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Impact of FAME Content on the Regeneration Frequency of Diesel Particulate Filters (DPFs)

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Impact of FAME Content on the Regeneration Frequency of Diesel Particulate Filters (DPFs)

Prepared for the Concawe Fuels and Emissions Management Group by members of its Special Task Force (FE/STF-25) on Diesel Particulates and Emissions and staff of the Laboratory of Applied Thermodynamics, Aristotle University of Thessaloniki, Greece.

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ABSTRACT

Modern diesel passenger cars utilize Diesel Particulate Filters (DPFs) to reduce particulate matter exhaust emissions. In addition oxygenated fuels and fuel blending components such as Fatty Acid Methyl Esters (FAMEs) are known to reduce PM formation in the combustion chamber and reduce the amount of soot that must be filtered from the engine exhaust by the DPF. This effect is also expected to lengthen the time between DPF regenerations and reduce the fuel consumption penalty that is associated with DPF loading and regeneration.

This study investigated the effect of FAME content, up to 50% v/v (B50), in diesel fuel on the DPF regeneration frequency by repeatedly running a Euro 5 multi-cylinder bench engine over the European regulatory cycle (NEDC) until a specified soot loading limit had been reached. The results verified the expected reduction of engine-out particulate mass (PM) emissions with increasing FAME content and the reduction in fuel economy penalty associated with reducing the frequency of DPF regenerations. Fuel dilution measurements on lubricant samples taken from the engine sump showed that the FAME content in the engine lubricant increased with higher FAME contents in the fuel blends.

KEYWORDS

diesel particulate filters, biofuel, fatty acid methyl esters, regeneration, fuel consumption

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SUMMARY

Recent European legislation, such as the Renewable Energy Directive (RED) [1] and the Fuel Quality Directive (FQD) [2], have set targets for increasing renewable energy and reducing greenhouse gas (GHG) emissions from road transportation by 2020. Meeting these targets has encouraged the use of bio-derived blending components in market fuels such as ethanol from sugar fermentation for gasoline blending and Fatty Acid Methyl Esters (FAME) from the esterification of vegetable oils and animal fats for diesel fuel blending. At the same time, vehicle emissions limits for both CO2 and other regulated pollutants will continue to tighten over this decade to further reduce transport-related emissions. In response to tightening emissions legislation, modern European diesel vehicles utilize Diesel Particulate Filters (DPF). DPFs are designed to remove filterable particulate matter (PM) and reduce particle number (PN) emissions from the diesel engine-out exhaust. Oxygenated fuels and fuel blending components such as FAMEs are known to reduce PM formation in the combustion chamber and reduce the amount of soot that must be filtered from the engine exhaust by the DPF. This effect is also expected to lengthen the time between DPF regenerations and reduce the fuel consumption penalty that is associated with DPF loading and regeneration.

The study, conducted for Concawe by the Laboratory for Applied Thermodynamics of the Aristotle University of Thessaloniki, Greece, had four objectives:

- develop a repeatable bench engine test protocol to evaluate the impact of FAME content on DPF regeneration frequency;
- use this test protocol to relate the DPF regeneration interval to the FAME content in diesel;
- assess the possible benefits or debits of FAME content on fuel consumption;
- assess effects of fuel FAME content on engine lubricant dilution.

This study used the developed protocol to investigate the effect of FAME content, up to 50% v/v (B50), in diesel fuel on the DPF regeneration frequency by repeatedly running a Euro 5 multi-cylinder bench engine over the European regulatory cycle (NEDC) until a specified soot loading limit had been reached. It was found that increasing the FAME content did increase the interval between necessary regenerations particularly for FAME concentrations of greater than 10%. The study also quantified the fuel economy penalty contributions of the back pressure versus the regeneration fuel economy penalty. The results verified the expected reduction of engine-out particulate mass (PM) emissions with increasing FAME content and the reduction in fuel economy penalty associated with reducing the frequency of DPF regenerations. Fuel dilution measurements on lubricant samples taken from the engine sump showed that the FAME content in the engine lubricant increased with higher FAME contents in the fuel blends.

1. INTRODUCTION

Recent European legislation, such as the Renewable Energy Directive (RED)[1] and the Fuel Quality Directive (FQD)[2], have set targets for increasing renewable energy and reducing greenhouse gas (GHG) emissions from road transportation by 2020. Meeting these targets has encouraged the use of bio-derived blending components in market fuels such as ethanol from sugar fermentation for gasoline blending and Fatty Acid Methyl Esters (FAME) from the esterification of vegetable oils and animal fats for diesel fuel blending. Although considerable work is in progress to develop more advanced products that utilize more of the plant's biomass, commercial volumes of these products are still quite small and are not expected to make a large contribution to transport fuels before 2020. At the same time, vehicle emissions limits for both CO2 and other regulated pollutants will continue to tighten over this decade to further reduce transport-related emissions.

In response to tightening emissions legislation, modern European diesel vehicles utilize Diesel Particulate Filters (DPF). DPFs are designed to remove filterable particulate matter (PM) and reduce particle number (PN) emissions from the diesel engine-out exhaust.

The addition of FAME into diesel fuel is well-known to decrease the PM emissions of diesel engines [3, 4, 5, 6, 7, 8]. This effect is largely attributed to the addition of oxygen into the fuel which increases the local oxygen concentration in the rich area of the diesel flame [3] and by diluting polyaromatic hydrocarbons in the diesel fuel with a polyaromatics-free blending component. Addition of FAME to diesel fuel also increases fuel consumption due to the lower volumetric heating value of FAME compared to diesel fuel [11].

The use of DPFs in modern vehicles results in a small but important increase in fuel consumption mainly due to two factors. Firstly, additional engine work is typically required to compensate for the back pressure increasing due to the DPF, which increases as the filter accumulates soot. As soot loading increases and the backpressure also increases across the DPF, the engine must compress exhaust gases to a higher pressure which requires additional mechanical work. Less energy is also extracted by the exhaust turbine which can affect the intake manifold boost pressure [9, 10]. Secondly, the DPF must be periodically regenerated to remove the accumulated soot. This is usually done by introducing a small amount of additional fuel through late cycle (post) injection. This injection of fuel results in higher concentrations of hydrocarbons in the exhaust, which are oxidized in the diesel oxidation catalyst (DOC) or the catalysed DPF. This exothermic process increases the temperature in the DPF to levels sufficient for the accumulated soot to be oxidised with the oxygen that is present in the exhaust. The total fuel economy penalty (FEP) associated with this process depends on the rate of soot build-up and on the frequency of the DPF regeneration.

Although the effect of FAME on emissions and fuel consumption during normal operation has been the subject of previous studies, [11, 12], the interactions specifically with DPFs is not well characterised. This study was designed to investigate in detail the effect of FAME content, ranging from 0 to 50% v/v (B0 to B50) in diesel fuel, on the DPF and related behaviours. The study, conducted for Concawe by the Laboratory for Applied Thermodynamics of the Aristotle University of Thessaloniki, Greece, had four objectives:

- develop a repeatable bench engine test protocol to evaluate the impact of FAME content on DPF regeneration frequency;
- use this test protocol to relate the DPF regeneration interval to the FAME content in diesel;
- assess the possible benefits or debits of FAME content on fuel consumption;
- assess effects of fuel FAME content on engine lubricant dilution.

This report pulls together work which has been documented in various publications which can be referred to for more details [13],[14],[15].

2. EXPERIMENTAL APPROACH

Measurements were performed on a Euro 5-compliant 1.4-liter turbocharged multi-cylinder diesel engine (66kW at 3800 rpm) installed on an AVL Dynoperform 350. Several parameters were constantly monitored including exhaust temperature at the DPF inlet and outlet, DPF pressure drop, O2 and NOx concentrations and engine data (speed, torque, acceleration pedal position, EGR, and inlet air flow rate). Fuel consumption was measured with an AVL 735 fuel meter.

The DPF was weighed before and after each test to provide an accurate value for the soot loading. For some selected tests, PM mass and PN emissions at the DPF inlet were measured according to the legislated method in the Constant Volume Sampler (CVS). The PM mass emissions were also monitored with the AVL Micro Soot Sensor. Additionally, gaseous emissions (CO, HC, NOx, and CO2) were measured with an AVL AMA i60 analyser (**Figure 1**).

