Filtration of soot-in-oil aerosols:

Why do field and laboratory experiments differ?

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Abstract:

This work has investigated the impact of different oil ageing mechanisms which typically occur in diesel vehicles (thermooxidative breakdown and particle contamination) on engine lubricant properties and their subsequent influence on the filtration of the combined or colloidal (i.e. solid and liquid particles) aerosol, using fibrous filters. Oil viscosity was found to increase with increasing soot contamination and decrease with thermooxidative breakdown of the oil. Filtration tests showed that the pressure drop across the filter correlated strongly with oil viscosity and increased linearly with increasing soot content in the oil. Concurrent to the laboratory work, a field test using 15 diesel vehicles was conducted. The vehicles were equipped with test filters identical to the laboratory test filters and were used for approximately 6 months without oil change. The filters were then analysed and it was found that the final pressure drop also increased linearly with the soot content in the filter. A comparative analysis showed a good agreement in pressure drop, filter saturation and filter efficiency between laboratory and field test filters, for similar soot contents.

It was found that the use of artificial oil ageing, combined with a discontinuous filtration method developed previously allowed reproduction (in the laboratory) of the filtration processes which occur in vehicle closed crankcase ventilation (CCV) systems. This therefore allowed "realistic" CCV tests to be conducted in a laboratory.

It is hoped that this work will, at least partially, bridge the gap between laboratory and field filtration studies, as well as improving the knowledge of "colloid" or "soot-in-oil" aerosol filtration, which to-date has received limited study.

Nomenclature

<u>Indices</u>

actual　　　　actual value

experimental　experimentally determined value

Filter　　　　of the filter

EQ1　　　　at first equilibrium state

EQ2　　　　at second equilibrium state

N　　　　　normalized

Oil　　　　of the oil

<u>Greek letters</u>

α_i　　　　Bayesian regression coefficients

ΔP　　　　filter pressure   drop

$\nu_{40°C}$　　　　kinematic viscosity (measured at 40 °C)

μ_i　　　　mean value of the Normal distribution

σ　　　　standard deviation

Latin letters

b_1, b_2	constants
Bypass	variable (boolean) if test vehicle was equipped with an oil bypass centrifuge
E	filter efficiency
c_{Soot}	soot content in the oil
$m_{Filter,0}$	initial mass of the clean filter
m_{Inert}	mass of the inert matter after heating
m_{Oil}	mass of oil held in the filter
$m_{Oil,max}$	maximum oil holding capacity (mass) of the filter
m_{Sample}	mass of the filter media sample strip
m_{Solid}	mass of the filter media sample strip after oil evaporation
m_{Soot}	mass of soot in the oil or filter
$mileage_{Filter}$	mileage since filter installation
Odo_0, Odo_E	odometer reading before and after the field test, respectively
P_{Engine}	engine power
S	filter saturation
SAE_u, SAE_i	SAE oil grade and W-SAE oil grade, respectively
y_i	expectation of the Bayesian regression
V_{Engine}	engine capacity

1   Introduction

It is vital for the durability of internal combustion engines that lubricant remains in good condition and therefore able to provide sufficient wear prevention and cooling. Since the lubricant is subjected to various temperature ranges and conditions, a highly sophisticated blend of hydrocarbons and additives is used to maintain a sufficient lubricant film on engine components at all times. However, heat, contamination and mechanical stresses result in oil deterioration and therefore a change in properties of the oil.

Solid contaminants, such as wear particles, dust and soot, pass the pistons with blow-by gases and are carried into the crankcase, where they are collected by the oil, accumulate in the sump and over time lead to a thickening of the oil. Due to the heat, lighter molecules in the oil can evaporate, leaving larger molecules (and thus a thicker oil) behind. Other thermal degradation processes which likely occur include oxidative breakdown and/or polymerization of oil molecules [1, 2] which may either increase or decrease the oil viscosity. It has been also reported [3] that during the evaporation of lighter oil fractions, additives such as viscosity index improvers can also evaporate, leading to a decreased oil viscosity. Additionally, oil contamination with fuel or cooling water results in dilution of the oil and thus decreased viscosity or emulsion formation. Furthermore, larger oil molecules can be effected by pressure and shear forces in contact with sliding parts of the engine [1].

The process of oil degradation in internal combustion engines has been investigated in some depth [4-7]. It was found that degraded oil could not maintain a permanent lubrication film on engine parts [1, 5] resulting in localised engine overheating and abrasion. However, many previous results are contradictive or ambiguous and testing methods differ greatly in

methodology and temperature range. Although several standardised laboratory tests are available (IP 48, DIN 51352, ASTM D7528), each testing method suggests different procedures and temperature ranges and thus results are not necessarily comparable. Since all testing methods require highly specialised equipment and the intention of the current work is primarily to investigate the influence of contaminated oil on filtration processes (rather than oil chemistry), it was decided to neglect complex vapour collection and analysis methods as used in previous works.

Due to increasingly stringent environmental regulations, aerosols produced in engine crankcases (blow-by gases, soot, wear particles, oil droplets) must be redirected into the air intake of the engine, where they are combusted, rather than vented to the atmosphere. Thus, it is important that solid and liquid particles are removed from the aerosol stream beforehand, so as to prevent soot deposition and damage to turbo chargers or other engine components and as much evaporated oil as possible is captured and returned to the crankcase to limit oil loss or oil thickening. Although liquid aerosol filtration using fibrous filters has been extensively studied in recent years [8-11], these studies have utilised pure (uncontaminated) liquids as aerosol. The few studies found by the authors [9, 12, 13] which have considered oil contaminants are either incomplete or not applicable, due to unrealistic conditions (soot dosage into the aerosol etc.). Furthermore, all studies used constant aerosol flow and loading rates which is in contrast to "real" filtration systems such as those used in automotive applications, which are typically operated discontinuously (cessation of flow for extended periods of time in which both air flow and aerosol generation are discontinued). It has been found in previous work [14] that fibrous (mist) filters undergo a second loading stage if they are operated discontinuously. This results in a significant increase in pressure drop and oil saturation over the continuous flow regime. Thus, it was found to be important to examine filtration behaviour under discontinuous conditions to obtain more realistic results and allow possible comparison with field (on-engine) testing.

This work investigates the filtration of soot-in-oil aerosol particles using fibrous filters. Furthermore, the work investigates the influence of different oil degradation mechanisms on the performance of such filters. Laboratory methods were developed to reproduce oil deterioration and to study its effect on oil properties. An extensive study of the influence of oil viscosity on filter performance during discontinuous filter operation was conducted, representing filter operation in a "real" engine crankcase ventilation system. Furthermore, a field test using 15 diesel vehicles was conducted over six months. At the conclusion of the test, the filters were tested under laboratory conditions and then thermogravimetrically analysed using a novel large-scale method adapted from [15]. The results obtained from the field test were then compared to the results from laboratory oil ageing and filtration testing.

It is hoped that this work will serve to narrow the gap between laboratory experiments and "real world" crankcase-ventilation filtration studies, as well as provide further insight into the filtration of "colloid" aerosols.

2   Experimental Apparatus and Methods

2.1   Laboratory filter testing apparatus and materials

The filtration experiments were conducted using a specially developed testing apparatus as presented previously by the authors [14]. Castrol RX Super (Castrol Ltd., UK) was used as the test aerosol for the laboratory experiments, as it is a common diesel engine lubricant for

subtropical conditions. The filters used in experiments were commercial CCV filters (MANN+HUMMEL GmbH, Ludwigsburg, Germany).

Based on previous findings [14], discontinuous filtration experiments were conducted in order to better approximate real-world conditions. The filters were first preloaded by submerging in oil and then allowing excessive oil to drain over several hours. This method (referred to as "Dipping and Draining", *DAD*) was developed and validated previously [14]. The filters were then loaded and operated at a constant flow rate of 55 LPM with aerosol at a loading rate of approximately 180 mg/m^3 and a mass-mean diameter of approximately 850 nm until they attained the first equilibrium state *(EQ$_1$)* and afterwards were operated discontinuously until the second equilibrium state *(EQ$_2$)* was reached. For each cycle, an average pressure drop value was calculated. The second equilibrium state was considered to be reached once oil drainage recommenced and the pressure drop showed no significant change over time.

