

Fuel Property Effects on Oil Dilution in Diesel Engines

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ABSTRACT

Light-duty diesel vehicles that make use of a diesel particulate filter (DPF) generally require periodic active regenerations. This is achieved by late, in-cylinder post-injections designed to add unburned fuel into the exhaust system to raise the DPF temperature and burn off the soot. These late injections do not atomise and evaporate as readily as during normal combustion causing a portion of this fuel to impinge on the cylinder wall and wash down, with the engine oil, into the sump. This can result in degradation of the engine oil which could lead to increased engine wear and/or engine failure.

When investigating which fuel properties have an effect on oil dilution, most literature suggests high final boiling point fuels increase fuel addition rates to engine oil. Through the use of accelerated oil dilution testing on an engine test bench, the findings of this paper suggest that a fuel with low viscosity, density and surface tension, and high front-end volatility (which are linked to fuel spray droplet size and associated in-cylinder droplet evaporation rates) is better correlated with low fuel addition rates to engine oil.

Fuel subtraction is where fuel is evaporated out of the engine oil during elevated oil temperatures which is a different phenomenon to fuel addition. Fuel subtraction rates were shown to follow the derivative of the back-end of a fuel's distillation curve (percentage volume distilled with respect to temperature).

Blends and neat forms of diesel fuels derived from crude oil, gas-to-liquids (GTL), coal-to-liquids (CTL), rapeseed methyl ester (RME) and soya bean methyl ester (SME) were used. GTL and CTL diesel resulted in significantly reduced oil dilution when compared to the other fuels used in this study.

CITATION: Watrus, M., "Fuel Property Effects on Oil Dilution in Diesel Engines," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi: 10.4271/2013-01-2680.

INTRODUCTION

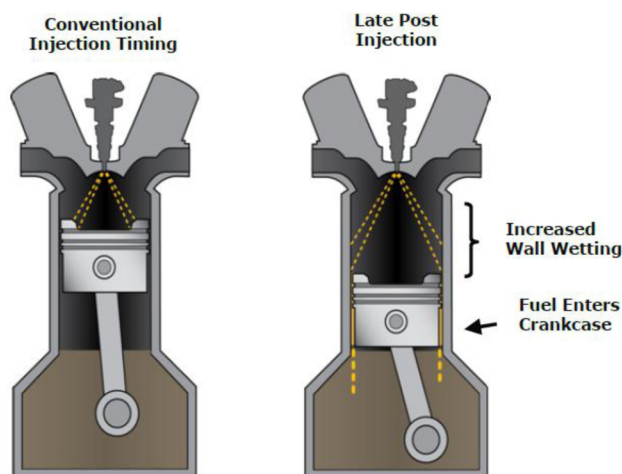
Particulate matter limits for diesel vehicles have been lowered with each new release of emission legislation, and are at the point now where a DPF is considered mandatory on light-duty diesel passenger cars. As the filter traps the soot emissions from the engine, the exhaust back pressure is slowly increased. As this is not desirable, these filters require periodic regeneration which is achieved by raising the filter bed temperatures to approximately 550-650°C.

These temperatures can be reached during high load operation which would result in passive regeneration of the filter. However, most vehicles are driven in a manner that does not passively regenerate the DPF, and there are several techniques employed to achieve this increase in temperature artificially [1, 2, 3, 4]. Retarding combustion to later in the cycle, and reducing air/fuel ratios can increase exhaust temperature, but usually cannot attain the required increase in temperature for particulate oxidation. Injecting fuel upstream

of the DPF is a very effective method of initiating particulate oxidation over the DPF but requires additional engine hardware which adds additional cost. Fuel can also be injected very late in the cycle, typically near exhaust valve opening. The idea is that the fuel vaporises but does not oxidise in the cylinder, thus generating unburned hydrocarbons that will oxidise over the diesel oxidation catalyst (DOC) thereby raising the exhaust gas temperature. This hot exhaust gas then flows through the DPF and oxidises the trapped soot. Typically the electronic control unit (ECU) uses closed-loop control of the post-injection duration to target the soot oxidation temperature upstream of the DPF [5].

The strategy most commonly used is late in-cylinder injection near exhaust valve opening due to it being a zero additional hardware cost option that makes use of existing engine hardware. Although this is a very attractive strategy it does come with some known disadvantages, one being engine oil dilution by fuel. When injecting very late in the

combustion cycle the pressures and temperatures in the cylinder are much lower, and this usually results in incomplete fuel vaporisation and subsequent fuel impingement on the cylinder wall. This fuel is then transported down the cylinder wall into the engine oil. A schematic of this mechanism is shown below in [Figure 1](#).