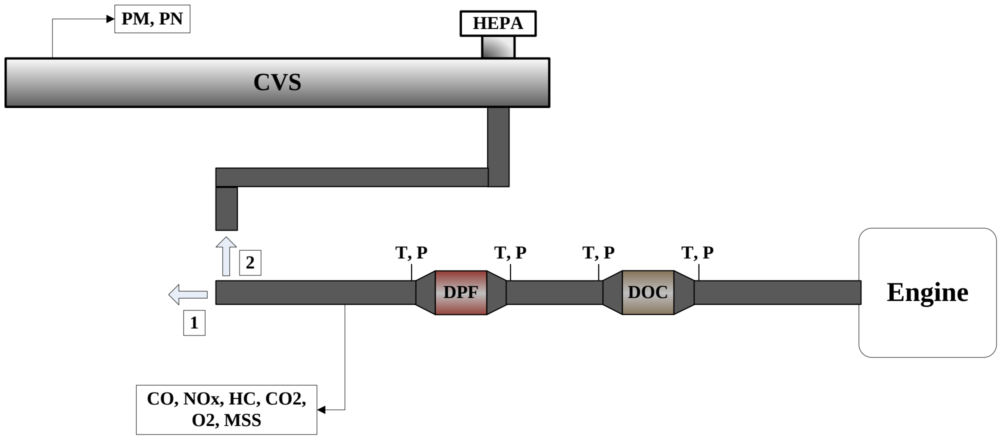
Fuels for this study were blended from a conventional diesel fuel complying with the European norm EN 590 and having a sulphur content less than 10 ppm. A single batch of Rapeseed Methyl Ester complying with the European norm EN 14214 was used to produce the FAME/diesel blends. The FAME was additized with butylated hydroxytoluene (BHT) antioxidant after production in order to ensure acceptable oxidation stability throughout the study. The oxidation stability of the FAME/diesel blends was measured at the beginning and end of the study using the Rancimat method (EN 15751). Selected fuel properties are shown in **Table 1** and full data can be found in **Appendix 1**.

Table 1. Selected fuel properties

Fuel Designation	FAME Content (% v/v) (EN 14078)	Density (kg/l) (EN ISO 12185)	Lower Heating Value (LHV) (MJ/kg) (IP 12)	Distillation Range (ºC) (EN ISO 3405)	Initial Oxidation Stability (h) (EN 15751)
B0	0.0	0.8334	42.93	173.0 to 357.8	==
B10	10.2	0.8386	42.53	174.0 to 355.7	39.2
B30	28.0	0.8472	41.34	178.0 to 354.3	21.5
B50	48.7	0.8578	40.34	183.5 to 352.7	16.7

The experimental setup is shown in **Figure 1**. The exhaust gas could follow two paths according to the needs of the measurement. During soot loading and DPF regeneration, the exhaust gas went through path 1, exiting the tail pipe. For emissions measurements, the exhaust gas followed path 2 to the CVS. A ceramic DOC (cordierite substrate, 600cpsi/3mils, 1.1l) was installed in the exhaust line, upstream of the DPF. The conventional DPF, a SiC, 300cpsi/12mils, 16 segment, 2.5l, was installed downstream of the DOC. Four identical and initially unused DPFs were used in this study, one for each test fuel.

Figure 1. Schematic of the experimental setup and measured quantities



The FAME content of lubricant samples which were taken after each regeneration was measured by IR spectroscopy according to DIN EN 14078 and confirmed by gas chromatography, while the fuel concentration was measured by gas chromatography according to method DIN 51454.

3. TEST PROGRAMME

A repeatable test procedure was first developed in a scoping study that was then used to evaluate the effects of FAME content in diesel fuel on fuel consumption and DPF regeneration.

3.1. DPF STABILISATION PROCEDURE

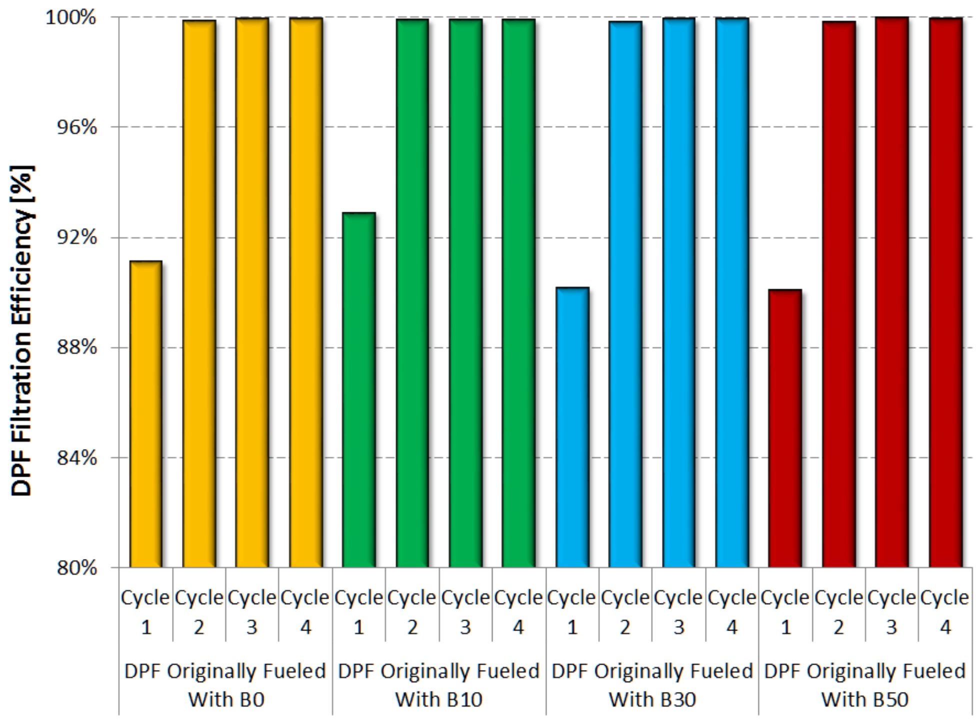
The DPFs were unused at the start of testing so a conditioning procedure consisting of a loading/regeneration cycle was used to stabilise them. The conditioning procedure consisted of running the engine over the NEDC for an equivalent distance of 100km after which the DPF was fully regenerated at 2000 rpm/40Nm using the active regeneration system of the engine. The post injection was adjusted to achieve at least 600°C temperature at the outlet of the DPF and ensure that the soot was completely removed from the filter. The duration of the regeneration was defined to be 5min after the pressure drop had been stabilized. Following this stabilization, the DPF weight at the clean condition was measured and a lubricant sample was taken.

3.2. TEST PROCEDURE

For each test fuel 20-25 NEDC cycles were run continuously for a test day with only the initial test having a cold engine start. The soot loading of the DPF was measured by removing and weighing the DPF at the end of each day. This procedure was repeated until a soot loading of 6 g/l had been achieved, The DPF was then fully regenerated according to the procedure described above in 3.1 and a lubricant sample was taken. This loading/regeneration cycle was repeated two more times to complete the testing on each test fuel. All of the recorded engine data were evaluated to check engine repeatability during the tests. End of test engine lubricant samples were analysed to determine FAME and fuel contamination.

After the end of all repetitions with all fuels, the filtration efficiency of the DPFs was measured to verify that no damage had occurred during regenerations that would affect the amount of soot collected on the DPF during loading. This was achieved by measuring the PM emissions at the outlet of the DPF with the AVL Micro Soot Sensor during the NEDC loading procedure. The same fuel (a market diesel fuel) was used for all DPFs. The test started from a clean condition where the lowest filtration efficiency was observed. After two NEDCs, the filtration efficiency of all the DPFs had reached 99% and slowly increased during the next cycles (**Figure 2**). This confirmed that there were no filtration problems with the DPFs.

Figure 2. DPF filtration efficiency using market diesel fuel



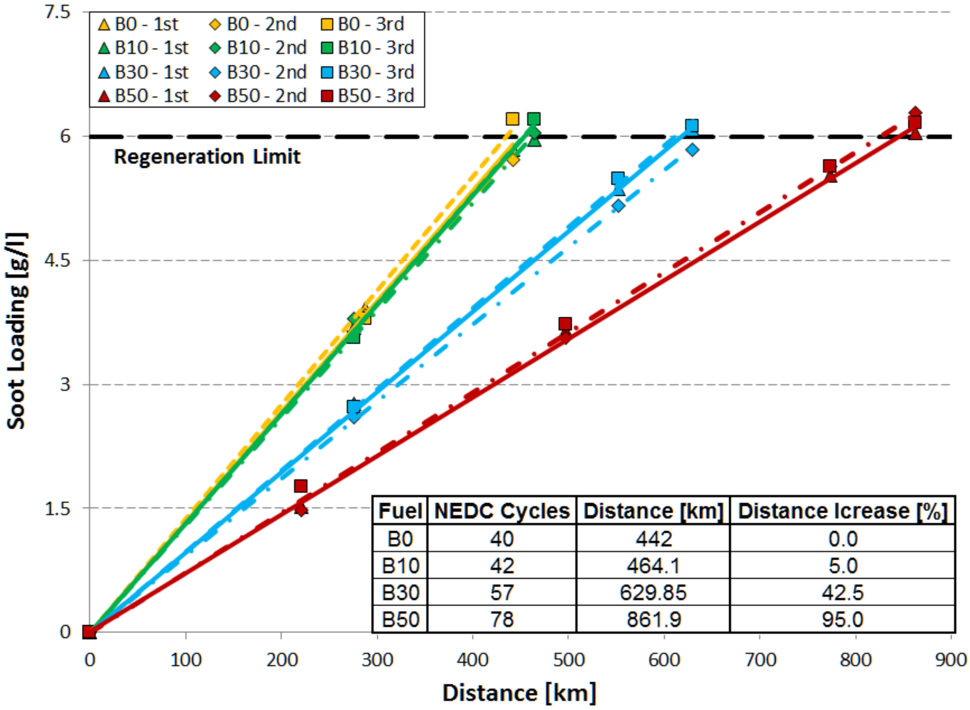
The next step included specific tests to measure the PM mass and PN emissions at the inlet of the DPF. This was done by removing the DPF and connecting the exhaust line to the CVS. PM and PN emissions were measured in the CVS using the legislated method, while the AVL Micro Soot Sensor measured the raw exhaust at the same time. This procedure gave a more precise measurement of emissions for all fuels and a good comparison with the emissions measured by the DPF weight measurement. The DPF was weighed (at 200°C to avoid water condensation which could affect the mass). The volatile part of the PM measured with the legislated gravimetric method was measured by heating the Teflon coated PM filter papers in a furnace. The heating was performed under nitrogen flow, from ambient temperature to 100°C (30min), then from 100 to 150°C (30min), from 150 to 200°C (30min), at 200°C for 60min, and cooled to ambient (30min).