A detailed description of the test rig, the properties of the oil, filters and the soot as well as the methods developed to investigate discontinuous filtration can be found in previously published works [14, 15].

2.2 Field test specifications

15 four wheel drive / light commercial vehicles were chosen for the field test. Three different diesel engine types were fitted to the test vehicles: (1) 2.5 litre 4 cylinder direct injection turbo Diesel meeting Euro-2 specification, (2) 2.5 litre 5 cylinder commonrail direct injection turbo diesel meeting Euro-3 specification and (3) 3.9 litre 4 cylinder direct injection turbo

diesel meeting Euro-1 specification. Additionally, type 2 engines were fitted with a bypass centrifuge for lubricant oil (MANN+HUMMEL (UK) LTD., Wolverhampton, United Kingdom). All other vehicles were fitted with full-flow lubricant oil filters only. The vehicles used SAE 15W-40 or SAE 5W-40 graded oil and were split into three groups as follows:

Group I: All vehicles that used 15W-40 (most type 1 and all type 3)

Group II: All vehicles that used 5W-40 and were not equipped with a bypass centrifuge (remaining type 1)

Group III: All vehicles that used 5W-40 and were equipped with a bypass centrifuge (all type 2)

The oil viscosities at 40 °C (as given by the manufacturers) ranged from 71 cSt to 107 cSt for the 5W-40 graded oils and from 95 cSt to 132 cSt for the 15W-40 graded oils. Due to the fact that the field test vehicles were distributed all over Australia an analysis of the engine oils after the 6 month test period was not possible.

The test filters were installed into the vehicles coinciding with an engine oil change and were in use for approximately 6 months. The initial weight of each filter was measured on a balance (OHAUS AS120, New Jersey, USA) before the filter was installed. During the test, the oil was not changed and the vehicles were driven as usual, the distance travelled during the test period ranged from 600 km to nearly 20,000 km, with an average of approximately 8500 km. The total mileage of the engines prior to commencement of the test ranged from approximately 60,000 km to over 350,000 km. All vehicles used commercially available diesel fuel conforming to the Australian diesel fuel quality specifications [16].

2.3   Oil and filter analysis

2.3.1   Thermogravimetric analysis (TGA)

Thermogravimetric analysis was shown to be a suitable technique to determine the soot content in diesel engine lubrication oils [17] and has been used extensively for commercial oil testing. A TGA procedure for soot-in-oil analysis has been standardized by the American Society for Testing and Materials (ASTM) and is now part of the ASTM 5967 diesel engine oil testing method [18]. However, it was previously shown [15] that this method can lead to a significant underestimation of the soot content by soot combustion if traces of oxygen were present during the analysis (which was shown to be common), or due to pyrolysis at higher temperatures. Therefore, a modified method was proposed and was proven to be much more reliable [15].

The filters used in the current work consisted of stainless steel fibres and were found to be non-reactive in the TGA (no detectable mass loss up to 750 °C in N_2 atmosphere). Therefore, it was considered possible to adapt the method [15] to conduct soot-in-oil of the used filters.

After testing in the laboratory filtration apparatus, the field test filters were cut open and the filter media was removed carefully. The filter media was cut from top to bottom into 20 mm wide strips which then were separated into their single media layers and weighed on a high-precision balance (AW220, Shimadzu, Kyoto, Japan) before being analysed thermogravimetrically. Of each filter 3 sample stripes were taken.

As conventional TGA instruments were not able to cope with the weight and the size of the 20mm x 90mm sample strips, a "scaled-up" version of the TGA process was developed. A quartz glass tube (500 mm length) was inserted into a Carbolite MTF 12/38/250 horizontal tube furnace (Carbolite, London, UK) and was purged with either dry air or high purity nitrogen (BOC, Australia) during the analysis. The sample strip was placed in a ceramic boat in the quartz tube. Glass wool on both ends of the tube helped to create slight overpressure in the tube thus preventing room air imbibition during the analysis.

The temperature profile for the analysis was adapted from the improved ASTM 5967 method [15]. However, to prevent the furnace tube from being damaged due to thermal stress in the quartz glass, a slower heating rate of 20 °C/min was used, as suggested by the manufacturer. After two minutes of nitrogen purge at a flow rate of 10 LPM, the sample was heated to 420°C in a nitrogen atmosphere (2 LPM) and held isothermal for 15 min. The flow volume was regulated by a flow meter (Cole Palmer, Illinois, USA). Once the oil was completely evaporated the sample was cooled down to room temperature by further nitrogen purging and its mass was measured (AW220, Shimadzu, Kyoto, Japan). This additional step was necessary to prevent the soot from spontaneously combusting once the sample came in contact with room air. After the purge gas was changed to dry air (5 LPM) the sample was placed back in the furnace and heated to 700°C where it was held isothermal for 15 min to allow all soot to combust. After cooling, the sample was weighed again.

A high flow (5 LPM) of nitrogen was used to purge the furnace tube and expel remaining oxygen prior to the analysis. The oxygen level in the tube was monitored by an ENERAC 3000 emission analyser (ENERAC, Westbury, NY, USA) where the ceramic boat was placed during the analysis. A heating test [19] was conducted using copper-II-oxalate hemihydrate

(STREM Chemicals, Newburyport, USA) after purging to detect for oxygen traces. No oxygen could be detected by this method.

Although this thermoanalysis method did not provide an in-situ monitoring of the sample weight (as is the case in conventional TGA instruments), it nevertheless delivered the necessary information to calculate the soot content of the oil captured in the filter.

The initial mass of the saturated filter decreased significantly during the first heating step under nitrogen atmosphere. The evaporation of the oil captured in the filter is responsible for this mass loss [17] and therefore the oil mass m_{Oil} can be calculated as $m_{Oil} = m_{Sample} - m_{Solid}$ with m_{Sample} being the initial mass of the sample strip and m_{Solid} the mass remaining after the evaporation of the oil. The following combustion of the soot in dry air reveals the mass of soot m_{Soot} in the filter [17] as $m_{Soot} = m_{Solid} - m_{Inert}$ with m_{Inert} being the inert mass (mainly fibres) remaining at the end of the analysis consisting of the filter fibres and traces of inert material in the filter referred to as ash [17]. Therefore the percentage soot content c_{Soot} in the oil captured in the filter can be calculated as

(1) $$c_{Soot} = \frac{m_{Soot}}{m_{Oil} + m_{Soot}} = \frac{m_{Soot}}{m_{Sample} - m_{Inert}}$$

The saturation S of the sample strip (which is representative for the whole filter) can be calculated as

(2) $$S = \frac{(m_{Oil} + m_{Soot}) m_{Filter}}{m_{Oil,max} \, m_{Sample}} = \frac{m_{Filter} - m_{Filter,0}}{m_{Oil,max}}$$

with $m_{Oil,max}$ being the maximum oil holding capacity of the whole filter (i.e. all void space is filled with oil at no flow velocity) and the factor m_{Filter}/m_{Sample} being the ratio between the mass of the whole filter media and the (initial) mass of the sample strip. $m_{Filter,0}$ is the mass of the clean filter. All filters were weighed on the same balance (OHAUS AS120, New Jersey, USA) before operation.

2.4 Oil contamination and filter testing

In this work, two different oil ageing methods were used in the laboratory to individually investigate the influence of each mechanism of oil degradation on the filtration performance of fibrous filters. The oil ageing method used in this work was based on the ASTM 7528 [20] method using a temperature of 170 °C and a heating period of 40 hours (as per the method), however the oil was heated in an open vessel. The ASTM method was chosen mainly for safety reasons, since the temperature was far below the flash point of the oil (230 °C).

