engine particulate emissions

Reducing PM emissions from diesel engines has been a priority of engine developers in recent decades. For example, when the Euro 1 standards for heavy-duty trucks was introduced in Europe (1992), the PM limit was 0.36 g/kWh [13]; with the introduction of the Euro 4 standards (2005), the PM limit was reduced to 0.02 g/kWh) [14]. A further reduction to 10 mg/kWh has been determined for 2013 (Euro 6) [15]. The Euro 6 legislation will probably also include particle-number regulations. Concurrent with the reduction in PM emissions, nitrous oxide (NO\textsubscript{x}) emissions have also been reduced (Figure 2).

![Figure 2. Development of the European emissions legislation [13–16]](image)

Particulate emissions from diesel engines can originate from both the fuel and the lubrication oil. Particulates are often divided into a solid fraction (consisting of carbon and ash), a liquid fraction (often referred to as SOF or VOF, i.e., soluble organic fraction or volatile organic fraction, respectively), and sulphates with water. During rich combustion, solid carbon is formed and the ash produced originates mainly from additives in the lubrication oil. The SOF/VOF comprises hydrocarbons from the fuel and lubricant that have not fully oxidized. Sulphur oxidation leads to the formation of sulphates and sulphuric acid, which are hydroscopic. The relative composition of the particulate matter from an American mid 1990s heavy-duty engine is shown in Figure 3.
Reducing particulate emissions from diesel engines has traditionally been synonymous with reducing the emissions of fuel-associated particles. Common measures used to do this include reduced fuel sulphur content, improved fuel injection systems, and improved air handling. As fuel-derived PM is reduced, the relative contribution of lubricant to PM will increase if it is not properly dealt with.

1.3 Diesel particle size distribution

Diesel particulate emissions are classified into accumulation mode and nucleation mode particles, the former including most of the particle mass and the latter most of the particle number (Kittelson [17]). The accumulation mode usually consists of carbon agglomerates of hydrocarbons and sulphate species with typical particle diameters of 100–300 nm [17]. Figure 4 clearly shows how particles have agglomerated and been caught on a measurement filter. The nucleation mode consists mainly of hydrocarbons and sulphates, but may also contain carbon and metal, with typical particle diameters of 5–50 nm [17].
Kittelson et al. [19] report the existence of nucleation mode particles formed from ash as well, their formation is conditioned by a sufficiently high metal-to-carbon ratio.

1.4 Purpose, outline, and limitations of the thesis

This thesis mainly seeks to increase our understanding of the process by which oil-related particles are created. Improved understanding will enable improved simulation capabilities, making engine development less dependent on timely and costly engine tests. Improvised simulation capability will be realised here by developing a model for modelling oil-related particulate emissions.

During the project, several engine tests were conducted, simulation work was performed, and the results combined with those of other authors when reviewing related work.

The work was conducted in a context in which diesel engines without exhaust after treatment are paid the most attention; the current Euro 5 legislation is often used as basis for discussion and for comparison when estimating oil-related particulate emissions.

2 Sources of oil consumption in diesel engines

The sources of oil consumption in diesel engines are the:

- turbo charger
- valve stem seals
- crank case ventilation
- cylinder system

Fairly early in the project, it was demonstrated that the cylinder system is normally the largest contributor to oil-related particles if best-known, commonly available technology is used [18]. In-cylinder oil consumption can be categorized as follows [18]:

- **throw-off**, when oil is driven towards the combustion chamber by inertia forces (Figure 5a)
- **reverse blow-by**, when gas-containing oil is driven by pressure to flow towards the combustion chamber (Figure 5b)
- **evaporation** from hot surfaces (Figure 5c)
- **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 5d)
The above in-cylinder oil consumption categorization is derived from Yilmaz et al. [20] and Herbst and Priebsch [21]. Yilmaz et al. [20] use the terms throw-off, transport with reverse gas flow, and evaporation, while Herbst and Priebsch [21] divide the in-cylinder oil consumption into evaporation, oil throw-off, reverse oil blow, and oil scraping by the piston top land.