4. RESULTS

4.1. PM EMISSIONS

The soot loading values based on DPF weight measurements indicated that increasing FAME content in the fuel blend lengthened the interval between DPF regenerations (**Figure 3**).

Figure 3. Soot loading based on DPF weight measurements for all fuels



As the soot accumulated on the DPF, the pressure drop across the DPF (ΔP) gradually increased (**Figures 4** and **5**) and all DPFs reached a similar ΔP level when 6 g/l loading had been reached. **Figures 4** and **5** show that the ΔP across the DPF was generally repeatable but with some exceptions. The ΔP measurement showed some discontinuities between readings taken at the end of test day and the beginning of the following test day. This might be attributed to humidity adsorbed overnight on the accumulated soot that changed the soot properties or disturbance of the soot during the DPF weighing procedure. Maximum ΔP (occurring at 120km/h) was appraised as the best way to evaluate soot loading instead of mean ΔP in order to minimise signal to noise errors associated with the low flow rates and thus low ΔP values typical of the NEDC cycle.

Figure 4. Mean NEDC pressure drop across the DPF for each fuel blend

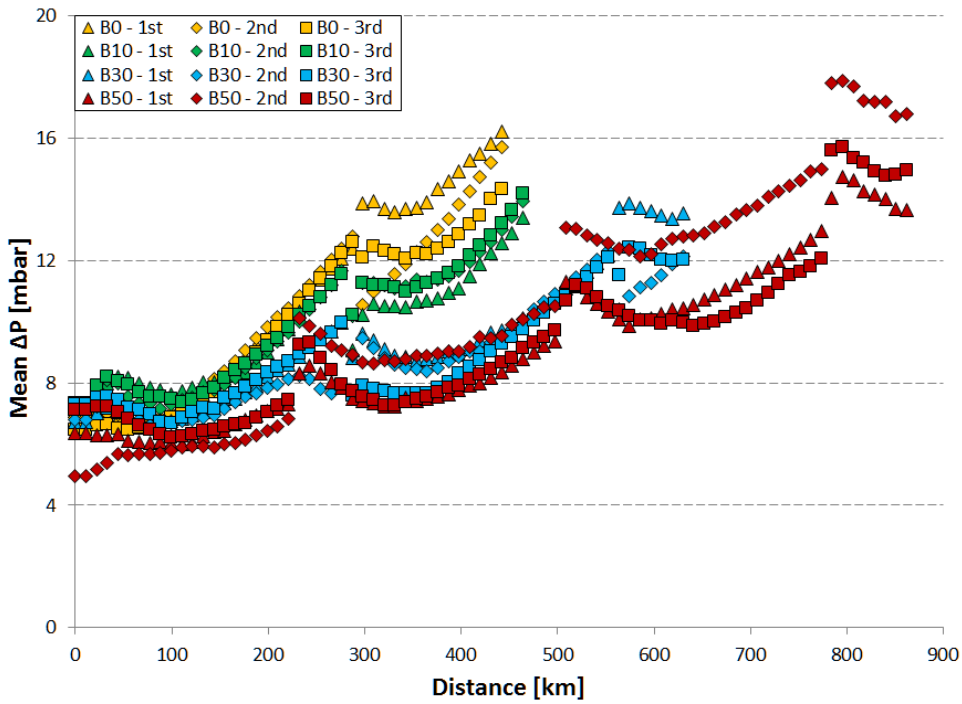
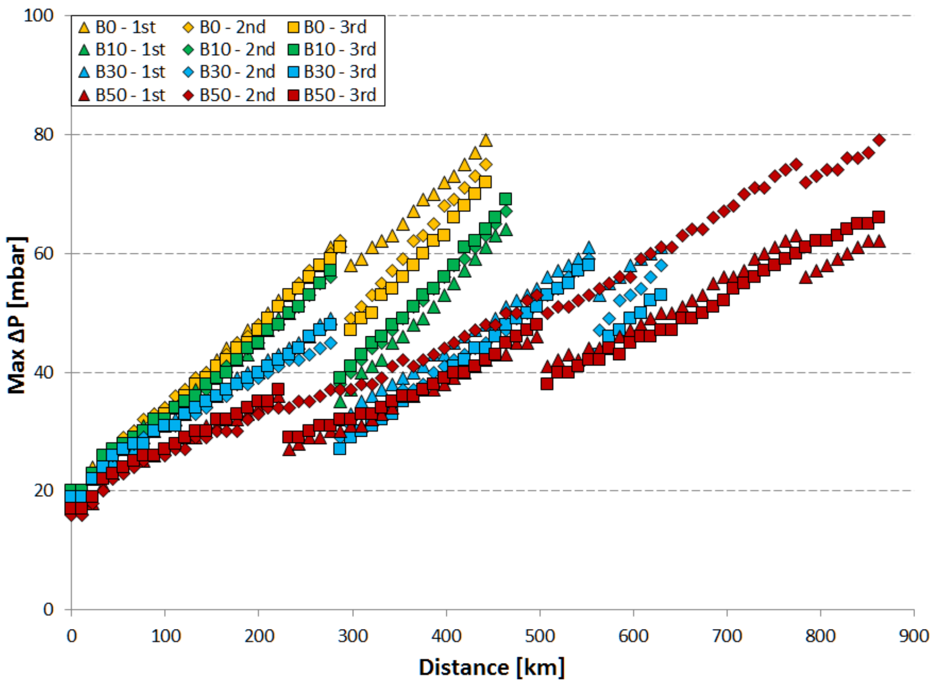
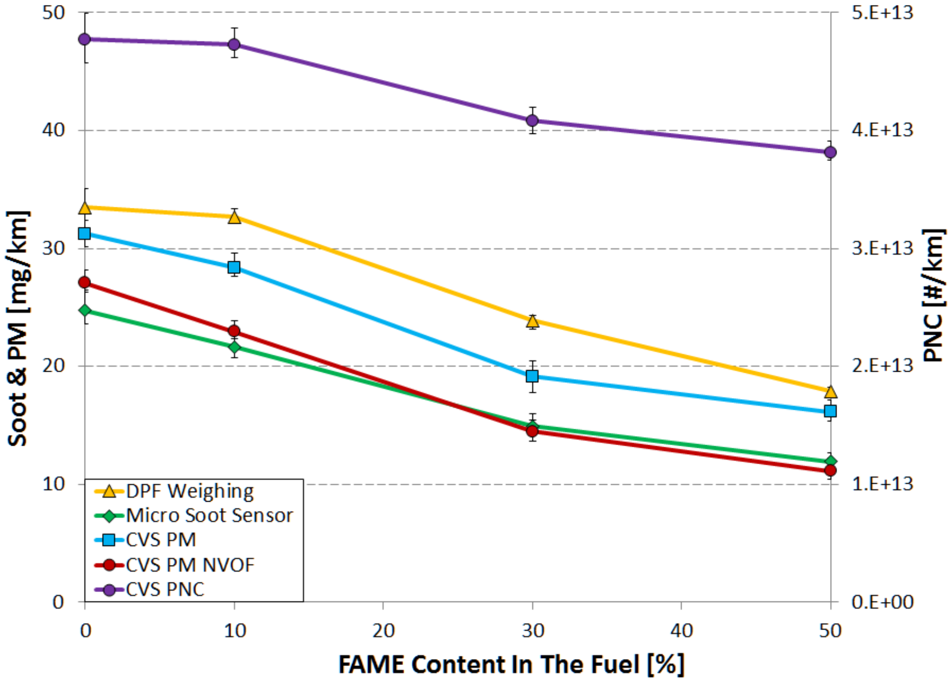