2000 ml of new, unused Castrol RX Super 15W-40 diesel engine oil (as provided by the manufacturer) was heated in a glass vessel, inside an oven. A stainless steel tube was used to inject air (1 LPM) into the oil, finely dispersed through a porous ceramic cylinder to provide fine bubbles, uniform mixing and therefore even oxidation. Volatilised material was not collected.

To distinguish between the influence of thermooxidative breakdown and contamination on filter performance, different oil samples were prepared according to Table 1. Three different

soot-in-oil standard samples (Castrol RX Super with 1.5%, 2.5% and 5% Printex U) were used to investigate the effect of soot contamination in oil on the filter performance. It was shown earlier [21, 22] that Printex U is a suitable substitute for real diesel soot. Soot was weighed on a balance (AW220, Shimadzu, Kyoto, Japan) and then mixed with clean oil by vigorously stirring until the mixture was homogenous. The soot content of the oil was verified using a TA SDT 600 thermogravimetric analyser (TA Instruments, Delaware, USA) accordingly to the procedure in [15]. Additionally, one sample of "new" oil treated by thermooxidation and an oil sample gathered from one of the test vehicles (used in the field test) were investigated. As a reference, new (clean) oil as provided by the manufacturer was used. All oils were Castrol RX Super 15W-40 diesel oil.

Table 1: Properties of oil samples used for laboratory filter testing and thermogravimetry.

#	Oil (-)	c_{Soot} (-)	$\nu_{40°C}$ (cSt)
A	untreated	0%	107.5
B	oxidized	0%	99.7
C	untreated	1.50%	118.3
D	untreated	2.50%	124.1
E	untreated	5%	188.6
F	used (field test)	1.80%	149.7

The test filters were pre-saturated using the "dipping and draining" (*DAD)* method [14] and were then challenged with (aerosolized) oil continuously. Once equilibrium saturation and pressure drop were reached at the first equilibrium state EQ_1, the filters were subjected to discontinuous operation until the second equilibrium state EQ_2 was attained. Air and aerosol flow were stopped for 120 minute intervals and recommenced for 120 minute intervals during discontinuous operation. All filter tests were repeated at least three times.

The field test filters were tested in the filter test apparatus prior to the thermogravimetric analyses. Clean oil was used as aerosol and the filter were operated for approximately 10 minutes until a stable pressure drop and efficiency was operated. The flow velocity and concentration of the aerosol was identical to the conditions in 2.1. Due to the short filtration time, it was expected that the soot concentration and oil properties in the field test filters did not change significantly during laboratory testing. The collected oil during laboratory testing represented <1% of the oil already in the filter.

2.4.1 Oil Viscosity Analysis

The soot-in-oil standard samples were analysed in a Brookfield LVDV II+ Pro viscometer (Brookfield Viscometers Ltd, Essex, UK) equipped with a small sample adapter and a #18 spindle. The temperature of the sample was maintained at 40 $\pm$0.1 °C by pumping heated water from a water bath to the sample cell adapter. Each oil sample was tested three times and the average value was calculated. The standard deviation was less than 0.25% for each repetition.

2.5 Statistical analysis

The effects of the range of engine and oil specification on the final pressure drop of the field test filters were examined using linear regression. Due to limited data, Bayesian regression was used to determine the relationship between ΔP_{EQ2} and the oil and engine related data. The observed ΔP_{EQ2} was modelled as $y_i \sim$ Normal (μ_i, σ^2), where y_i is the ΔP_{End} for i=1...N observations. Bayesian regression was performed using Markov chain Monte Carlo (MCMC)

using WinBUGS 1.4.3 [23]. Convergence of the model was assessed using all convergence diagnostics in the CODA package [24]. From these diagnostics, the burn-in selection of the model was 10,000 iterations and a further 1,000,000 iterations were used to estimate the parameters α_i. The deviance information criterion (DIC) and model predictions were used to compare between the models [25]. The coefficients were modelled as Normal distributions, $\alpha \sim$ Normal $(0, \sigma^2)$, where σ^2 was set to a large constant, thus all coefficients were treated as non-informative priors.

3 Results and discussion

3.1 Validation of the TGA method

The TGA method was thoroughly validated in previous work [15]. However, preliminary experiments were conducted to validate the "scaled-up" tube furnace method used in this work.

Calibration tests with soot-in-oil mixtures of known soot content were conducted to validate the tube furnace analysis method. Three different mixtures (Castrol RX Super with 1.5%, 2.5% and 5% Printex U) were used and the method was repeated three times for each sample. A 20 mm wide strip of new filter media was submerged into the oil sample for 1 hour and drained overnight before being analysed in the tube furnace the same way the sample strips of the field test filter were later analysed. The sample strips and the oil samples were analysed in commercial thermoanalysers. 7mm x 7mm samples of the used filters were analysed in a TA TGA Q5000 instrument (TA Instruments, Delaware, USA) and the liquid oil samples were analysed in a TA SDT Q600 thermoanalyser (TA Instruments, Delaware,

USA) to ensure the different methods for soot content determination were in agreement. The results are shown in Fig. 1.
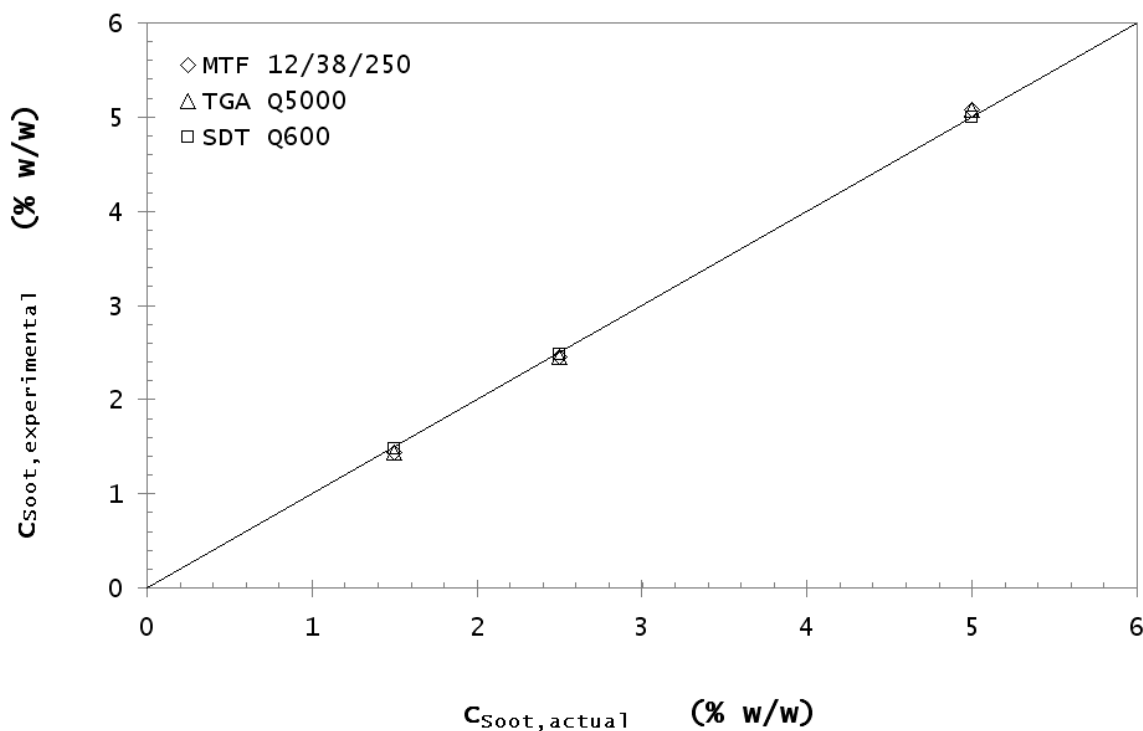

Fig. 1: Validation of the large-scale TGA method in the tube furnace. Filter samples with a known soot content ($c_{Soot,actual}$ = 1.5%, 2.5%, 5%) were used to validate the test method against a TA TGA Q5000 and a TA SDT Q600 thermo analyser. A line showing the ideal relationship (y = x) has been added.