The SAE Piston and Rings Standards Committee [22] uses a very similar approach but different terms:

- liquid oil consumption, oil that is scraped, flowing or being squeezed around the ring
- oil vaporization
- oil in mist

Liquid oil consumption corresponds to throw-off, vaporization to evaporation, and oil in a mist to reverse blow-by.

Mihara et al. [23] suggest dividing the in-cylinder oil consumption into vapour oil consumption (VOC) and liquid oil consumption (LOC) and assume that the oil consumed via VOC consumes no lubricant ash as the oil evaporates from the cylinder liner and the ash is scraped down, enriching the oil ash. In contrast, LOC is assumed to consume ash at the same rate as oil.
3 Modelling oil-related particulate emissions

When discussing oil-related particles, often only the oil-related hydrocarbons fraction is referred to. The present work uses a broader approach in which the contribution of oil not only to the hydrocarbons, but also to the ash, sulphate, and carbon particles is examined.

A model (Figure 6) was developed during the project. The model contains sub-models of the HC, ash, sulphates, and carbon particles. Typical inputs to the models are oil consumption, oil ash, and sulphur levels.

![Conceptual model of predicted oil-related particulate emissions](image)

Figure 6. Conceptual model of predicted oil-related particulate emissions; figure from paper C.

The variables in the model are divided into input and tuning parameters. Examples of input parameters are oil consumption and oil ash content. The oil ash transfer rate is an example of a tuning parameter and is defined as oil ash particulate emissions divided by calculated oil ash consumption (oil consumption times the oil ash content).

The models are literature based and have been complemented by experimental results where necessary. The models are designed for engines without exhaust after treatment; the current Euro 5 legislation is often used as a basis for comparison in the discussions.
4 Contributions

This thesis comprises six appended papers (Appendices A–F), the main scientific contributions of which are summarized below:

In paper A, modelling results indicate that ring gap rotation induces considerable variation in inter-ring pressure and piston ring movement under steady-state conditions. When using an experimental setup (also suitable for other engines) developed by the author, considerable variations in inter-ring pressure over time were evident even under steady-state engine conditions. The inter-ring pressure measurement setup could easily be used in other engines, since the only special part needed is a cylinder liner equipped with pressure sensors.

Paper B develops a novel model of oil-related particle emissions. The model summarizes the contribution of lubrication oil to the hydrocarbon, ash, carbon, and sulphate particle fractions; the parts of the model are compared with each other. Applying the model shows that low-load and motoring conditions constitute an area in which achieving low oil consumption should be prioritized. The model is a suitable tool for engineers working on reducing oil-related particle emissions.

Paper C develops a model of the survival of oil hydrocarbons. The survival rate is modelled using crank angle-resolved in-cylinder temperature and oil consumption. Measurements of the oil survival in a Euro 5 engine without exhaust after treatment were made and used to tune the model. Fast oil consumption measurements were facilitated by using a sulphur trace technique.

Paper D summarizes the oil ash transfer rate as found in the literature, finding large variations from study to study. The oil ash emission model derived from the literature was tuned using the results of engine tests in which ash was accumulated in diesel particulate filters. Engine tests indicated that the oil specifications greatly influenced the oil ash transfer rate. The expected influence of engine load derived from the literature could not be verified by engine testing.

Paper E estimates the oil carbon particle emissions from a modern diesel engine. The estimate is based on literature findings and measurements made by others; theory is combined with the history of emission legislation development to yield a model for predicting oil carbon particle emissions.

Paper F estimates the oil sulphate and water particle emissions from a diesel engine, based on findings from the literature.

* Oil ash transfer rate is defined as oil ash emission divided by calculated oil ash consumption (oil consumption times oil ash content).
5 Summary of appended papers

This thesis comprises six appended papers (Appendices A–F), selected parts of which are referred to in this chapter.