Figure 5. Maximum NEDC pressure drop across the DPF for each fuel blend



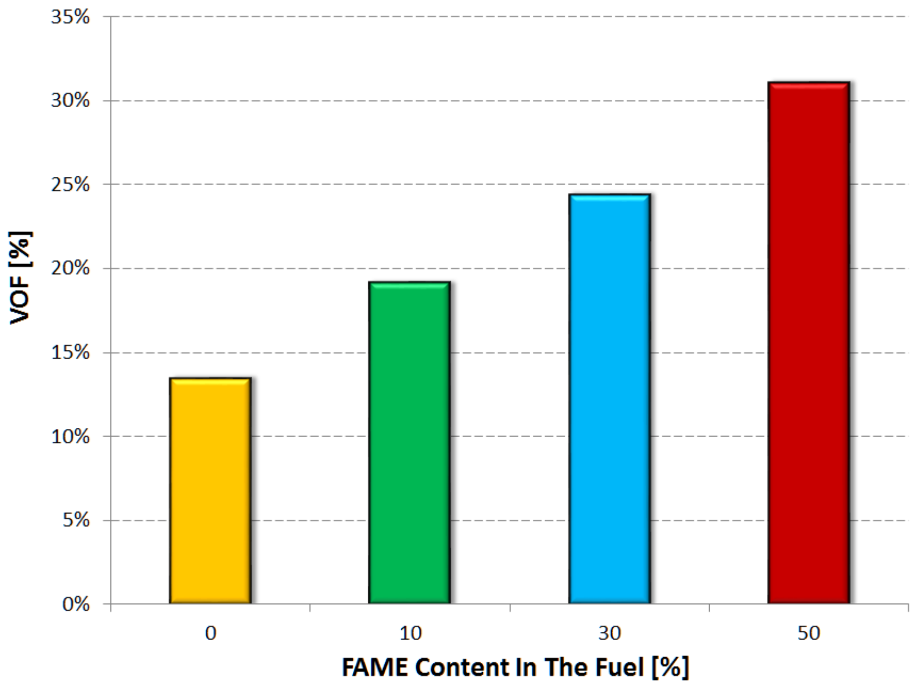
The specific PM emission measurements (without DPF) carried out after the end of the loading repetitions with all fuels provided additional information and a comparison with the results from the DPF weight measurements. The trend of decreasing PM emissions with increasing FAME content indicated by the trend in DPF weight was confirmed by measurements of the PM emissions using the AVL Micro Soot Sensor and the CVS gravimetric measurements (**Figure 6**). The PM emissions calculated after the thermal removal of the volatile fraction (as described) for PM collected on PM-measuring filters agreed with the Micro Soot Sensor measurements, which also measures only the solid part of the PM emissions. The trend was much steeper between B10 and B30 suggesting that a stronger effect on PM emissions may occur in this range of FAME content.

Figure 6. Soot and PM emissions (left axis) and particle number concentration (PNC) (right axis) versus FAME content



Consistent with the results of Czerwinski et al. [6], the volatile part of the PM emissions increased as the FAME content increased (**Figure 7**).

Figure 7. Volatile organic fraction (VOF) vs. FAME content



4.2. FUEL ECONOMY PENALTY

The Fuel Economy Penalty (FEP) attributed to the pressure drop over the DPF (FEP_p) can be expressed as [16]:

$$FEP_p \text{ (in \%)} = 100 \frac{\Delta P}{BMEP} \quad (1)$$

Where:
- FEP_p: Fuel Economy Penalty due to increased backpressure [%];
- ΔP: pressure drop over the DPF [kPa]; and
- BMEP: brake mean effective pressure of the engine [kPa].

The BMEP of the engine can be calculated by the following formula [17]:

$$BMEP = 2\pi \frac{N_R \cdot T}{V_d} \quad (2)$$

Where:
- NR: number of crank revolutions for each power stroke per cylinder (which is two for four-stroke cycles and one for two-stroke cycles);
- T: engine torque [Nm]; and
- V_d: engine displacement volume [dm^3].

The FEP due to the extra fuel consumed to regenerate the DPF (FEP_r) is calculated from the fuel used to actively regenerate the filter and the fuel consumed by the vehicle [18]:

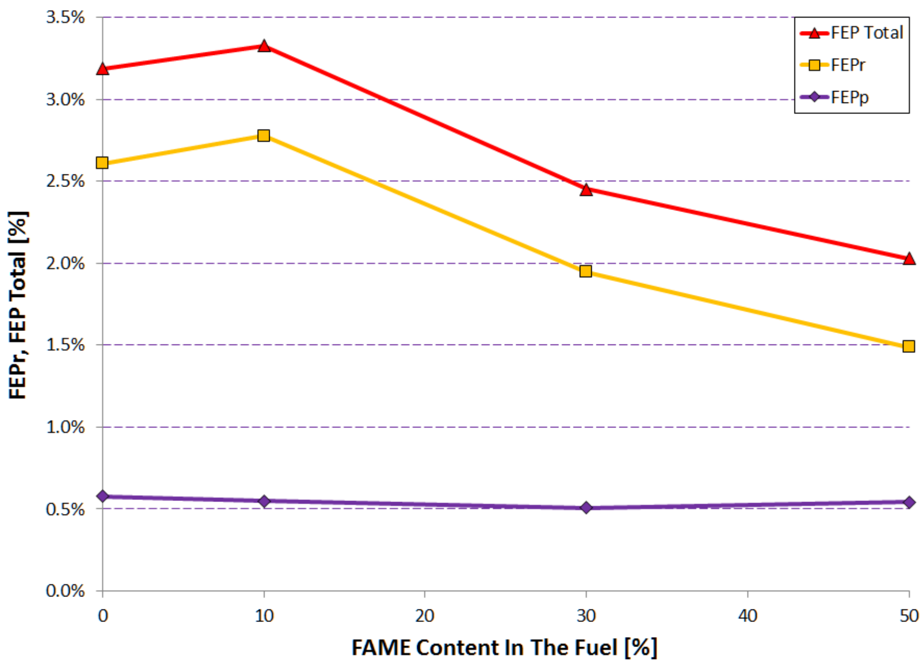
$$FEP_r \text{ (in \%)} = 100 \frac{\text{Fuel injected during post injection}}{\text{Total fuel consumed by the engine}} \quad (3)$$

The FEP_{total} is then the sum of individual Fuel Economy Penalties due to backpressure and regeneration [19]:

$$\mathrm{FEP_{total}} = \mathrm{FEP_p} + \mathrm{FEP_r} \tag{4}$$

The calculated FEPs for all fuel blends are shown in **Figure 8**. As shown, FEPp is almost constant because it depends mainly on the DPF backpressure and the BMEP, which is the same for all fuels. In general, the backpressure differences among the four test fuels are small (**Figure 4**) so the variation from fuel to fuel is also quite small. The FEPp values (0.5 - 0.6%) are somewhat lower than the values found in previous literature [4, 10, 18, 19, 20]. This may be attributed to the relatively low exhaust flow rates during the NEDC. The pressure drop across the filter depends on the exhaust velocity, so, if the engine operates at higher speeds and loads, the ΔP will be higher and, consequently, the FEPp will increase, though this may be partly mitigated by the higher tendency for passive regeneration in higher flow/higher exhaust gas temperature cycles.

Figure 8. Fuel Economy Penalty (FEP) factors at the same soot loading (6 g/l) vs. FAME content



The FEP_{total} for B10 seems to be higher compared to B0 although the difference is very small (3.3 vs. 3.2%). The higher FAME contents in the other two fuels reduce the FEP_r as expected.

This trend is the result of two opposing effects. First, the lower energy content (LHV) of the FAME/diesel blends (**Table 1**) means that slightly more fuel must be consumed during post injection in order to achieve the same exhaust temperature at the DPF. However, during engine operation over the NEDC, the final soot loading on the DPF was the same for all fuels (6 g/l), so the fuel quantity that must be consumed when the engine runs on B50 is much higher than with B0 due to its lower soot loading rate (**Figure 3**). From the definition of FEP_r (Equation 3), both the numerator and denominator increase with increasing FAME content. However, the B50 fuel consumed over the NEDC is almost doubled compared to the B0 fuel, while the corresponding fuel consumed during post injection is only 14% higher (**Appendix 4**). The overall effect is a 43% reduction in FEP_r when the engine runs with B50 compared to B0. The calculated FEP_r values are similar to those found in the literature [18, 21].