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Figure 1. Schematic showing fuel entry into engine oil
[10]

The result is that the fuel dilutes the oil which adversely affects engine wear, due to a lowering of the oil's viscosity. A typical design consideration for allowable oil dilution is up to 5% [6].

Optimisation of late in-cylinder post-injections can reduce the quantity of fuel entry into the oil sump. Splitting the post-injection into two shorter injections enabled an oil dilution reduction of 27% without any negative effects on the particulate filter regeneration [5]. The reduction was attributed to two phenomena: 1) a reduction of injection volume per post-injection event, thereby reducing the jet pulse and reducing impingement on the cylinder wall, and 2) a reduction in average injection pressure per injection caused by the nozzle throttling during opening and closing.

Oil dilution is a phenomenon that has two competing mechanisms at work; fuel addition and fuel subtraction. Fuel addition to oil occurs when the injected fuel fails to vaporise and makes contact with the cylinder wall in liquid form and washes down into the sump. Fuel vaporisation is affected by a variety of factors including charge motion, charge density, in-cylinder temperatures, and injection strategy [7]. Fuels with higher final boiling points also affect the spray characteristics of the fuel into the combustion chamber. The effect is that the fuel does not vaporise as readily as a lower final boiling point fuel, thus more fuel impingement occurs on the cylinder wall thereby increasing oil dilution [6].

Other fuel properties that affect the spray characteristic, more specifically the mean droplet size, are surface tension,

viscosity and density. An increase in any of these properties will increase mean droplet size. A larger droplet size coupled with a decrease in volatility, such as in fatty acid methyl ester (FAME), will cause fuel droplets not to evaporate as readily, and thereby increase the amount of liquid fuel impinging on the cylinder wall. The net result will be increased oil dilution by fuel [8, 9, 10].

Once the fuel is in the oil, the fuel can be removed through evaporation; either from the oil on the cylinder walls or from the oil in the sump or valve train, and exit through the crankcase breather or blow-by tube. This removal of fuel is referred to as fuel subtraction.

Fuel addition occurs mostly during DPF regeneration due to late in-cylinder post injections, and only a fraction of engine operation is spent in this regeneration mode. However, fuel subtraction occurs continuously - provided certain conditions are met. During fuel subtraction, typically the more volatile fuel components will be removed, but higher boiling point components may also be removed from the oil on the cylinder walls during combustion. Balancing these addition and subtraction rates will ultimately determine the amount of oil dilution.

Biodiesel and Engine Oil Interactions

As fuel dilutes the engine oil, the oil's viscosity will decrease due to the lower viscosity of the fuel. It has been shown that, in some cases, the viscosity will eventually start to increase. This has been attributed to the oxidation and polymerization of unsaturated fuel components in biodiesel [11]. Oxidation of lubricating oil can lead to corrosive weak acids that corrode lead which is a material used in journal bearings [13].

Viscosity increases are particularly evident in biodiesels with a high content of unsaturated acids in the esters (shown by a higher iodine number). Furthermore, biodiesels with increasing iodine number have also resulted in increasing piston ring deposits; noticeably around the second ring groove [13]. Similar deposits were reported in a VW TDI lubricating test using a 15% RME blend [12]. Piston ring groove deposits may lead to piston ring sticking, blow-by, excessive oil consumption and soot contamination.

Contrary to many of these negative impacts on engine oil properties in literature, some research has shown that there is no significant difference in wear protection between biodiesel (canola oil, peanut oil, soybean oil, and chicken fat) and mineral diesel, when these are added as a diluent to engine oil [14].

Fresh FAME diluted into engine oil resulted in reduced wear when tested on a high frequency reciprocating rig (HFRR) and four-ball wear test bench. This was attributed to the intrinsically higher lubricity of FAME. However, aged FAME in engine oil showed the opposite. The increase in wear was linked to the interaction of oxidation products with anti-wear additives (ZDDP) in the oil [8, 15].

Mack T-12 engine tests conducted on Ultra Low Sulfur Diesel (ULSD 15ppm) and a 20% SME blend (B20) with

ULSD showed that the B20 had more than double the used oil lead level than ULSD. Due to increased lead corrosion and oxidation of biodiesel in crankcase oil, equipment operators are encouraged to reduce oil drain intervals to ensure adequate component protection when running on biodiesel [12].