5.1 Variations in piston second land pressure as a function of ring gap position (paper A)

The pressure build-up between the piston rings is a key parameter affecting the movement of piston rings in their grooves. It can greatly influence blow-by and oil consumption, and thereby also oil-related particulate emissions, and has therefore attracted the attention of several researchers.

There are two main ways of measuring the inter-ring pressure: pressure sensors can be placed either on the moving piston or in the stationary cylinder. Yilmaz et al. [20] and Johansson [24] placed the sensor in the cylinder, while Herbst and Priebsch [21], De Petris et al. [25], Furuhama et al. [26], Iijima et al. [27], Tamminen et al. [28], Truscott et al. [29], Dursunkaya et al. [30], and Miyachika et al. [31] placed the sensors in the piston. Richardson [32] and Chen and Richardson [33] used a combination of both sensor positions.

In paper A, inter-ring pressure is measured by placing the pressure sensors in the (stationary) cylinder liner, according to the setup previously presented by Johansson [24], Figure 7.

![Figure 7. Cylinder liner prepared for inter-ring pressure measurement; figures from paper A](image)

The second land (the piston land between the top ring and the second ring) pressure measurements in paper A indicate low cycle-to-cycle variations, though variation over time was evident. The piston ring rotation, which results in varying ring gap positions, was considered worth examining in simulations, to determine whether it explains the differences in pressure recorded over time.

Based on the experimental work and on simulations using AVL EXCITE Piston and Rings software, paper A concludes that the second land pressure varies considerably over
time and that those variations can be explained by the calculation results when varying
the ring gap positions. The variation in second land pressure also induced variation in the
movement pattern of the top ring.

This is in line with the findings of Chen and Richardson [33], who state that “a small
difference in pressure predictions can sometimes cause a completely different ring
motion”. Min et al. [34] report cyclic variation in oil consumption due to piston ring
rotation, with maximum values of 3–4 times the minimum value.

The following can cause the differences in second land pressure demonstrated to occur
when changing the ring gap position:

- piston secondary motion
- piston land ovalities
- bore distortion

The above factors will influence the volumes of gas flowing through the ring pack, and
the precise areas where this occurs, and thus the second land pressure and the pressure
gradient over the top ring.

5.2 Modelling lubrication oil particulate emissions from heavy-duty diesel
ingines (paper B)

Paper B aims to develop a model (Figure 6) for predicting oil-related particulate
emissions from heavy-duty diesel engines based on the contributions of hydrocarbons,
ash, carbon, and sulphate with water particles (papers C–F).

The total oil-related particulate emissions are the sum of the models presented in papers
C–F and applied to a Euro 5 engine without exhaust after treatment:

\[ PM_{Oil} = PM_{Oil, HC} + PM_{Oil, Ash} + PM_{Oil, Carbon} + PM_{Oil, Sulphate + H2O} \] (1)

The oil-related hydrocarbon particulate emissions are estimated using a linear relationship
in which oil consumption is multiplied by the oil survival rate (SRHC):

\[ PM_{Oil, HC} = Oil\ consumption \times SR_{HC} \] (2)

The oil ash emissions are estimated using a linear relationship with the calculated ash
consumption (oil consumption times oil ash content), which is multiplied by a transfer
rate (TROil,Ash):

\[ PM_{Oil, Ash} = \frac{Oil\ consumption \times Oil\ ash\ content \times TR_{Oil, Ash}}{Calculated\ ash\ consumption} \] (3)

The carbon particulate emissions (soot) associated with oil consumption are estimated by
taking a fraction (oil fraction of carbon) of the total carbon particulate emissions
(PMCarbon,Total):

\[ PM_{Oil, Carbon} = PM_{Carbon, Total} \times Oil\ fraction\ of\ carbon \] (4)
The sulphate with water particulate emissions from the oil are estimated using linear relationships in which the oil consumption and oil sulphur content are multiplied by a transfer rate (\(T_{\text{Oil, Sulphur}}\)):

\[
PM_{\text{Oil, Sulphate+H}_2\text{O}} = \text{Oil consumption} \times \text{Oil sulphur content} \times T_{\text{Oil, Sulphur}}
\]  

(5)

The model is demonstrated and input data and tuning parameters are chosen to reflect wise but not extreme choices for minimizing oil-related particulate emissions.