As can be seen, the soot content ($c_{Soot,experimental}$) in the filter samples obtained from both the MTF tube furnace and the TGA Q5000 instrument showed an outstanding agreement with the actual soot content ($c_{Soot,actual}$) and the measured soot content in the oil by the SDT Q600 instrument. The reproducibility was found to be excellent, with deviations of less than 0.15% for all replicates.

3.2 Filtration Test Results

The pressure drop behaviour during discontinuous operation is shown in Fig. 2. All pressure drop values were averaged during the air flow step for each cycle [14] and normalized (ΔP_N) by dividing all value by the pressure drop present at the first equilibrium stage ΔP_{EQ1} of the untreated (i.e. as provided by the manufacturer) RX Super oil (15.5 mbar). Therefore the curves do not always commence at 1 on the y-axis. Cycle #0 shows the normalized pressure drop at EQ_1 before discontinuous operation commenced.
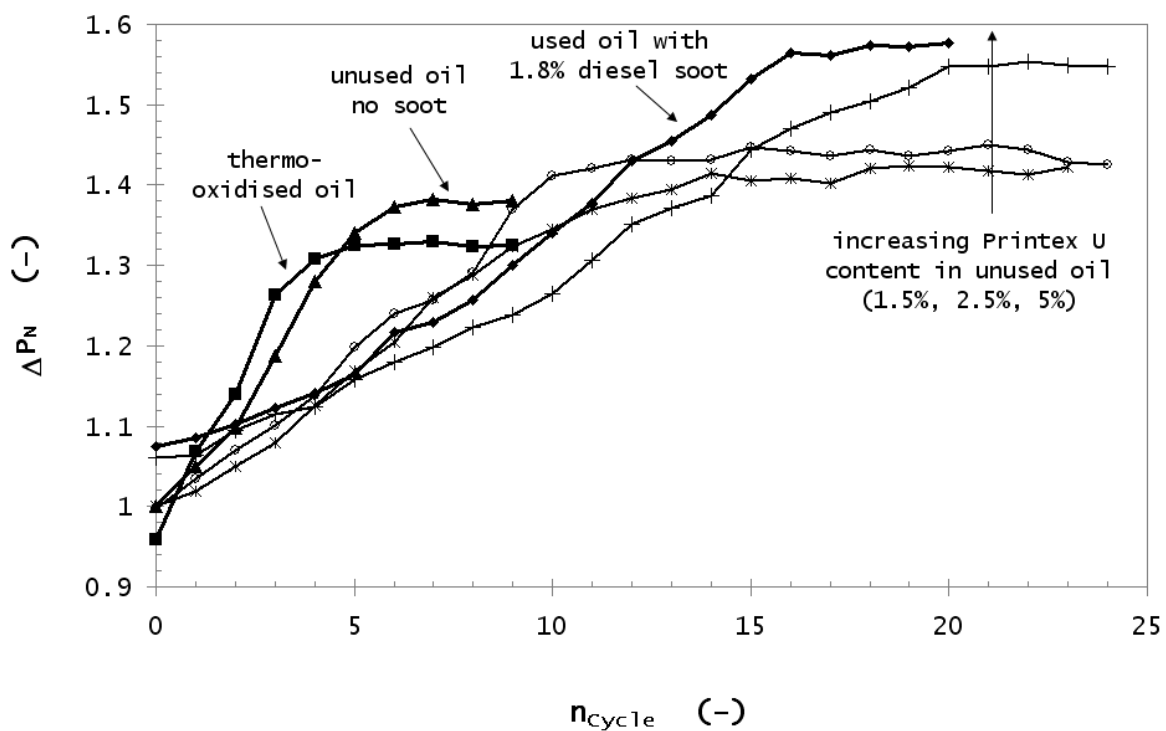

Fig. 2: Normalized pressure drop behaviour ΔP_N during initial cycles of discontinuous filtration. The oil samples consisted of untreated oil, artificially aged oil and three different mixtures (1.5%, 2.5% and 5%) of Printex U in unused oil. Additionally one "real" diesel oil sample (1.8% diesel soot) was examined.

It can be seen that all filters showed an increase in pressure drop during the initial cycles and reached a constant value ΔP_{EQ2} greater than ΔP_{EQ1} for each curve. This higher pressure drop, once reached, was found to be stable (i.e. the filter would remain at ΔP_{EQ2}). Furthermore, the drainage rate (not shown) decreased during this stage from its equilibrium value to nearly zero and - after the second equilibrium state EQ_2 was reached - returned to a similar rate as before. The increase in pressure drop and the cessation of the drainage rate were attributed to a second loading stage beyond EQ_1 as discussed [14].

Table 2: Results of discontinuous operation: pressure drop ΔP_{EQ1} and ΔP_{EQ1}, the number of cycles in the second loading stage, soot content in the filter and the filter saturation S_{EQ2}. Oil properties (A-F) as per Table 1.

| #	$c_{Soot,Filter}$ (-)	ΔP_{EQ1} (mbar)	ΔP_{EQ2} (mbar)	Cycles (-)	S_{EQ2} (-)
A	0%	15.5 $\pm$0.24	21.39 $\pm$ 0.33	6 $\pm$1	0.72 $\pm$0.02
B	0%	14.8 $\pm$0.13	20.276 $\pm$0.18	5 $\pm$1	0.69 $\pm$0.02
C	1.6% $\pm$0.15%	15.5 $\pm$0.15	22.01 $\pm$0.21	14 $\pm$1	0.72 $\pm$0.01
D	2.7% $\pm$0.12%	15.4 $\pm$0.20	22.176 $\pm$0.38	11 $\pm$2	0.72 $\pm$0.04
E	5.2% $\pm$0.19%	16.4 $\pm$0.12	24.108 $\pm$0.23	19 $\pm$2	0.76 $\pm$0.04
F	1.8% $\pm$0.11%	16.6 $\pm$0.11	24.476 $\pm$0.16	16 $\pm$1	0.73 $\pm$0.02

It can be seen in Table 2 that most filters indeed attained a similar ΔP_{EQ1} of approximately 15.5 mbar. However, the sample containing the artificially thermooxidated oil (B) showed a 0.7 mbar lower pressure drop ΔP_{EQ1} whereas the sample containing the highest soot content (E) and the sample obtained from the field test engine (F) showed a pressure drop that was slightly greater than the average.

The pressure drop increase between EQ_1 and EQ_2 was 5-10% higher for all samples containing soot (C-F) in comparison to the untreated oil (A) whereas the artificially oxidized oil (B) showed a slightly lower pressure drop increase. For the standard samples (C–E), which contained untreated oil dosed with soot, an increasing tendency of 42% to 47% could be observed for increasing soot content (ΔP_{EQ2} = 22.01 ±0.21 mbar, 22.18 ±0.38 mbar and 24.11 ±0.23 mbar respectively). The oil sample taken from a test vehicle (F) showed an increase of 47% (ΔP_{EQ2} = 24.48 ±0.16 mbar) which is in the same range as for the other samples containing soot, however the increase was relatively high for a soot content of only 1.8% compared to the increase that sample (C) and (D) showed. It should be noted that oil (F) possessed significantly higher viscosity. This suggests that the aging processes which occur in real cases are not the same as those which occur during laboratory aging (B).

The number of cycles required to reach EQ_2 during discontinuous operation reflects the same tendencies as were observed for the pressure drop increase. The artificially oxidized oil sample (B) required fewer cycles to reach EQ_2 than the untreated oil sample (A). For the standard samples containing soot (C-E), it required between 11 and 19 cycles which is between double and three times the number of cycles than the untreated sample (A). The test vehicle engine oil sample (F) showed a value that was in a similar range with 16 cycles.