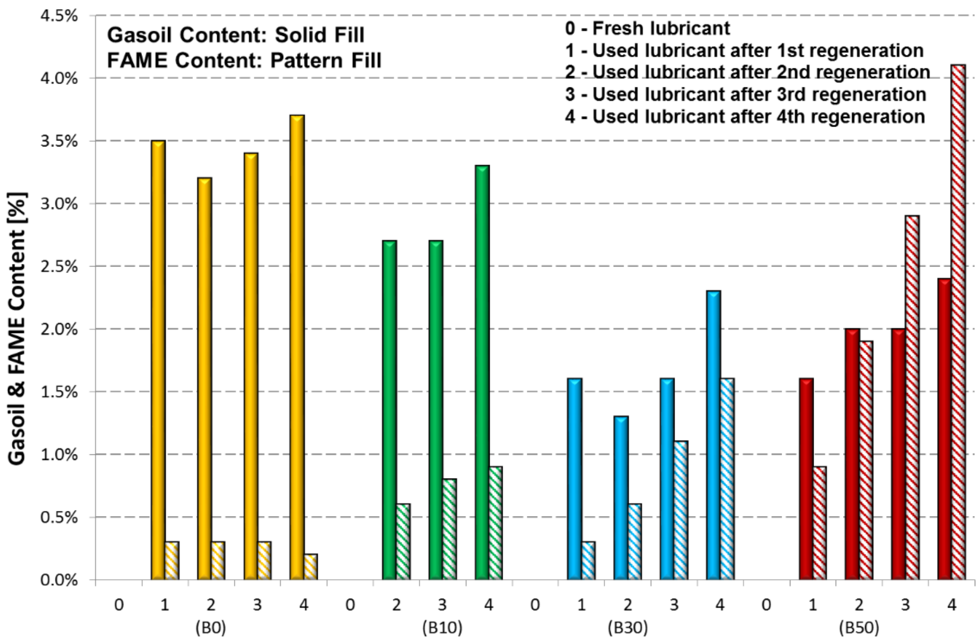
The FEP_{total} shows the same trend as FEP_r which is not surprising because the FEP_p is almost constant for all fuel blends. The FEP_{total} is within the range previously reported in the literature [18]. Higher FAME contents in diesel fuel clearly have a beneficial effect on FEP_{total}.

4.3. FUEL DILUTION IN ENGINE OIL

The analysis of the engine oil samples taken after each regeneration is shown in the following figures. The FAME content was measured by IR spectroscopy according to DIN EN 14078 and confirmed by gas chromatography, while the fuel concentration was measured by gas chromatography according to method DIN 51454.

The fuel concentration in the engine lubricant reached a given value after the first DPF regeneration and remained within a relatively constant range for the next regenerations (**Figure 9**). Overall, the fuel concentration in the lubricant is lower as the FAME content in fuel increases.

Figure 9. Diesel and FAME content (DIN 51454) in the lubricant samples



The FAME content in lubricant increases with the number of DPF regenerations. The higher the FAME content in the fuel blend, the higher the increase of the FAME content in the engine lubricant whilst gasoil content stays the same or increases slightly. (**Figure 9**). It is observed that a low level of FAME is indicated as being present in the B0 lubricant, this is believed to be due to a measurement error. For the measurements with B10 there is a small increase from 0.6 to 0.9% over successive regenerations. This effect becomes more apparent for B30 where the final FAME concentration is more than five times that after the first regeneration. For B50, this effect is more evident, with the FAME content reaching 4.1% after the last regeneration.

These results, combined with the total diesel content measurements, confirm that the evaporation rate of FAME is lower than that of diesel fuel in the lubricant. When the FAME content in the fuel blend increases, the FAME fraction of the total fuel diluted in the lubricant is higher and increases with the number of DPF regenerations (**Figure 10**). This effect can be attributed to the lower evaporation rate of FAME compared to diesel fuel. As was described above, there is a cycle of constant fuel addition into the lubricant mostly during DPF regenerations and removal through evaporation from the lubricant. FAME evaporates at a lower rate, so with an increasing number of DPF regenerations, more FAME and diesel are added to the lubricant, but most of the diesel fuel evaporates. It can be noted that there appears to be FAME in the total fuel diluted using B0. This is thought to be due to misidentification of the peaks due to FAME in the GC method used rather than FAME being present in the sump of the engine.

Figure 10. FAME content in total fuel diluted (DIN 51454) in the lubricant samples

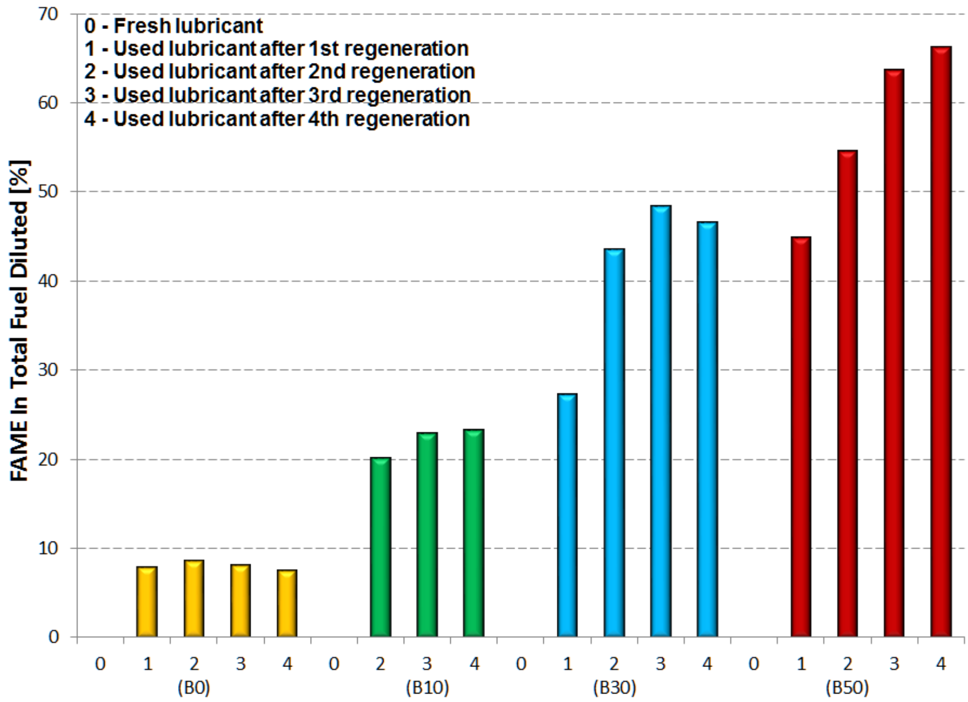
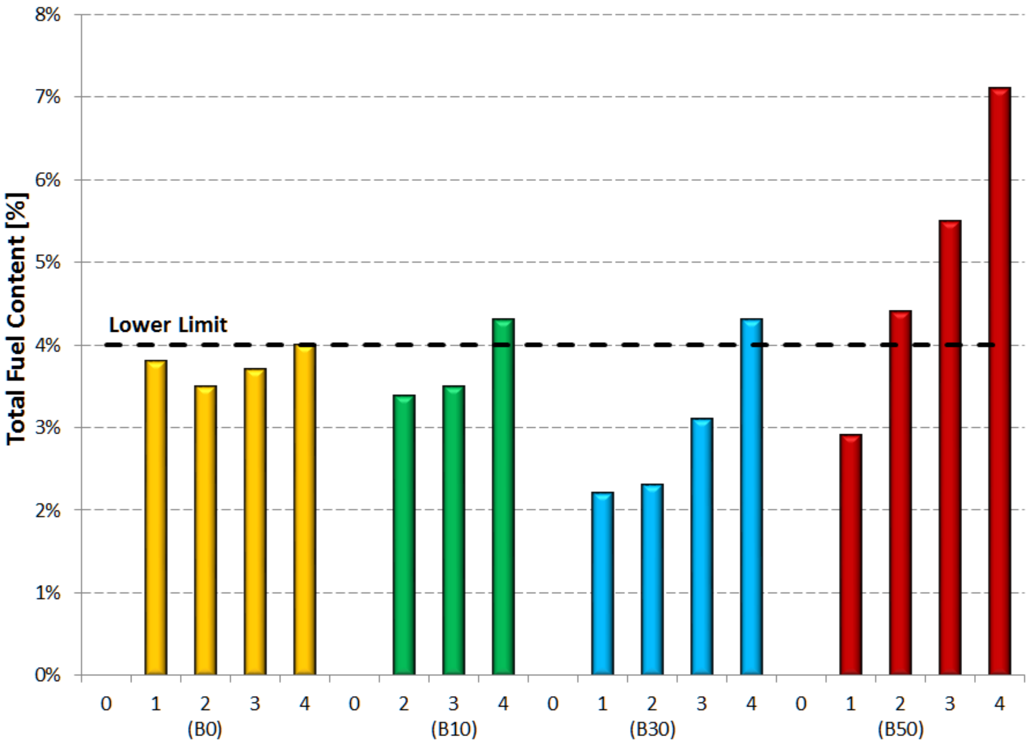


Figure 11. Total fuel content (DIN 51454) in the lubricant samples



It should be noted that the dilution of engine oil with fuel should be kept below certain levels defined by the manufacturer. The recommended dilution limits range from 4-10% [22, 23, 24, 25]. Dilution levels up to 10-15% are considered to be unacceptable [26]. This indicates that this specific regeneration procedure has a significant effect on engine oil dilution with fuel. This appears to be exacerbated in the FAME containing fuels, in particular with B50 (**Figure 11**).

It should be noted that the interval between DPF regenerations was extended with FAME blends, therefore a more representative comparison of fuel dilution tendency for FAME free and FAME containing blends would be on a mileage instead of a number of regenerations basis (**Table 2**). Given that the DPF regeneration interval is almost doubled with B50 this would offset the tendency for FAME accumulation over an oil drain interval in terms of contribution to total oil dilution of the fuel FAME content.