GTL Diesel and Engine Oil Interactions

No literature was found relating to oil dilution using GTL diesel or blends with FAME or mineral diesel. However, literature was found on hydrogenated vegetable oil (HVO) which is also a highly paraffinic fuel and has many similar properties to GTL diesel. A reduction in oil dilution was observed when 5% HVO was blended into a B5 diesel (resultant blend 5% HVO, 5% FAME and 90% EN590 diesel), as compared to 5% FAME and 95% EN590 diesel [16]. It was suggested that the HVO acts like a “combustion and/or evaporation booster”.

METHODOLOGY

An in-house developed test method was used to quantify oil dilution by each fuel. This method has been developed to accelerate oil dilution in a controlled engine test. The test procedure consists of a 6 hour bench test on a 6-cylinder diesel passenger car engine. In order to induce accelerated oil dilution, a reprogrammable ECU is used. This ECU is configured to constantly regenerate the DPF through very late in-cylinder injections near exhaust valve opening.

Engine

The details of the Mercedes Benz OM642 test engine used for this research are presented in [Table 1](#).

Table 1. Test engine specifications

Name	OM642
Manufacturer	Mercedes Benz
Cylinders	V6
Capacity	2987cm ³
Compression ratio	18:1
Fuel System	Common rail direct injection using piezo injectors
Max Power	165kW
Max Torque	510Nm
General	Variable geometry turbocharger, EGR, intake throttle, intake swirl flaps
Emission control	Close-coupled diesel oxidation catalyst (DOC), secondary DOC, catalysed diesel particulate filter (CDPF)
Emission level	EURO 4

The engine operates with an in-house developed reprogrammable ECU (based on National Instruments hardware) for full authority control. [Figure 2](#) below shows the ECU installed in the test cell.

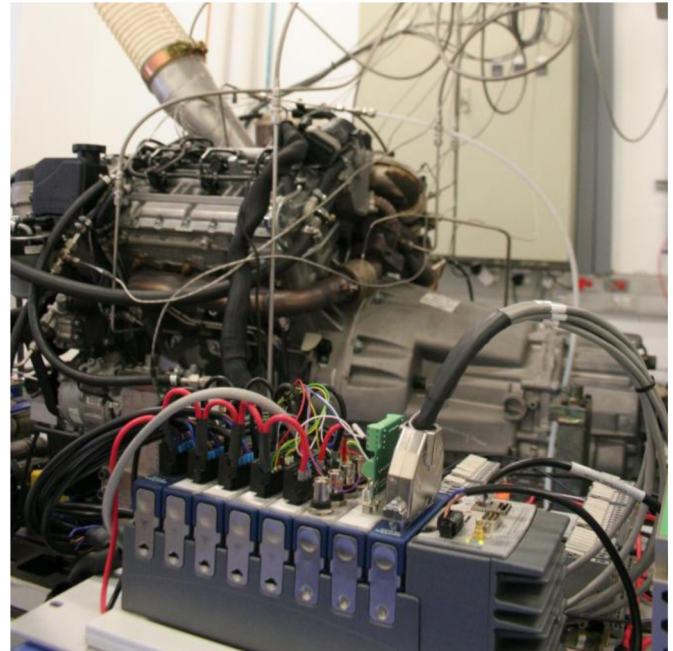


Figure 2. Photograph of reprogrammable ECU installed in test cell

Test Fuels and Engine Oil

The test fuels consisted of binary blends of GTL or EN590 diesel with RME and SME. Additionally a neat CTL diesel and an experimental low viscosity diesel were also included.

GTL and CTL are synthetic diesel fuels that are produced using the Fischer-Tropsch (FT) process. The low viscosity diesel is a fuel blend component extracted from the FT process which was included to test the correlations presented in the subsequent sections.

The test fuel matrix is shown below in [Table 2](#). For full fuel specification analysis refer to [Appendix A](#).

Table 2. Test fuel matrix

Fuels Matrix	(% volume)					
	RME	SME	EN590	GTL	CTL	LOW VISCOSITY
EN590			100			
GTL				100		
7% RME + EN590	7		93			
7% SME + EN590		7	93			
7% RME + GTL	7			93		
7% SME + GTL		7		93		
20% RME + EN590	20		80			
20% SME + EN590		20	80			
20% RME + GTL	20			80		
20% SME + GTL		20		80		
CTL					100	
LOW VISCOSITY						100

The engine oil specifications are shown in [Table 3](#) below. A fully-synthetic oil as specified by the OEM was selected for this test procedure.

