

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

Kenneth Rose, Heather Hamje, Liesbeth Jansen, Corrado Fittavolini, Richard Clark, and Maria Dolores Cardenas Almena
Concawe

Dimitris Katsaounis, Christos Samaras, Savas Geivanidis, and Zissis Samaras
Aristotle University of Thessaloniki

ABSTRACT

Modern diesel vehicles utilize two technologies, one fuel based and one hardware based, that have been motivated by recent European legislation: diesel fuel blends containing Fatty Acid Methyl Esters (FAME) and Diesel Particulate Filters (DPF). Oxygenates, like FAME, 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 soot 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 verify 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 increases with higher FAME contents in the fuel blend.

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INTRODUCTION

Recent European legislation, such as the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD), 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.

Modern diesel vehicles utilize two technologies that have been motivated by this combination of European fuel and vehicle legislation: diesel fuel blends containing FAME and Diesel Particulate Filters (DPF). DPFs are now widely used on newer European diesel vehicles and are responsible for removing filterable particulate matter (PM) and much of the ultrafine 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 [1, 2, 3, 4, 5, 6]. 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 [1] and by diluting polyaromatic hydrocarbons in the diesel fuel with a polyaromatics-free blending component.

The use of DPFs in modern vehicles results in a small but important increase in fuel consumption mainly due to two factors. First, additional engine work is required to compensate for the increasing pressure drop across the DPF 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 [7, 8].

Second, 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 injection using the post injection system of the engine. This injection of fuel results in higher concentrations of hydrocarbons in the exhaust, which are oxidized in the diesel oxidation catalyst (DOC) or the catalytic DPF. This exothermic process increases the temperature at the DPF to sufficient levels that the accumulated soot is burned away 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 this process is generally understood, the nature of the effect and the role of FAME have not been systematically investigated. 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 regeneration frequency. The study had three objectives: (1) develop a repeatable bench engine test protocol to evaluate the impact of FAME content on DPF regeneration frequency, (2) use this test protocol to relate the DPF regeneration interval to the FAME content in diesel, and (3) assess the possible benefits or debits of FAME content on fuel consumption.

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, O_2 and NO_x 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 , NO_x , and CO_2) were measured with an AVL AMA i60 analyzer (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.

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 ($^{\circ}C$) (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, 600cps/3mils, 1.1 liters) was installed at the exhaust line, upstream of the DPF. The conventional DPF, a SiC, 300cps/12mils, 16 segment, 2.5 liter, was installed downstream of the DOC. Four identical and initially unused DPFs were used in this study, one for each test fuel.

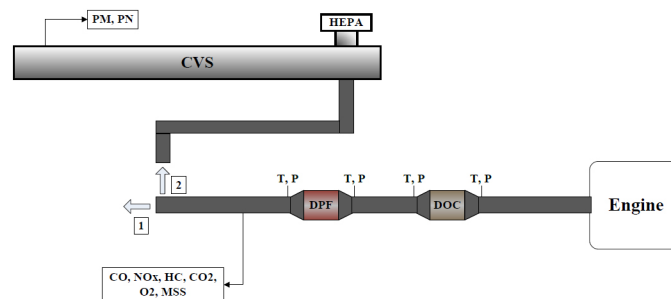


Figure 1. Schematic of the experimental setup and measured quantities

TEST PROCEDURE

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.

Before each test on a new diesel blend, the engine oil was changed and a sample of the fresh oil was taken. At the start of each test, the engine was warmed up with the DPF removed from the exhaust line, until a sufficient operating temperature had been reached. This avoided any repeatability problems that might occur during cold start and ensured that the DOC would be active from the beginning of each measurement. After this preconditioning, the prepared DPF (see below) was installed in the exhaust to start the test. The engine simulated multiple repetitions of the New European Driving Cycle (NEDC) until a specified loading limit on the DPF had been reached, at which point the DPF was regenerated using post injection.

The DPFs were unused at the start of testing so a conditioning procedure consisting of a loading/regeneration cycle was used to bring the filters to a state similar to that after some road use. The engine was operated 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 another lubricant sample was taken.

The soot loading procedure was then initiated over the NEDC with a continuous engine speed and torque demand from the dynamometer. The soot loading of the DPF was measured by weight measurements at the end of each day. The tailpipe gaseous emissions after the DPF were measured during the first 6 cycles of the last loading day, to check engine repeatability. This procedure was repeated until a soot loading of 6 g/l had been achieved (DPF weighing at 200°C). The DPF was then fully regenerated according to the procedure described above and another 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. The engine lubricant samples were analyzed to measure the FAME and fuel contents.

After the end of all repetitions with all fuels, the filtration efficiency of the DPFs was measured to verify proper condition and ensure that no damages 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.

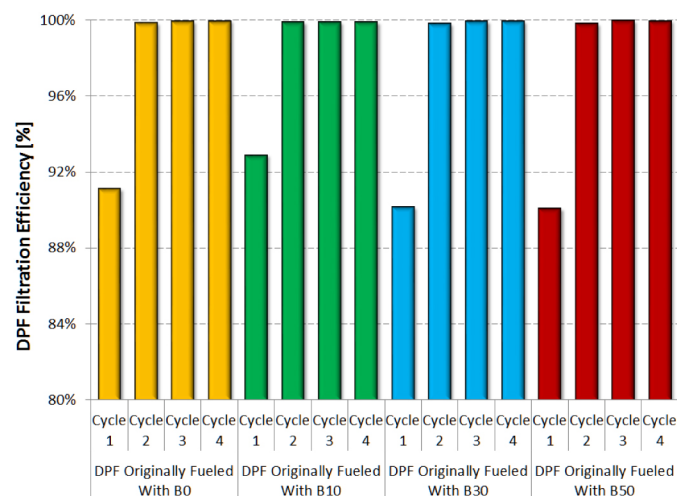


Figure 2. DPF filtration efficiency using market diesel fuel

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 (at 200°C). The volatile part of the PM measured with the legislated gravimetric method was measured by heating the PM filters 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), remained at 200°C for 60min, and cooled to ambient (30min).

RESULTS

PM Emissions

As was described above, the test procedure was followed until 6 g/l of soot loading on the DPF had been reached. The soot loading values based on DPF weight measurements indicated that increasing FAME content in the fuel blend lengthens the time between DPF regenerations (Figure 3). For example, the required mileage to reach the 6g/l regeneration limit was about two times greater for the B50 fuel compared with the B0 fuel.

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. The PM emissions with each fuel defined the number of NEDC cycles and the total time required for each repetition to complete. For instance, when using B0, the 6 g/l loading limit was reached in 2 days, while the test duration doubled for the B50 fuel (4 days). The number of cycles and the corresponding distance between regenerations for each fuel is shown in Figure 3.