Altogether it can be said that the artificially aged oil sample (B) showed a lower pressure drop ΔP_{EQ1}, a lower pressure drop increase and required fewer cycles to attain EQ_2 than the untreated oil sample (A). The samples containing soot (C-F) on the other hand showed a higher pressure drop increase and the second loading stage requiring 2-3 times more cycles to attain EQ_2.

As can be seen in Table 2, the viscosity of the untreated oil (A) was measured as 107.5 cSt which is very similar to the viscosity given by the oil manufacturer (114 cSt). For the artificially aged oil (B) a slightly lower viscosity of 99.7 cSt was measured, whereas for the standards of the standard samples dosed with 1.5% and 2.5% (C-D) soot was only approximately 10 cSt and 15 cSt respectively higher than the viscosity of the untreated oil (A). The sample with 5% soot (E) however showed a greatly increased viscosity of 188.6 cSt which corresponds to a viscosity increase of approximately 75%. The viscosity of the oil sample taken from the test car (F) was measured as 149.7 cSt and thus was relatively high compared to the oil samples with corresponding soot content (C and D) which may be caused by additional factors in "real" engines that were not considered during laboratory oil ageing. These factors might be additional contamination with inert material (dust, dirt) or the fact that wear metal components in the oil act as catalysts and therefore change the oil ageing behaviour. Alternately, evaporation of lighter fractions may be more significant in the "real-world" case.
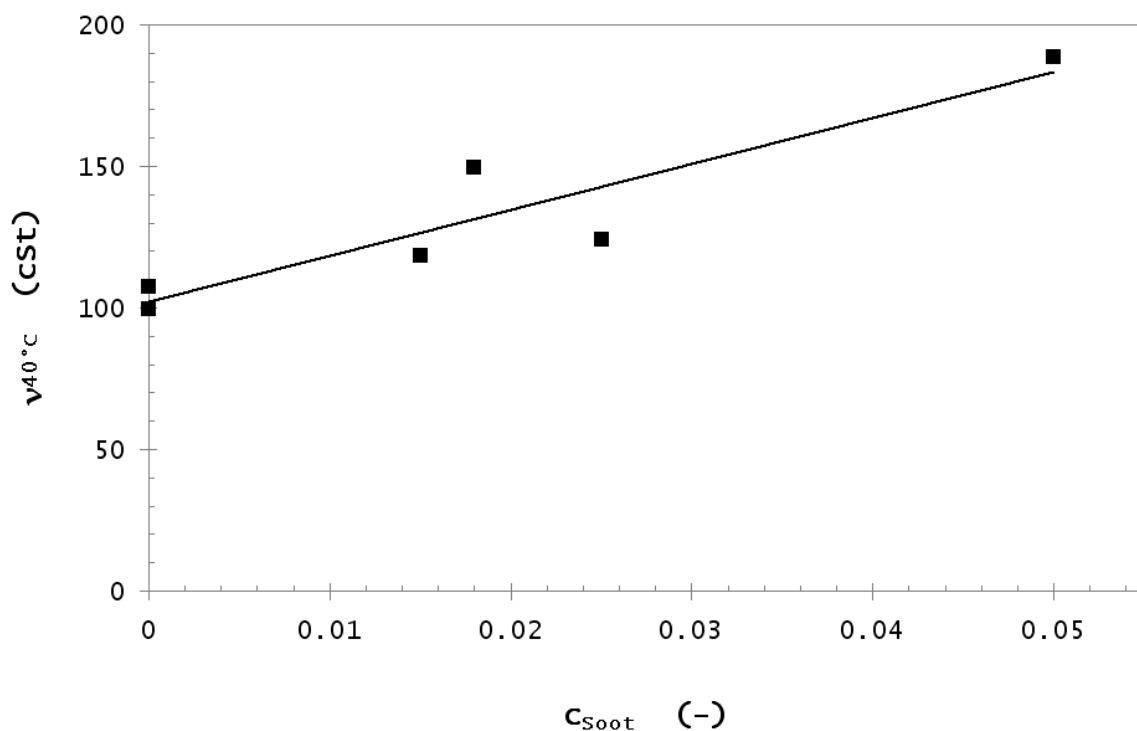
Fig. 3: Influence of the soot content c_{soot} on the (kinematic) oil viscosity $\nu_{40°C}$.

If the viscosity of the oil is plotted against the soot content of the oil, a linear correlation could be observed as can be seen in Fig. 3. This agrees with findings by other authors [6], who found a near linear relationship between viscosity and soot up to levels of 5%. However, a more rapid increase was found when the oil viscosity at 100 °C or the base stock only was measured. Since both the viscosity and the soot concentration were determined with a high degree of accuracy, error bars were omitted for this figure.

The influence of the oil viscosity on the final pressure drop $\Delta P_{EQ2,N}$ of the filters after the second loading stage is displayed in Fig. 4. The pressure drop values are normalized by dividing all values by the lowest $\Delta P_{EQ2,N}$ of the data points. It can be seen that the final pressure drop increases linearly with the viscosity of the oil sample used. Samples with a higher viscosity increased the pressure drop ΔP_{EQ2} and lead to a greater number of cycles to *EQ2*.
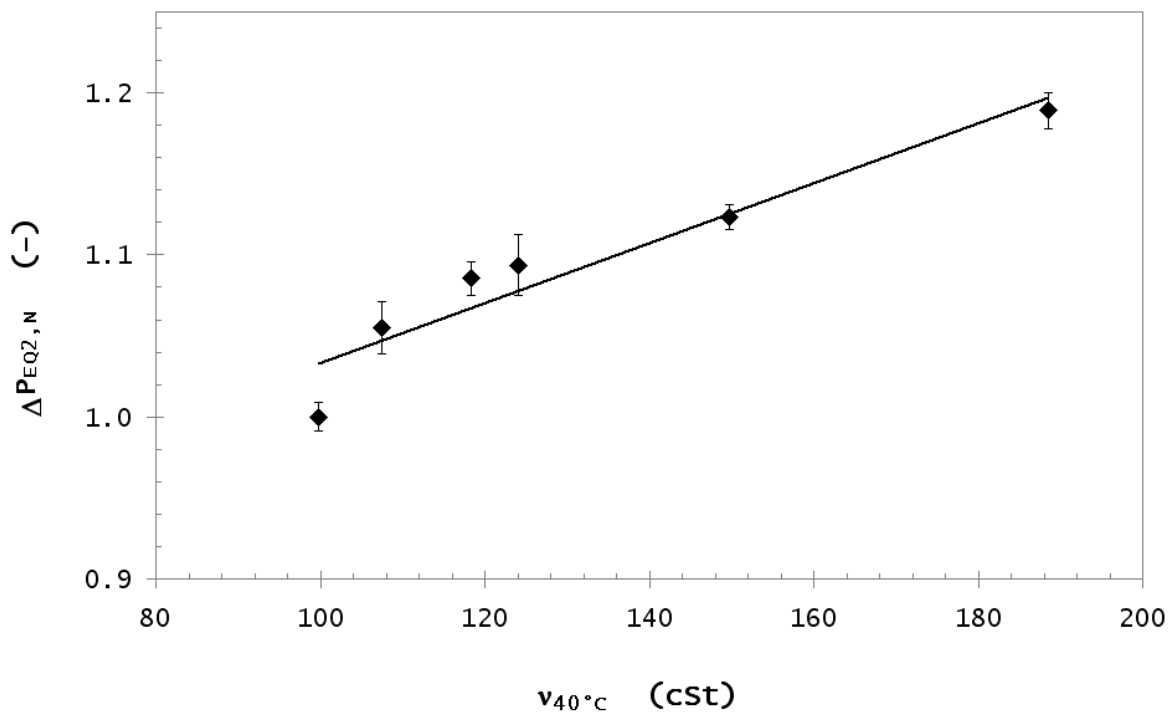
Fig. 4: Influence of the oil viscosity $v_{40°C}$ on the final pressure drop ΔP_{EQ2} of the filters after the second loading stage (normalized).