Table 2. Mileage to reach a) 6g/l on the DPF and b) 4% fuel dilution limit

	B0	B10	B30	B50
Number Of Cycles [-]	40	42	57	78
a) Mileage To Reach DPF 6g/l [km]	442	464.1	629.85	861.9
	B0	**B10**	**B30**	**B50**
Number Of Cycles [-]	160	168	228	156
b) Est. Km To Reach 4% dilution [km]	1768	1856	2520	1724

Furthermore, the NEDC cycle is a very low load and low temperature cycle with little opportunity for passive DPF regeneration to occur. In realistic drive patterns with higher loads, more passive regeneration and therefore fewer active DPF regenerations, the effect of FAME on fuel dilution may be less pronounced.

5. CONCLUSIONS

A repeatable procedure for determining fuel effects on DPF regeneration frequency was developed on a Euro 5-compliant 1.4l turbocharged diesel bench engine. The DPFs were loaded over the regulatory NEDC until a specific soot loading limit had been reached and the filters were then regenerated.

The results confirmed that the addition of FAME in diesel fuel decreases the engine-out PM emissions and DPF regeneration frequency. The effects can be substantial with the DPF regeneration interval for B50 blend being almost twice that with the B0 blend. This trend was confirmed with other measurements that showed a good agreement between the DPF weighing procedure, the PM measured gravimetrically in the CVS, and the solid PM measured with the Micro Soot Sensor.

The fuel economy penalty due to increased backpressure (FEPp) over the DPF was essentially constant at 0.5-0.6% for all four test fuels. The fuel economy penalty due to DPF regeneration (FEPr) decreased with increasing FAME in the fuel, from 2.6-2.7% for the B0 and B10 blends reducing to 1.5% for the B50 blend. Since the FEPp from backpressure was essentially constant, the FEPtotal for DPF regeneration followed the same trend as FEPr reaching 3.1-3.2% for B0-B10 and about 2% for B50.

The fuel dilution measurements showed that the FAME content in the engine oil increased with higher FAME content in the fuel blend, however this was offset by a tendency for a lower diesel content in the lubricant used during engine testing with the fuel containing FAME, except in the case of the B50 which accumulated a level of FAME approaching lower recommended limits for lubricant dilution after 4 regenerations. It should be noted that the interval between DPF regenerations was extended with FAME blends, therefore a more representative comparison of fuel dilution tendency for FAME free and FAME containing blends would be on a mileage instead of a number of regenerations basis. Furthermore, the NEDC cycle is a very low load and low temperature cycle with little opportunity for passive DPF regeneration to occur. In realistic drive patterns with higher loads, more passive regeneration and therefore fewer active DPF regenerations, the effect of FAME on fuel dilution may be less pronounced.

6. GLOSSARY

BHT	Butylated Hydroxy Toluene
BMEP	Brake Mean Effective Pressure
CVS	Constant Volume Sampler (System)
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
FAME	Fatty Acid Methyl Ester
FEP	Fuel Economy Penalty
FQD	Fuel Quality Directive (2009/30/EC)
GHG	Greenhouse Gas
IR	Infrared (spectroscopy)
NEDC	New European Driving Cycle
NVOF	Non-Volatile Organic Fraction
PM	Particulate Matter
PN	Particle Number
PNC	Particle Number Concentration
RED	Renewable Energy Directive (2009/28/EC)
ΔP	Pressure drop across the DPF

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APPENDIX 1 – FUEL ANALYTICAL DATA

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G11/347	**Contact:**	Ken Rose
Fuel Type:	EN590 B0	**Order No:**	201112190 W/O 3
Customer:	CONCAWE	**Date:**	06/01/2012

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual		Report		C&B
Cetane Number	ASTM D613		51	-	52.6
Cetane Index	EN ISO 4264		46	-	51.9
Density @ 15°C	EN ISO 12185	kg/L	0.820	0.845	0.8334
Polycyclic Aromatics	IP 391	% m/m	-	11	4.4
Total Aromatics	IP 391	% m/m	Report		24.8
Total Aromatics	ASTM D1319	% v/v	Report		23.0
Olefins	ASTM D1319	% v/v	Report		0.9
Saturates	ASTM D1319	% v/v	Report		76.1
Sulfur	EN 20846	mg/kg	-	10	10.0
Flash Point	EN ISO 2719	ºC	55	-	63.0
Carbon Residue (10% Dis. Res)	ASTM D4530	% m/m	-	0.3	0.01
Ash	ASTM D482	% m/m	-	0.01	<0.001
Water and Sediment	ASTM D2709	% m/m	-	0.02	0
Copper Corrosion (3h at 50ºC)	ASTM D130	rating	1	-	1a
Fatty Acid Methyl Ester (FAME) Content	EN 14078	% v/v	Report		0
Oxidation Stability	ASTM D2274	g/m^3	-	25	5
Lubricity, Corrected Wear Scar Diameter (WSD 1.4) at 60ºC	EN ISO 12156-1	µm	-	460	234
Viscosity at 40ºC	ASTM D445	mm^2/s	2.0	4.5	2.514
Strong Acid Number	ASTM D974	mgKOH/g	Report		0
Carbon Content	ASTM D5291	% m/m	Report		86.41
Hydrogen Content	ASTM D5291	% m/m	Report		13.59
Oxygen Content	Calculation	% m/m	Report		0
Gross Calorific Value	IP 12	MJ/kg	Report		45.82
Net Calorific Value	IP 12	MJ/kg	Report		42.93
CFPP	EN 116	ºC	-	-15	-31
Cloud Point	ASTM D2500	ºC	-	-5	-12

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CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G11/347	**Contact:**	Ken Rose
Fuel Type:	EN590 B0	**Order No:**	201112190 W/O 3
Customer:	CONCAWE	**Date:**	06/01/2012

Test	Method	Unit	Limit		Result
			Min	Max	
Distillation					
E250	ASTM D86	% v/v	-	65	40.7
E350	ASTM D86	% v/v	85	-	95.9
IBP	ASTM D86	°C	Report		173.1
10% Volume Recovered	ASTM D86	°C	Report		206.6
20% Volume Recovered	ASTM D86	°C	Report		221.9
30% Volume Recovered	ASTM D86	°C	Report		234.9
40% Volume Recovered	ASTM D86	°C	Report		249.1
50% Volume Recovered	ASTM D86	°C	Report		262.5
60% Volume Recovered	ASTM D86	°C	Report		275.3
70% Volume Recovered	ASTM D86	°C	Report		289.3
80% Volume Recovered	ASTM D86	°C	Report		306.4
90% Volume Recovered	ASTM D86	°C	Report		329.3
95% Volume Recovered	ASTM D86	°C	-	360	345.4
FBP	ASTM D86	°C	Report		357.6
Residue	ASTM D86	% v/v	Report		1.4

Date:	06/01/2012
Signed:	

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Certificate of Analysis

Fuel Blend No: CAF-G11/438 **Contact:** Ken Rose
Fuel Type: B10 Diesel **Order No:** 201112190 W/O 3
Customer: CONCAWE **Date:** 06/01/2012

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual		Report		C&B
Cetane Number	ASTM D613		Report		52.4
Cetane Index	EN ISO 4264		Report		52.1
Density @ 15°C	EN ISO 3675	kg/L	Report		0.8386
Flash Point	EN ISO 2719	ºC	Report		66.0
Polycyclic Aromatics	EN 12916	% m/m	Report		5.0
Total Aromatics	EN 12916	% m/m	Report		22.3
Sulfur	IP 490	mg/kg	Report		9.0
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.02
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	IP 439	mg/kg	Report		71.0
Total Contamination	EN ISO 12662	mg/kg	Report		6.0
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME Type	Blending		Report		RME
FAME	EN 14078	% v/v	Report		10.2
FAME	Blend Addition	% v/v	Report		10.0
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		177
Viscosity at 40ºC	ASTM D445	mm^2/s	Report		2.651
Gross Calorific Value	IP 12	MJ/kg	Report		45.35
Cloud Point	EN ISO 23015	ºC	Report		-11
CFPP	EN 116	ºC	Report		-22

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Certificate of Analysis

Fuel Blend No:	CAF-G11/438	**Contact:**	Ken Rose
Fuel Type:	B10 Diesel	**Order No:**	201112190 W/O 3
Customer:	CONCAWE	**Date:**	06/01/2012