Even though the input data for the model were chosen for low oil-related particulate emissions, the study concludes that the oil has a significant impact on total exhaust particulate emissions, especially under low-load and motoring conditions. Oil ash particulate emissions are also worth examining, since they were the largest contributor to oil-related particulate emissions at high engine loads.

The response study of the model indicates that the oil consumption and oil survival rate (survival of hydrocarbons) have the largest impact on total oil-related particulate emissions.

5.3 Towards a model for engine oil hydrocarbon particulate matter (paper C)

The fraction of exhaust particulate emissions often referred to as oil-related particles comprises unburnt hydrocarbons.

Several studies (Essig et al. [35], Andrews et al. [36], Inoue et al. [37], Shore [38] and Kawatani et al. [39]) have reached similar results, finding that low engine load promotes high oil survival. In addition, Inoue et al. [37] point out: “oil consumed upstream of the combustion chamber is easily burned, while oil consumed in the exhaust regions is largely converted to PM”. Essig et al. [36] found a nearly linear relationship between oil-related particles and oil consumption when altering oil consumption by changing the cylinder components. This linearity between oil-related hydrocarbon particulate emissions and oil consumption has been used here and is later described as the oil survival rate.

Paper C proposes modelling the survival of in-cylinder oil using crank angle-resolved oil consumption combined with cylinder temperature. The model has been tuned to predict the measured oil survival rate with reasonable accuracy (Figure 8 and Figure 9), for a Scania engine originally developed to fulfil the Euro 5 criteria without exhaust after treatment.
Oil consumption was measured using a sulphur trace technique, which relies on low-sulphur fuel and a relatively high oil sulphur content. Given known sulphur levels and fuel consumption combined with measured SO$_2$ emissions, the oil consumption can be calculated (Figure 10). This method has the advantage of relatively short measuring times, which enable oil consumption mapping (Figure 11). Please note that the oil consumption values in Figure 11 have been normalized by the maximum value (in g/h) measured in paper C.

The oil-related hydrocarbons were measured by capturing PM on filters analysed using gas chromatography. Given known oil consumption and levels of oil-related hydrocarbon particles, the oil survival rate could be calculated.

5.4 Modelling of lubricant ash particles in diesel engine exhaust (paper D)

The introduction of diesel particulate filters (DPFs) has increased interest in assessing exhaust ash emissions. The ash accumulates in the DPF, where it increases the exhaust back pressure and thereby also the fuel consumption, since the ash is not removed when
the filter is regenerated. The ash accumulation can eventually lead to costly filter cleaning or replacement.

Paper D concludes that, with today’s technology, lubrication oil is the dominant source of ash emissions.

Paper D models ash emissions using a linear relationship in which the calculated ash consumption (oil ash content times oil consumption) is multiplied by a transfer rate (\(\text{TR}_{\text{ash}}\)). The linearity is justified by the findings of Givens et al. [40] and Bardasz et al. [41], who found good linear correlation between ash emissions, oil ash content, and oil consumption.

Ash transfer rates (defined as ash emissions divided by oil consumption and ash level) reported in the literature and summarized in paper D range from 20% to 70%. This wide range of reported ash transfer rates prompted engine tests to establish the transfer rate in a Scania engine. The ash was accumulated in DPFs and the oil consumption was measured using the engine dipstick.

To promote oil consumption per time unit, high engine speed and load were chosen. The low-ash oil clearly displayed a lower oil ash transfer rate than did the high-ash oil (Figure 12). The low-load test was run to determine whether there is a clear difference in ash transfer rate between high-load and low-load oil consumption. This could be the case if there is a principle difference between liquid oil consumption (LOC) and vapour oil consumption (VOC), as could be inferred from Mihara et al. [23]. The slight increase in ash transfer rate when reducing the engine load (Figure 12) indicated that the oil ash transfer rate might be load dependent, even though the effect was clearly smaller than that of the changing oil. The reduction in oil ash emissions when running the low-ash oil is larger than could be anticipated from Figure 12, since the specific ash emissions are defined as the ash transfer rate times the oil ash content times the oil consumption.