The soot content measured in the filters can be seen in Table 2. A slightly increased soot content of 0.1% to 0.3% in the filter was found for all samples. This increase however is marginal and is well in the range of the standard deviations. Thermogravimetric analysis of the drained oil captured during the filtration tests with a 5% soot-in-oil sample (E) revealed a soot content of 4.7% in the drained oil. Therefore it is believed that some soot accumulates in the filter over time during filtration, however, significantly longer filtration tests would be needed to investigate this issue since the accumulation rate appears very low.

The saturation S_{EQ2} of the filters was indeed different and seemed to follow the trend as was observed for the pressure drop. Samples dosed with soot (C-E) had a slightly higher

saturation whereas the sample containing thermally oxidated oil (B) showed a slightly lower saturation than the reference sample with untreated oil (A). This result was also attributed to the different viscosities of the samples which affected liquid movement in the filter – the same effect that was found to be the reason for different pressure drop behaviour discussed in the previous section.

From these results, we can conclude that contamination in the oil (such as the presence of soot) leads to an increased viscosity and therefore a corresponding increase in pressure drop. This increase appears to be linear. A viscosity increase was also observed by other authors [26] for oils of the same grade, however it was found not to be linear. Although the soot level in the engine oil sample (F) was similar to the soot content in the standards (C and D) the pressure drop and viscosity was elevated. Likely reasons for this were discussed earlier.

Thermooxidation on the other hand was found to lead to a decrease in oil viscosity in the laboratory case. This was also reflected in the filter performance. It was assumed that the evaporation of viscosity index improvers is responsible for the decrease and FTIR analysis of thermooxidated engine oil published by other authors [5] showed a decrease in the concentration of viscosity index improvers in the oil during oxidation. Other works indeed observed an increase in viscosity which was attributed to the evaporation of the lighter fractions and subsequent polymerisation of the larger (remaining) molecules , however the increase was strongly dependant on oil quality and oil blending. These results therefore show that the thermal stability of oil varies due to a broad range of additives and various blends used to satisfy different lubricant requirements and to optimize lubrication abilities under different conditions, and also to the conditions to which the oil is subjected.

The findings from the filtration and thermoanalytical tests in this work suggested that two different mechanisms occur during oil deterioration which influence oil viscosity. Oil viscosity changes due to contaminants were found to have the strongest effect on mist filter performance, whereas thermooxidation had a less significant effect.

3.3 Field Test Results

Coincident with the laboratory tests, the field test was conducted using identical filters. Upon removal, these filters were analysed in the laboratory to determine ΔP_{EQ2}, S and soot content c_{Soot}.
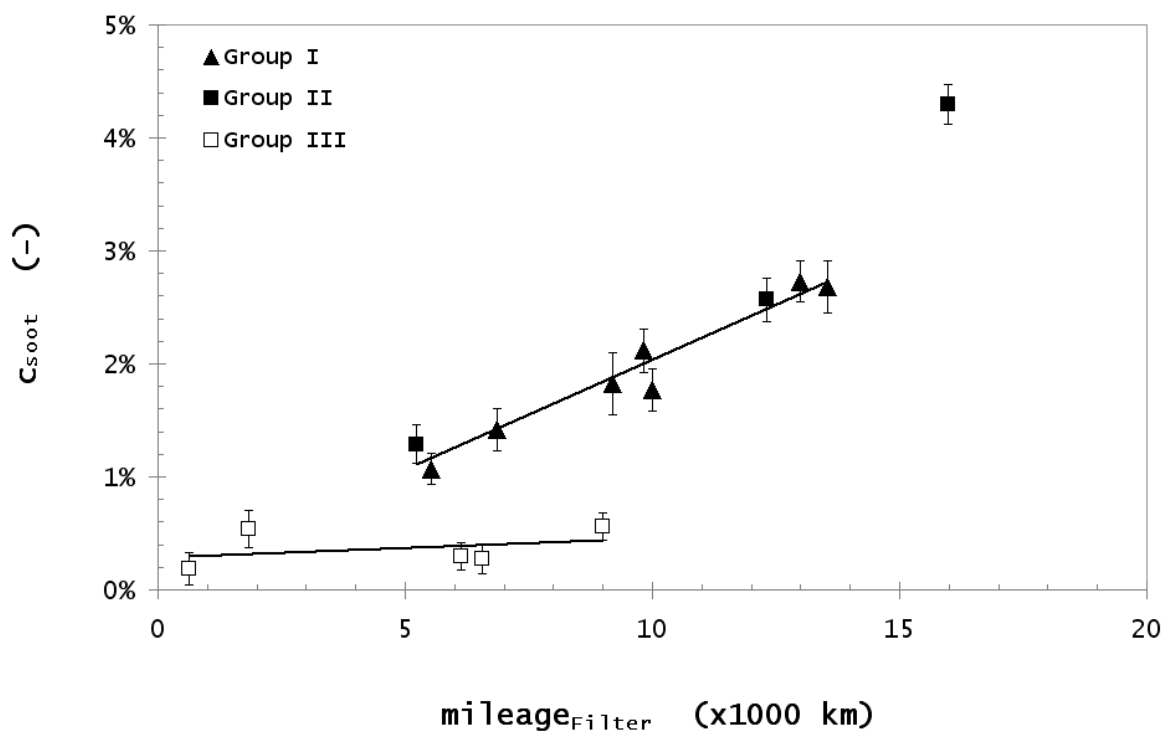
Fig. 5: Soot content of the oil in the test filters after the distance travelled during 6 months field test.

The results of the thermoanalytical tests are shown in Fig. 5. The measured soot content in the filters is plotted against the mileage of the vehicle travelled during the 6 month testing period. It can be seen that the soot content in the filters increased near to linearity for all engines that were not equipped with a bypass centrifuge. The soot content for the filters ranged between 1% and 2.7% with one exception that stood out with the soot content reaching a concentration greater than 4%. This particular engine had user-modifications to increase engine output and the engine was nearing the end of its service life. Both these issues combined could be expected to increase the quantity of blow-by gases (and soot content of blow-by) and thus soot contamination of the oil. Therefore the data obtained from this engine were omitted for the calculation of the fit. Additionally, oil analysis conducted by a commercial company (Wear Check Oil Analysis, Hamilton, Australia) revealed high wear metal (lead, iron, aluminium) levels in the oil of this particular engine, up to 65 times higher than normal. The engines fitted with a bypass centrifuge (type 3) showed a lower rate of soot increase.
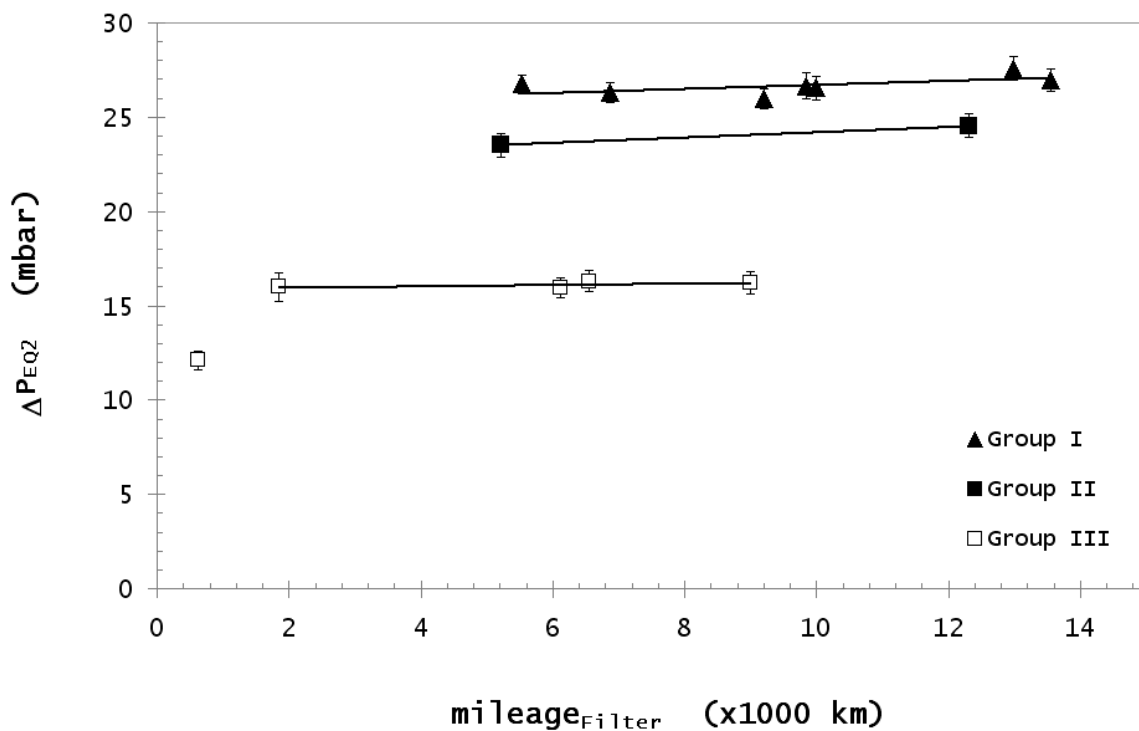
Fig. 6: Pressure drop of the test filters as measured under laboratory conditions.