Test	Method	Unit	Limit		Result
			Min	Max	
Distillation					
E250	EN ISO 3405	% v/v	Report		34.4
E350	EN ISO 3405	% v/v	Report		96.1
IBP	EN ISO 3405	ºC	Report		174.0
10% Volume Recovered	EN ISO 3405	ºC	Report		209.6
20% Volume Recovered	EN ISO 3405	ºC	Report		227.3
30% Volume Recovered	EN ISO 3405	ºC	Report		243.1
40% Volume Recovered	EN ISO 3405	ºC	Report		258.8
50% Volume Recovered	EN ISO 3405	ºC	Report		274.0
60% Volume Recovered	EN ISO 3405	ºC	Report		288.6
70% Volume Recovered	EN ISO 3405	ºC	Report		304.4
80% Volume Recovered	EN ISO 3405	ºC	Report		320.1
90% Volume Recovered	EN ISO 3405	ºC	Report		335.6
95% Volume Recovered	EN ISO 3405	ºC	Report		346.1
FBP	EN ISO 3405	ºC	Report		355.7
Residue	EN ISO 3405	% v/v	Report		1.4

Date:	06/01/2012
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Certificate of Analysis

Fuel Blend No:	CAF-G11/439	**Contact:**	Ken Rose
Fuel Type:	B30 Diesel	**Order No:**	201112190 W/O 3
Customer:	CONCAWE	**Date:**	06/01/2012

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual		Report		C&B
Cetane Number	ASTM D613		Report		51.2
Cetane Index	EN ISO 4264		Report		52.5
Density @ 15°C	EN ISO 3675	kg/L	Report		0.8472
Flash Point	EN ISO 2719	ºC	Report		69.0
Polycyclic Aromatics	EN 12916	% m/m	Report		5.4
Total Aromatics	EN 12916	% m/m	Report		19.1
Sulfur	IP 490	mg/kg	Report		7.6
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.02
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	IP 439	mg/kg	Report		118.0
Total Contamination	EN ISO 12662	mg/kg	Report		9.3
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME Type	Blending		Report		RME
FAME	EN 14078	% v/v	Report		28.0
FAME	Blend Addition	% v/v	Report		30.0
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Oxidation Stability	EN ISO 12205	g/m^3	Report		8
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		162
Viscosity at 40ºC	ASTM D445	mm^2/s	Report		2.924
Gross Calorific Value	IP 12	MJ/kg	Report		44.12
Cloud Point	EN ISO 23015	ºC	Report		-10
CFPP	EN 116	ºC	Report		-20

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CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G11/439	**Contact:**	Ken Rose
Fuel Type:	B30 Diesel	**Order No:**	201112190 W/O 3
Customer:	CONCAWE	**Date:**	06/01/2012

Test	Method	Unit	Limit Min	Limit Max	Result
Distillation					
E250	EN ISO 3405	% v/v	Report		25.3
E350	EN ISO 3405	% v/v	Report		96.1
IBP	EN ISO 3405	°C	Report		178.0
10% Volume Recovered	EN ISO 3405	°C	Report		217.3
20% Volume Recovered	EN ISO 3405	°C	Report		239.6
30% Volume Recovered	EN ISO 3405	°C	Report		259.1
40% Volume Recovered	EN ISO 3405	°C	Report		279.1
50% Volume Recovered	EN ISO 3405	°C	Report		295.7
60% Volume Recovered	EN ISO 3405	°C	Report		310.8
70% Volume Recovered	EN ISO 3405	°C	Report		322.9
80% Volume Recovered	EN ISO 3405	°C	Report		332.0
90% Volume Recovered	EN ISO 3405	°C	Report		339.8
95% Volume Recovered	EN ISO 3405	°C	Report		347.0
FBP	EN ISO 3405	°C	Report		354.3
Residue	EN ISO 3405	% v/v	Report		1.3

Date:	06/01/2012
Signed:	

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Certificate of Analysis

Fuel Blend No: CAF-G11/440 **Contact:** Ken Rose
Fuel Type: B50 Diesel **Order No:** 201112190 W/O 3
Customer: CONCAWE **Date:** 06/01/2012

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual		Report		C&B
Cetane Number	ASTM D613		Report		51.3
Cetane Index	EN ISO 4264		Report		52.0
Density @ 15°C	EN ISO 3675	kg/L	Report		0.8578
Flash Point	EN ISO 2719	ºC	Report		75.0
Polycyclic Aromatics	EN 12916	% m/m	Report		2.3
Total Aromatics	EN 12916	% m/m	Report		12.6
Sulfur	IP 490	mg/kg	Report		5.6
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.06
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	IP 439	mg/kg	Report		176.0
Total Contamination	EN ISO 12662	mg/kg	Report		16.1
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME Type	Blending		Report		RME
FAME	EN 14078	% v/v	Report		48.7
FAME	Blend Addition	% v/v	Report		50.0
Oxidation Stability Rancimat	EN 15751	h	Report		16.7
Oxidation Stability	EN ISO 12205	g/m^3	Report		4
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		187
Viscosity at 40ºC	ASTM D445	mm^2/s	Report		3.294
Gross Calorific Value	IP 12	MJ/kg	Report		43.04
Cloud Point	EN ISO 23015	ºC	Report		-9
CFPP	EN 116	ºC	Report		-20

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Certificate of Analysis

Fuel Blend No:	CAF-G11/440	**Contact:**	Ken Rose
Fuel Type:	B50 Diesel	**Order No:**	201112190 W/O 3
Customer:	CONCAWE	**Date:**	06/01/2012

Test	Method	Unit	Limit Min	Limit Max	Result
Distillation					
E250	EN ISO 3405	% v/v	Report		15.3
E350	EN ISO 3405	% v/v	Report		96.0
IBP	EN ISO 3405	ºC	Report		183.5
10% Volume Recovered	EN ISO 3405	ºC	Report		233.1
20% Volume Recovered	EN ISO 3405	ºC	Report		262.2
30% Volume Recovered	EN ISO 3405	ºC	Report		288.1
40% Volume Recovered	EN ISO 3405	ºC	Report		307.1
50% Volume Recovered	EN ISO 3405	ºC	Report		319.5
60% Volume Recovered	EN ISO 3405	ºC	Report		327.9
70% Volume Recovered	EN ISO 3405	ºC	Report		333.1
80% Volume Recovered	EN ISO 3405	ºC	Report		337.2
90% Volume Recovered	EN ISO 3405	ºC	Report		341.4
95% Volume Recovered	EN ISO 3405	ºC	Report		348.3
FBP	EN ISO 3405	ºC	Report		352.7
Residue	EN ISO 3405	% v/v	Report		1.4

Date:	06/01/2012
Signed:	

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APPENDIX 2 – EMISSIONS AND FUEL CONSUMPTION RESULTS

Description			AMA - g/cycle				l/cycle	AMA - g/km				l/100 km
Repetition	Date	No.	CO	NOx	CO2	HC	FC (PUMA)	CO	NOx	CO2	HC	FC (PUMA)
B0	8/2/2013 R10	1	0.031	2.918	1148.811	0.085	0.452	0.003	0.264	103.965	0.008	4.093
	8/2/2013 R11	2	0.093	2.897	1146.975	0.133	0.438	0.008	0.262	103.799	0.012	3.966
	8/2/2013 R12	3	0.123	2.896	1146.486	0.148	0.451	0.011	0.262	103.754	0.013	4.077
B10	7/2/2013 R3	1	0.032	2.849	1188.047	0.090	0.465	0.003	0.258	107.516	0.008	4.210
	7/2/2013 R4	2	0.068	2.790	1188.773	0.133	0.461	0.006	0.252	107.581	0.012	4.172
	7/2/2013 R5	3	0.076	2.836	1184.909	0.146	0.454	0.007	0.257	107.232	0.013	4.109
B30	8/2/2013 R6	1	0.046	3.102	1152.477	0.106	0.454	0.004	0.281	104.297	0.010	4.109
	8/2/2013 R7	2	0.088	3.059	1149.969	0.141	0.454	0.008	0.277	104.070	0.013	4.106
	8/2/2013 R8	3	0.123	3.050	1149.162	0.156	0.452	0.011	0.276	103.997	0.014	4.086
B50	8/2/2013 R2	1	0.053	3.224	1164.121	0.107	0.459	0.005	0.292	105.350	0.010	4.156
	8/2/2013 R3	2	0.086	3.223	1165.891	0.132	0.464	0.008	0.292	105.510	0.012	4.195
	8/2/2013 R4	3	0.110	3.246	1161.286	0.144	0.455	0.010	0.294	105.094	0.013	4.118