Table 3. Engine oil specification

Oil name	Sasol Engine Oil Synthetic W507
Grade	SAE 5W-30
Viscosity @ 100°C @ 40°C	11.6 mm ² /s 73.7 mm ² /s
Viscosity Index	151
Pour Point	-39°C
Flash Point (COC)	246°C
Density @ 15°C	0.85 kg/m ³
Sulphated Ash	0.6 % m/m
Total Base Number	6.1 mg KOH/g

Analysis

A modified version of an ASTM method for oil dilution was employed for oil analysis. The original method is documented in ASTM D3524 and makes use of a GC-FID to analyse the oil samples to determine the mass percentage of fuel in the oil.

The modified method reduces analysis time by tenfold by optimising peak separation to resolve fuel from oil, and not to resolve individual fuel components. Excellent agreement ($R^2=0.999$) was achieved using this method with samples of used engine oil spiked with diesel fuel through the range of 0.5 to 40 percent diesel oil dilution. The method defines diesel fuel as n-C13 through n-C20, and biodiesel elutes just after n-C20. After biodiesel fuel elutes, all higher boiling oil is back-flushed from the head of the column to maintain column life. [17]

In addition to oil dilution testing, conventional oil analysis methods were used to determine oil quality. This included: TBN, viscosity, wear metals and oxidation tests.

Test Cycle

Before the start of each test, a fuel change was done, followed by a 5 minute period of high load running (80% of full load) in order to oxidise any soot that may have built up on the oxidation catalyst. Thereafter, the engine was operated at 2000rpm and 30% accelerator pedal position value for 30mins to precondition the engine on the new fuel. Finally, an engine oil change was carried out. This procedure ensured that there was no fuel or wear metal contamination at the start of each test.

The actual test involved operating the engine in regeneration mode for 6 hours at a constant engine speed of 2000rpm and torque of 50Nm. This low load operating point was chosen as it approximately represents road loads experienced when driving at a constant speed of 70km/h, and is also an operating point where active DPF regeneration could be initiated by the ECU.

Regeneration mode means operating the engine with post injections near exhaust valve opening for 4 minutes and then 4 minutes without regeneration. The latter period was done to periodically resume normal operation and allow the catalyst and DPF to return to normal operating temperatures for component protection.

For the purposes of establishing a baseline from which to compare the data, a reference test was run - using the same test cycle above - where no regeneration was used. Analysis from this reference test shows how the oil changes during normal operation.

The duration of the post-injection was determined by setting it to a value that increased the DPF inlet temperature to around 550°C. This temperature is achieved when the un-combusted fuel from the late injection reacts over the oxidation catalyst. Soot readily oxidises between 550-650°C, however through the use of a CDPF, such as on the OM642 test engine, this temperature is reduced to between 300-400°C [18]. Despite this lower temperature requirement, the method targeted a more severe temperature of 550°C. The post-injection duration set for this procedure was 0.38ms at a timing of 80CAD after TDC. Fuel rail pressure was determined by the engine operating point and was approximately 500bar.

As indicated in literature [5], the post-injection is typically operated in closed-loop control to a target post-DOC temperature. This was not followed to reduce the variability between tests.

Oil was sampled from the oil gallery at the start of the test (after warm-up), and hourly thereafter. Before each 40ml sample was drawn, 60ml was purged through the sample point to remove the dead volume.

RESULTS AND DISCUSSION

The results in this section include the primary analysis technique of percentage fuel in oil for each test, as well as a brief discussion on other standard oil analysis results.

Fuel Addition to Oil

The primary result for each fuel was the rate at which fuel entered the engine oil during DPF regeneration. This result was calculated from the hourly oil samples taken throughout the 6 hour test. Each data point is the percentage mass of fuel in the engine oil. An example of these results for EN590 diesel is shown below in [Figure 3](#). The baseline test is also shown where DPF regeneration was disabled using the same test cycle.

The data for each fuel was corrected to a volume percentage using the fuel and oil's densities, and all fuels are now presented in [Figure 4](#) as a rate of fuel addition to the engine oil by volume.