![Figure 12. Oil ash transfer rate; figure from paper D](image-url)
5.5 The contribution of oil to carbon particle emissions from diesel engines (paper E)

The particulate emissions most strongly associated with diesel combustion are the carbon particles often referred to as soot. The soot is created during the typical diesel diffusion flame combustion, in which the fuel is combusted under oxygen deficiency. The equivalence ratio, $\phi$, describes the fuel-to-air ratio; an equivalence ratio over one indicates oxygen deficiency, below one indicates excess oxygen.

Akihama et al. [42] presented maps, such as Figure 13, to illustrate soot formation rate as a function of local temperature and equivalence ratio. Akihama et al. [42], using n-hexane as fuel, found maximum soot production at ~2000K. Others using the same methodology have often found maximum soot formation rates shifted towards lower temperatures. For example, Charlton [43] demonstrated maximum soot formation at ~1500 K.

![Figure 13. Soot formation rate dependency on local temperature and equivalence ratio, based on Akihama et al. [42]; figure from paper E](image)

Paper E summarizes the diesel soot formation theories of Haynes and Wagner [44] and Frenklach [45] as follows:

- **particle inception**: the first soot particles arise from condensed material, typical diameter <20Å
- **surface growth**: gas-phase species adhere to the surface and increase the particle mass; this is where most of the solid phase is generated, the number of particles remaining constant but the mass increasing
- **particle coagulation**: the particle size increases by either coalescence or agglomeration, the total particle mass remaining constant while the particle number decreases
- **soot oxidation**
The surface growth is where the bulk of the (solid) soot particles is formed [44]. The end product of soot leaving the cylinder will depend on the balance between the formation and subsequent oxidation of soot particles.

Studies of the contribution of oil to soot particles are summarized in paper E (Figure 14). Hilden and Mayer [46], Buchholz et al. [47], and Schneider at al. [48] have all used $^{14}$C methods to distinguish between carbon particles from the lubricant or the fuel. In the method, either the lubricant is doped with $^{14}$C [46, 48] or a biodiesel [47] is used to obtain $^{14}$C levels distinguishing between fuel or oil carbon particles.

\[ \text{Figure 14. Oil contribution, with one standard deviation, to soot/carbon particulate emissions depending on engine build year and fuel; figure from paper E} \]

Notably, Schneider et al. [48] found that fuel was still the main contributor to soot particles, even when a spark-ignited port-injected gasoline engine was used. Such engines are generally accepted as not having a soot problem. Or as Heywood [49] states: “In properly adjusted spark-ignited engines, soot in the exhaust is not a significant problem”.

Paper E uses a maximum/minimum approach, graphically presented in Figure 15, to assess the oil soot particulate emissions:

1. The maximum limit is given by the oil consumption and carbon content in the lubrication, resulting in 0.17 g/kWh.

2. The maximum limit (from 1) is well above the PM limit for the Euro 4/5 standards, which can be met without exhaust after treatment [50]. The Euro 4/5 PM limit is therefore a better maximum limit.

3. Assume the same transfer rate into soot (soot emissions divided by available carbon in fuel or oil) as for fuel. This provides a minimum estimate (~10 μg/kWh), since it can be concluded from the $^{14}$C [46–48] measurements that the oil contributes relatively more to soot than its mass proportion to fuel.

4. The most recent diesel engine study reported in Figure 14 is that of Buchholz et al. [47], who found a 4% oil contribution to soot. Applying this figure to a
modern diesel engine meeting Euro 4/5 standards without exhaust after treatment leads to oil carbon particles of 0.4 mg/kWh (minimum estimate).

5. The Buchholz et al. [47] study was performed on a 1993 year engine; applying the emission standards of that time leads to oil carbon emissions of 6.7 mg/kWh (upper estimate).