Average - Repetitions Comparison

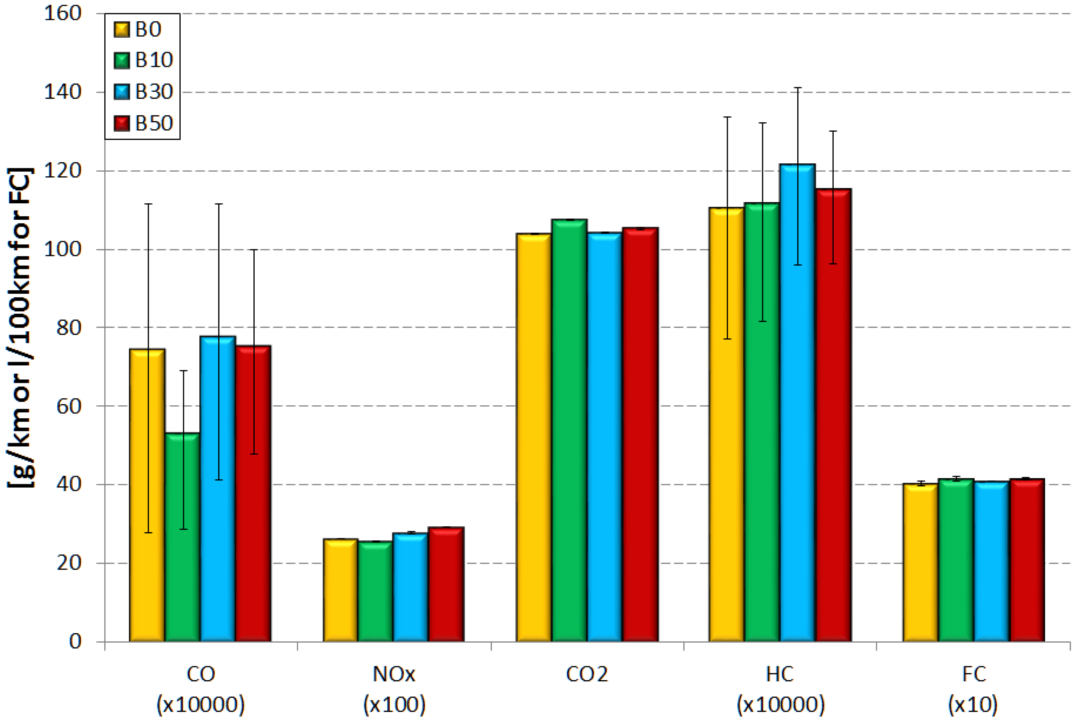
	AMA - g/km				l/100 km
No.	CO (x10000)	NOx (x100)	CO2	HC (x10000)	FC (x10)
B0	74.501	26.279	103.839	110.272	40.453
B10	53.162	25.566	107.443	111.410	41.637
B30	77.658	27.788	104.121	121.486	41.005
B50	75.204	29.240	105.318	115.244	41.563

Positive Error Value (Max - Average)

	AMA - g/km				l/100 km
No.	CO (x10000)	NOx (x100)	CO2	HC (x10000)	FC (x10)
B0	37.005	0.127	0.125	23.331	0.480
B10	15.999	0.218	0.138	20.702	0.467
B30	34.001	0.286	0.176	19.783	0.083
B50	24.681	0.135	0.192	14.917	0.390

Negative Error Value (Average - Min)

	AMA - g/km				l/100 km
No.	CO (x10000)	NOx (x100)	CO2	HC (x10000)	FC (x10)
B0	46.734	0.069	0.085	33.060	0.796
B10	24.346	0.316	0.211	29.890	0.552
B30	36.392	0.184	0.124	25.576	0.142
B50	27.492	0.074	0.224	18.827	0.382


160
140
120
100
80
60
40
20
0
[g/km or l/100km for FC]
B0
B10
B30
B50
CO
(x10000)
NOx
(x100)
CO2
HC
(x10000)
FC
(x10)

APPENDIX 3 – LUBRICANT ANALYTICAL RESULTS

ASG Analytik-Service Gesellschaft mbH
Trentiner Ring 30 • D-86356 Neusäss / Germany

CONCAWE
Boulevard du Souverain 165
B-1160 BRUSSELS

your reference : Mr. Ken Rose

sample receipt : 23.07.2013
sampling : University Thessaloniki
report date : 31.07.2013
page : 1 of 2

Report-No. : 214637

Customer : Mr. Dimitris Katsaounis, Lab of applied Thermodynamics Polytechnik School, BLDG Gamma Aristotle University Campus Thessaloniki

Sample	ASG-ID	Parameter	Method	Result	Unit
lubricant sample #01	238251	Fatty acid methylester content	DIN EN 14078	0,3	% [V/V]
		Gasoil content	ASTM D 7169	<0,5	% [m/m]
lubricant sample #02	238252	Fatty acid methylester content	DIN EN 14078	0,9	% [V/V]
		Gasoil content	ASTM D 7169	4,0	% [m/m]
lubricant sample #03	238253	Fatty acid methylester content	DIN EN 14078	1,1	% [V/V]
		Gasoil content	ASTM D 7169	4,0	% [m/m]
lubricant sample #04	238254	Fatty acid methylester content	DIN EN 14078	1,2	% [V/V]
		Gasoil content	ASTM D 7169	5,0	% [m/m]
lubricant sample #05	238255	Fatty acid methylester content	DIN EN 14078	0,3	% [V/V]
		Gasoil content	ASTM D 7169	<0,5	% [m/m]
lubricant sample #06	238256	Fatty acid methylester content	DIN EN 14078	0,6	% [V/V]
		Gasoil content	ASTM D 7169	5,0	% [m/m]
lubricant sample #07	238257	Fatty acid methylester content	DIN EN 14078	0,6	% [V/V]
		Gasoil content	ASTM D 7169	5,0	% [m/m]
lubricant sample #08	238258	Fatty acid methylester content	DIN EN 14078	0,6	% [V/V]
		Gasoil content	ASTM D 7169	5,0	% [m/m]
lubricant sample #09	238259	Fatty acid methylester content	DIN EN 14078	0,5	% [V/V]
		Gasoil content	ASTM D 7169	6,0	% [m/m]
lubricant sample #10	238260	Fatty acid methylester content	DIN EN 14078	0,9	% [V/V]
		Gasoil content	ASTM D 7169	4,0	% [m/m]
lubricant sample #11	238261	Fatty acid methylester content	DIN EN 14078	1,2	% [V/V]
		Gasoil content	ASTM D 7169	6,0	% [m/m]

Thomas Wilharm
Dr. Th. Wilharm

This report is related only to the samples stated above and may not be reproduced except in full, without approval of the testing laboratory. Storage of the samples: 4 weeks from report date

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your reference : Mr. Ken Rose
your order-no. :
date of order :
sample receipt : 23.07.2013
sampling : University Thessaloniki
report date : 31.07.2013
page : 2 of 2

Report-No. : 214637

Sample	ASG-ID	Parameter	Method	Result	Unit
lubricant sample #12	238262	Fatty acid methylester content	DIN EN 14078	1,5	% [V/V]
		Gasoil content	ASTM D 7169	6,0	% [m/m]
lubricant sample #13	238263	Fatty acid methylester content	DIN EN 14078	2,0	% [V/V]
		Gasoil content	ASTM D 7169	7,0	% [m/m]
lubricant sample #14	238264	Fatty acid methylester content	DIN EN 14078	2,5	% [V/V]
		Gasoil content	ASTM D 7169	7,0	% [m/m]
lubricant sample #15	238265	Fatty acid methylester content	DIN EN 14078	0,9	% [V/V]
		Gasoil content	ASTM D 7169	4,0	% [m/m]
lubricant sample #16	238266	Fatty acid methylester content	DIN EN 14078	1,8	% [V/V]
		Gasoil content	ASTM D 7169	5,0	% [m/m]
lubricant sample #17	238267	Fatty acid methylester content	DIN EN 14078	2,8	% [V/V]
		Gasoil content	ASTM D 7169	6,5	% [m/m]
lubricant sample #18	238268	Fatty acid methylester content	DIN EN 14078	3,8	% [V/V]
		Gasoil content	ASTM D 7169	6,0	% [m/m]
lubricant sample #19	238269	Fatty acid methylester content	DIN EN 14078	5,0	% [V/V]
		Gasoil content	ASTM D 7169	6,0	% [m/m]

Thomas Wilharm
Dr. Th. Wilharm

This report is related only to the samples stated above and may not be reproduced except in full, without approval of the testing laboratory. Storage of the samples: 4 weeks from report date

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APPENDIX 4 – REGENERATION FUEL CONSUMPTION SUMMARY

	B0	B10	B30	B50	
Expected Lifetime Mileage [km]	250,000	250,000	250,000	250,000	
Number Of Cycles [-]	40	42	57	78	
Mileage To Reach DPF 6g/l [m]	442	464.1	629.85	861.9	
Number Of Regenarations [-]	**566**	**539**	**397**	**290**	-48.76%
FC To Reach DPF 6g/l [l]	**18.31**	**19.22**	**26.97**	**36.63**	**Average from all repetitions of each fuel**
				200.14%	
FC On NEDC Cycles [l]	**18.20**	**19.11**	**26.83**	**36.43**	
FC From BMEP Formula [l]	**0.11**	**0.11**	**0.14**	**0.20**	**Average from all repetitions of each fuel**
FC For Regeneration (PUMA) [l]	**0.48**	**0.53**	**0.52**	**0.54**	
				114.04%	
FEPp [%]	**0.58%**	**0.55%**	**0.51%**	**0.54%**	
FEPr [%]	**2.61%**	**2.78%**	**1.95%**	**1.49%**	
Total FEP [%]	**3.19%**	**3.33%**	**2.45%**	**2.03%**	

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