The pressure drops of the test filters are shown in Fig. 6. The filters operated in the vehicles that were not equipped with bypass centrifuges showed a higher pressure drop between 23.5 mbar and 71.9 mbar. There was no significant difference found between the oils of different SAE grades. The engines with bypass centrifuges showed a lower pressure drop of only 12.1 mbar to 16.3 mbar with the lowest pressure drop originating from a filter which was only in use for 600 km and therefore had not yet reached full saturation yet ($S = 0.25$) and ΔP_{EQ2}. The other filters (for all engines) showed a saturation of $S = 0.64 \pm 0.07$. This suggests that S_{EQ2} was reached between 600 km and 1800 km. The engine with the mechanical fault stood out with a pressure drop of 71.9 mbar (not shown in Fig. 6). For the linear fits both the filter obtained from the faulty engine and the filter that had not yet reached S_{EQ2} were omitted since they were found to not being representative The filter collection efficiency was measured for all filters as $E = 76.8\% \pm 3.3\%$, with no significant trends observed.

As was discussed earlier, the laboratory test filters (Fig. 3) showed a markedly linear correlation between viscosity and pressure drop of the filter. However, since the field test was conducted with oils of two different oil grades and no viscosity data for the (used) oil were available an alternative means of determining an equivalent viscosity of the used oil was found by multiplying the viscosity of the <u>clean</u> (unused) oil with the soot content after the field test. This allowed a comparison of the results obtained from both the field test and the laboratory results and is shown in Fig. 7. As before, the filter that was found to be not fully saturated and the filter obtained from the faulty engine were omitted in this graph.
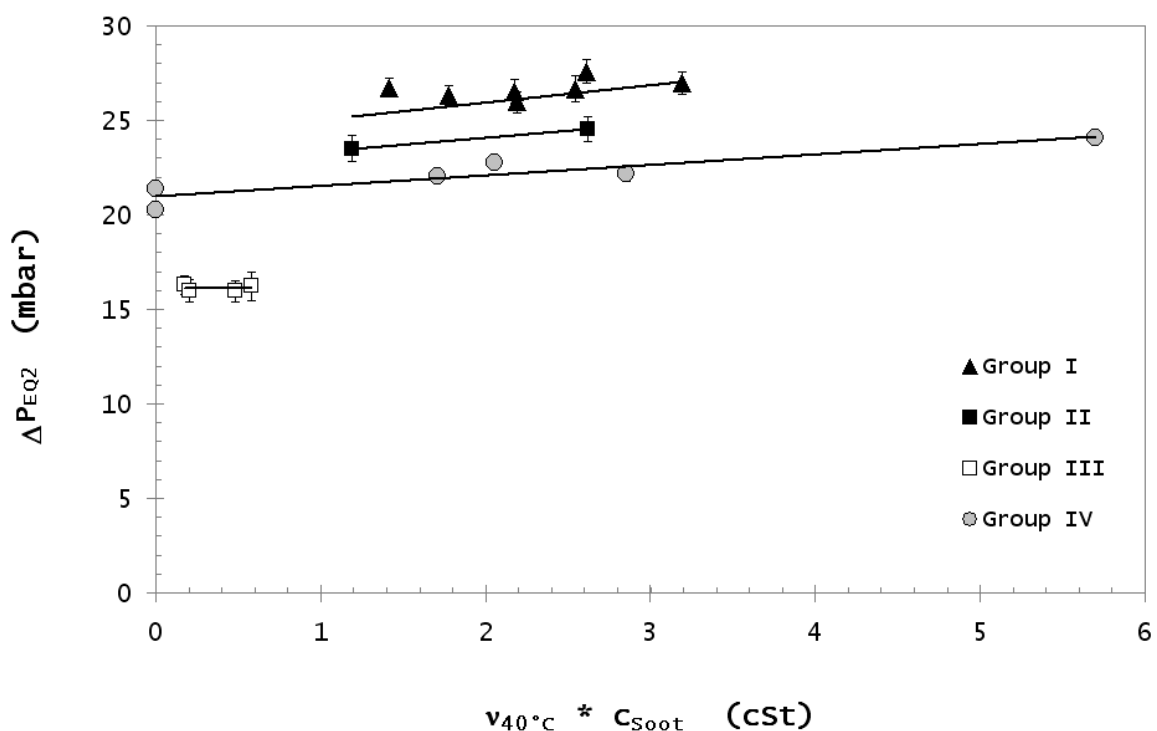

Fig. 7: Correlation between the viscosity x soot term ($v_{40°C,cleanoil} * c_{Soot}$) and pressure drop.

It can be seen that all four datasets follow a linear trend of similar slopes which permits us to describe the pressure drop increase of a filter during use by a linear function of the form

(3) $\Delta P = b_1 (\nu_{40°C} * c_{Soot}) + b_2$

with b_1 and b_2 being constants that describe the rate of increase (b_1) and the offset (b_2) of the pressure drop. By applying a least squares fit onto each data set the following values were obtained for b_1 and b_2 (Table 3):

Table 3: Parameters b_1 and b_2 to describe the linear pressure drop increase of the filters.

Group	Oil	b_1 (mbar/cSt)	b_2 (mbar)
I	15W-40 (field test)	0.923	24.07
II	5W-40 (no bypass centrifuge)	0.725	22.65
III	5W-40 (bypass centrifuge)	~0	16.15
IV	15W-40 (laboratory)	0.561	20.97

Both the 15W-40 and the 5W-40 graded oils obtained from the engines with no bypass centrifuge installed showed a similar slope of 0.92 mbar/cSt and 0.73 mbar/cSt, respectively. The laboratory experiments (15W-40 graded oil) showed a linear increase rate of 0.56 mbar/cSt which lower than the rate found for most test engines. The oils obtained from engines with a bypass filter installed showed no significant increase in pressure drop. It is

believed that solid particles (wear, soot, dust), which promote an increase in oil viscosity are removed by the centrifuge. Such an effect is likely apparent for the laboratory test filters, as no contaminants other than soot are added. It is also likely that a bypass filter would remove the largest soot agglomerates. A final consideration is that the engine of type 3, the only Euro-3 engine, may influence the soot morphology.

These findings may suggest that the rate of the pressure drop increase is not significantly affected by the oil grade, but by oil ageing (thermooxidation and contamination) mechanisms which change the oil viscosity.