6. The highest oil contribution to soot shown in Figure 14 is 11%, as reported by Schneider at al. [48], who studied a port-injected spark-ignited gasoline engine. Applying the 11% from Schneider at al. [48] in the same manner as in (4) results in oil carbon emissions of 1.1 mg/kWh (upper estimate).

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In paper E it is concluded: “The oil contribution to carbon particles for a Euro 5-compliant heavy-duty diesel engine (without exhaust after treatment), based on the present study, is estimated to be 0.4–1.1 mg/kWh.”

5.6 Impact of sulphur on particulate matter, paying special attention to the lubricant (paper F)

The impact of sulphur on particulate emissions has long been known. Paper F offers a comprehensive summary of the impact of fuel sulphur on PM from diesel engines.

A part of the fuel, sulphur ends up as sulphates. The sulphur is oxidized or burned, creating sulphur dioxide (SO$_2$), which is further oxidized to sulphur trioxide (SO$_3$). The SO$_3$ combines with water and forms sulphuric acid aerosol (H$_2$SO$_4$) (Heywood [49]). The sulphuric acid (H$_2$SO$_4$) is hygroscopic, so water will add to the PM weight. The SAE Handbook [51] estimates the relationship with relative humidity (RH) as almost exponential, and at RH 50% and 25°C, 1.32 g of H$_2$O is associated with every gram of H$_2$SO$_4$. The sulphuric acid/sulphate production is roughly proportional to the sulphur content of the fuel, Kittelson [17].

Paper F summarizes the “Diesel Emission Control–Sulfur Effects (DECSE) Program” [52, 53], along with studies by Wall and Hoekman [54], Wall et al. [55], Baranesescu [56], and Yost et al. [57]. The main conclusion is that for every gram of sulphur in the fuel,
PM increases by 0.15 g, corresponding to 2% of the available sulphur giving rise to sulphates. Hence there is a 50-fold potential for increasing sulphate emissions if all available fuel sulphur gives rise to sulphates. Oxidation catalysts can promote the SO$_2$ to SO$_3$ conversion and thereby increase the sulphate particles (Heywood [49]).

Lubrication oil is less involved in the combustion; it is therefore less prone to produce SO$_3$ and thereby also less prone to produce sulphates. Hence, using the same sulphur transfer rate for oil as for fuel overestimates, rather than underestimates, the oil-related sulphate and water emissions.
6 Discussion

This thesis and the appended papers establish a foundation for modelling oil-related particulate emissions. The model includes not only oil-related hydrocarbon particulate emissions, but also the ash, carbon (soot), and sulphates with water particles. Use of the model is demonstrated on a heavy-duty diesel engine designed to meet Euro 5 PM standards without exhaust after treatment. In this project, the oil-related particulate emissions are mainly modelled using linear relationships with oil consumption. The difference between oil consumption and oil-related particulate emissions is described by the oil survival rate for the hydrocarbons; transfer rates for the ash and sulphur and the carbon particles are defined as percentages of the total carbon particulate emissions.

The model offers a tool suitable for assessing the oil-related particulate emissions during an engine development process. It can be used to pinpoint areas in which further development is needed. In this case (i.e., a Euro 5 heavy-duty diesel engine without exhaust after treatment), the modelling results clearly indicate the importance of low oil consumption under low-load and motoring conditions to minimize the oil-related particulate emissions.

Previous models for predicting oil-related particulate emissions have not been found in the literature. The closest to such a model found is reports of a linear relationship between oil-related HC particles when changing the oil consumption by altering in-cylinder components (Essig et al. [35]) and linear relationships between ash emissions and oil consumption and oil ash content (e.g., Givens et al. [40] and Bardasz et al. [41]). Modelling soot formation from diesel combustion is a fairly popular task. One way to do this is to use the two-stage model of Hiroyasy et al. [9], in which the change in soot particle mass is the difference between soot production and oxidation. More refined soot models, for example, those of Kitamura et al. [10] and Tao et al. [11], explain the soot kinetics better. Soot models are often incorporated into computational fluid dynamics (CFD) calculations, resulting in time-consuming computations heavily dependent on the model tuning. Westlund et al. [12] uses a multi-zone model to calculate fuel soot and thereby do not need to use CFD, which speeds up the calculations.

A general emission model, the ARTEMIS road model (Assessment and Reliability of Transport Emission Models and Inventory System), developed by the EU [7,8] and used by Sjödin et al. [6], was developed for other purposes than engine development and is more suitable for assessing the emissions from a fleet of cars in a traffic environment. This could be of great interest when assessing the environmental impact of a planned road.

The models discussed above are all intended for modelling particles, but at various levels from a detailed level of soot formation inside the engine cylinder to a global level at which the emissions from fleets are assessed. The model of oil-related particles presented here is at an intermediate level suitable for use as an engineering tool at a system level for engine development.
6.1 Oil consumption

Oil consumption plays an important role in creating oil-related particles and has been central to this project.

The model presented in Figure 6 relies on good oil consumption data. Various techniques have been used in the project to assess oil consumption. Paper C uses a sulphur trace technique and paper D uses the dipstick technique. The sulphur trace technique has one very large advantage, namely, its short measurement times, enabling oil consumption maps such as Figure 11. It has two disadvantages that must be dealt with: complex system handling, making the involvement of a dedicated engineer almost essential, and sensitivity to fuel sulphur level. Just using a certification diesel with a sulphur level below 10 ppm is not enough for accurate measurements. Offsetting the fuel sulphur level of 1 ppm will influence the oil consumption measurements by roughly 20%. In contrast, dipstick measurements are easy to perform, resemble the customer experience, but are time consuming to perform.

EXCITE Piston and Rings (EPR) from AVL can be used to calculate piston secondary motion, piston ring dynamics (including ring movement), and gas flows through the piston ring pack; the program also contains an oil consumption module. Internal work at Scania has achieved success when using the ring dynamics module in EPR. The oil consumption module, on the other hand, has not been completely satisfactory. Therefore, a masters thesis [58] aimed at building an oil transport model from the output from the ring dynamics calculations was part of this project.

The measurements presented in Paper A indicate large differences in second land pressure over time even under steady-state running conditions. Calculations in which the ring gap positions have been rotated indicate inter-ring pressure, and the top ring movement pattern can be greatly affected. The sensitivity of the piston ring pack has previously been pointed out by Chen and Richardson [33], who state that “a small difference in pressure predictions can sometimes cause a completely different ring motion”. In addition, Min et al. [34] report a cyclic variation in oil consumption due to piston ring rotations, with maximum values of 3–4 times the minimum value. An oil consumption increase of 3–4 times will have a major impact on oil-related particulate emissions.

6.2 The difference between oil consumption and oil-related particulate emissions

The difference between oil consumption and oil-related particulate emissions is described by the oil survival rate for the hydrocarbons, transfer rates for the ash and sulphur, and the carbon particles defined as a percentage of the total carbon particulate emissions.

The impact of oil consumption on oil-related particulate emissions has been long known; for example, Essig et al. [36] found a nearly linear relationship between oil-related particle emissions and oil consumption when altering oil consumption by changing in cylinder components. Efforts in paper C to develop a model able to predict the oil survival rate
ended up in a model in which crank angle-resolved oil consumption is combined with in-cylinder temperature. Measurements (and modelling) indicate that the oil survival rate reached its maximum under motoring conditions (Figure 8 and Figure 9), dominating the total oil-related particulate emissions under low-load and motoring conditions, i.e., when the cylinder temperature is low. The finding of maximum oil survival under low-load and motoring conditions is in line with the findings of others, such as Essig et al. [35], Andrews et al. [36], Inoue et al. [37], Shore [38], and Kawatani et al. [39], all of which indicate that low engine load promotes high oil survival.