A Bayesian regression model was fitted to the whole data set to predict ΔP_{EQ2} for the field test data, based on known oil, contaminant and engine parameters. The resultant model

$$\Delta P_{EQ2} = \alpha_0 + \alpha_1 S + \alpha_2 E + \alpha_3 c_{Soot} + \alpha_4 SAE_u + \alpha_5 SAE_i + \alpha_6 V_{Engine} + \alpha_7 Bypass + \alpha_8 Odo_0 + \alpha_9 Odo_E + \alpha_{10} P_{Engine}$$

(4)

includes the saturation S, the filter efficiency E, the soot concentration c_{Soot}, the SAE SAE_u and W-SAE SAE_i oil grades, the engine capacity V_{Engine}, the odometer reading before and after he field test Odo_0 and Odo_E respectively and the engine horsepower P_{Engine}. *Bypass* is a dummy (Boolean) variable denoting wether a bypass centrifuge was used or the filter was operated under full flow. The coefficients are shown in Table 4.

Table 4: Coefficients for the Bayesian regression model

α_0	5.544991
α_1	18.135615
α_2	228.226020
α_3	732.945872
α_4	0.238692

α_5	-0.007854
α_6	27.002820
α_7	36.792138
α_8	-18.211766
α_9	18.889031
α_{10}	-2.2125831

A comparison between the pressure drop values obtained from the Bayesian regression model and the pressure drop values from the field test filter analysis in the laboratory showed a good agreement as can be seen in Fig. 8. It should be noted that none of the filters were excluded from this analysis.
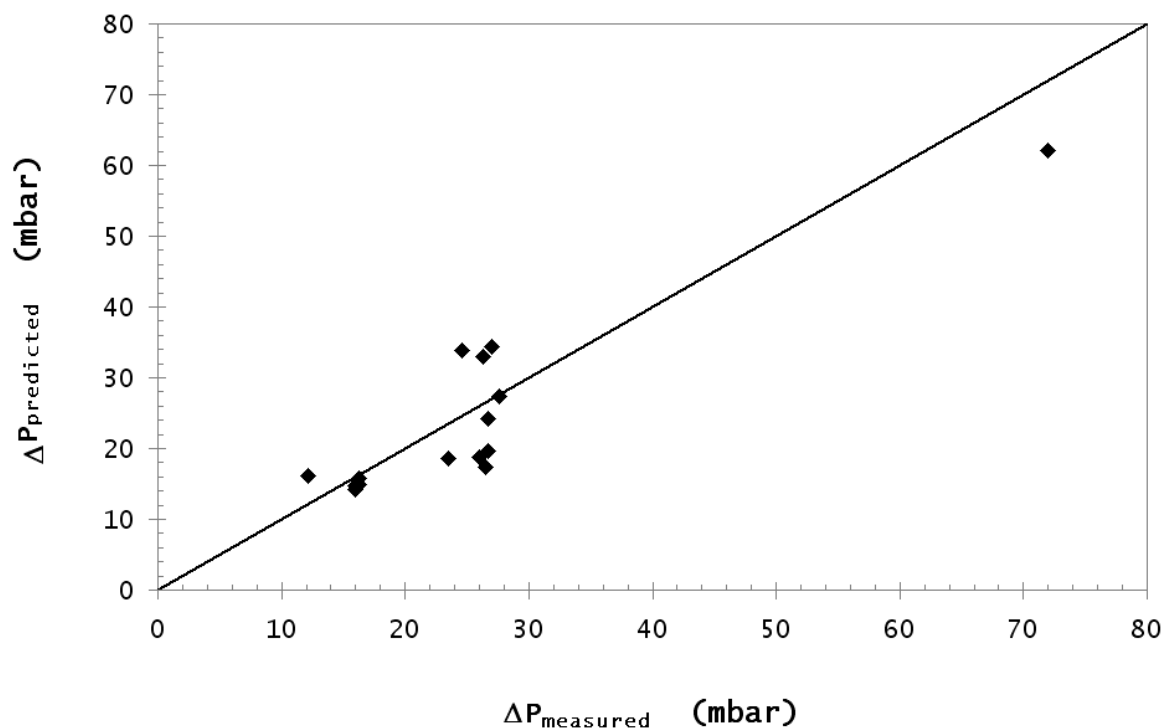

Fig. 8: Comparison between the predicted pressure drop by the Bayesian regression model and the measured pressure drop in the laboratory.

To identify the parameters which had the greatest impact on the pressure drop, the mean value of each parameter (S, E, …, P_{Engine}) was multiplied against the corresponding coefficient. It was found, that, the engine configuration (P_{Engine} and V_{Engine}) had the biggest impact on the pressure drop, followed by the filtration efficiency E. Little to no influence can be attributed to the oil grade (SAE_i and SAE_u) as was found previously. Soot content c_{Soot} and saturation S were found to be of minor importance.

These findings agree quite well with the conclusions drawn from the previous (laboratory) study, which showed that the pressure drop increase rate of both the field test and the laboratory test filters was not dependant on the oil grades of the different oils but on changes in the oil viscosity, which is predominantly affected by oil ageing. It is evident that the engine configuration (P_{Engine} and V_{Engine}) has a great impact on the ageing process of the lubricant since it significantly affects the amount of blow-by gases, contaminants, mechanical stress on the oil and operation temperature. The finding that the soot concentration c_{soot} has a minor impact on the pressure drop evolution suggests the assumption that oil ageing and the concomitant increase in oil viscosity is dominated by other factors such as mechanical stress, catalytic activity of wear metal etc.

Special attention should be paid to the oil sample obtained from one of the type 1 engines. This oil was used in both the field test (for the engine in question) and in the laboratory filtration test. The soot content of the sample was determined as 1.8% which was considered representative for the soot content of the (field test) oil samples examined in this work. The field test filter from this engine revealed a pressure drop of 25.9 ±0.25 mbar (in laboratory testing), whereas the pressure drop (ΔP_{EQ2}) after discontinuous operation in the laboratory filtration test with the oil sample obtained from this engine (F) was measured as 24.4 ±0.16

mbar. The saturation was calculated as 0.72 $\pm$0.16 for the field test filters using the same oil and 0.73 ±0.12 for the laboratory filter with an efficiency of 78.4 $\pm$1.7% for the field test and 80.1 $\pm$1.1% for the laboratory filter respectively.

Based on these findings it seems reasonable to suggest that the laboratory test methods are able to reproduce conditions similar to those experienced in a real diesel engine. However, additional factors which impact the viscosity change of the oil such as mechanical stress or non-soot contaminants also need to be taken in account when artificially ageing engine oil for laboratory experiments.

4   Conclusions

This work has investigated the impact of different oil deterioration effects on the properties of engine oil and their influence on the combined aerosol filtration of solid and liquid particles in fibrous mist filters.

Laboratory filtration tests showed that the oil viscosity had a major impact on the pressure drop behaviour of the filter. A higher soot content in the oil resulted in a higher oil viscosity and in an increased final pressure drop (ΔP_{EQ2}) oil. Lower oil viscosity again (as for thermooxidated oil samples) resulted in a more rapid stabilization of pressure drop but in a lower final overall pressure drop ΔP_{EQ2}. It was found, that ΔP_{EQ2} increased linearly with viscosity.

A field test was conducted using 15 vehicles equipped with three different diesel engine types. The filters were analysed in the laboratory after the test. It was found that the filters from the engines with a bypass centrifuge installed showed no noticeable pressure drop during the field test period. The other filters showed a linear correlation between oil viscosity and ΔP_{EQ2} which agreed well with the findings obtained from the laboratory filter tests. However, the increase rate was slightly higher for the field test filters which was attributed to additional oil ageing effects in the engine that were not taken into account during oil ageing in the laboratory. It furthermore was found that the oil grade is rather unimportant for the pressure drop development whereas the engine configuration has a major influence. These findings could be confirmed by a statistical analyze using Bayesian regression.

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