At high load, the hydrocarbons are burnt and the oil ash emissions are the largest contributor. The linear relationships between ash emissions and oil consumption and oil ash content in the model are justified by the findings of Givens et al. [40] and Bardasz et al. [41], who clarified such a relationship. The ash transfer rate (oil ash emissions divided by calculated oil ash consumption) has shown itself to be a parameter worth looking into. The tests in paper D indicate that the choice of oil additive package could influence the oil ash emissions, by changing not only the oil ash level but also the transfer rate. A tendency for increased oil ash transfer at low load was also noted, even though the tendency was clearly smaller than the influence of changing the oil additive package. The measured ash transfer rates presented in paper D (38–59%) are well in line with the transfer rates summarized from the literature, i.e., 20% to 70%.

The oil contribution to carbon particulate emissions (soot) has previously been studied by Hilden and Mayer [46], Buchholz et al. [47], and Schneider at al. [48], who used $^{14}$C methods to distinguish carbon particles from the lubricant or the fuel, see Figure 14. Paper E reviews soot formation theories, combining them with the findings of Hilden and Mayer [46], Buchholz et al. [47], and Schneider at al. [48] to assess the oil contribution to carbon particulate emissions. In paper E, oil contribution to carbon particles are estimated to be 0.4-1.1 mg/kWh.

A linear or almost linear relationship between fuel sulphur level and sulphate emissions is well known and reported by, for example, Kittelson [17]. Paper F examines this linearity by reviewing and summarizing studies in the field. The findings are then used to assess a maximum estimate of the oil-related sulphate emissions. Even though the sulphate emissions from the oil were overestimated, they were the smallest of the modelled fractions (see paper B).

6.3 Generalization and development of the oil-related particles model

The model presented here is demonstrated in a context in which oil-related particulate emissions are calculated for a heavy-duty diesel engine meeting the Euro 5 PM standards without exhaust after treatment. The main setup of the model, in which oil consumption is multiplied by input and tuning parameters, could be employed for similar engines. The tuning parameters for the hydrocarbon survival rate would likely have to be reset to match the particular engine. For engines with exhaust after-treatment devices (as many Euro 6 engines will likely have), the tuning parameters will have to be reset or complemented by a transfer rate for the device. In cases in which DPFs are used, the
new transfer rate for oil ash to PM would be zero or almost zero. The new tuning parameters could be divided to illustrate what comes into the exhaust after-treatment device and what comes out.

In line with improved knowledge of the factors influencing oil-related particulate emissions, the model offers a versatile foundation for further development. For example, a load and engine speed-dependent ash transfer rate could easily be incorporated in the same manner as the oil survival rate for HC. This would be justified if a clear difference were found in ash transfer rate depending on the relationship between vapour oil consumption (VOC) and liquid oil consumption (LOC), as inferred from Mihara et al. [23]. Such information could be useful when calculating ash accumulation DPFs. At this stage, finding the overall ash transfer rate for a particular oil and engine combination would be more important, since it has a larger impact on oil ash emissions; however, when that factor is well established, fine tuning with load dependency could easily be incorporated into the model.
7 Conclusions

This thesis deals with the oil contribution to exhaust emissions from heavy-duty diesel engines. A model able to predict oil-related particulate emissions has been developed and demonstrated. Some of the findings of the research are worth highlighting:

- Oil consumption is the single most important factor in reducing oil-related particulate emissions.
- Special attention should be paid to oil consumption under running conditions with low in-cylinder temperature when optimizing oil consumption for low PM emissions.
- Natural variations over time, even under steady-state conditions, in inter-ring pressure (and thereby piston ring movement), blow-by oil consumption, and therefore also oil-related particulate emissions should be anticipated when making such studies.
- The expected load dependency on the oil ash transfer rate,† obtained from the literature, could not be verified.

† Oil ash transfer rate is defined as oil ash emission divided by calculated oil ash consumption (oil consumption times oil ash content).
8 References


[38] Shore, P.R. “Advances in the use of tritium as a radiotracer for oil consumption measurements”. SAE Paper 881583, 1988.


