

Biodiesel Impact on Engine Lubricant Dilution During Active Regeneration of Aftertreatment Systems

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Xin He, Aaron Williams, Earl Christensen, Jonathan Burton and Robert McCormick
National Renewable Energy Laboratory

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ABSTRACT

Experiments were conducted with ultra low sulfur diesel (ULSD) and 20% biodiesel blends (B20) to compare lube oil dilution levels and lubricant properties for systems using late in-cylinder fuel injection for aftertreatment regeneration. Lube oil dilution was measured by gas chromatography (GC) following ASTM method D3524 to measure diesel content, by Fourier transform infrared (FTIR) spectrometry following a modified ASTM method D7371 to measure biodiesel content, and by a newly developed back-flush GC method that simultaneously measures both diesel and biodiesel. Heavy-duty (HD) engine testing was conducted on a 2008 6.7L Cummins ISB equipped with a diesel oxidation catalyst (DOC) and diesel particle filter (DPF). Stage one of engine testing consisted of 10 consecutive repeats of a forced DPF regeneration event. This continuous operation with late in-cylinder fuel injection served as a method to accelerate lube-oil dilution. Stage two consisted of 16 hours of normal engine operation over a transient test cycle, which created an opportunity for any accumulated fuel in the oil sump to evaporate. Light duty (LD) vehicle testing was conducted on a 2010 VW Jetta equipped with DOC, DPF and a NO_x storage catalyst (NSC). Vehicle testing comprised approximately 4,000 miles of operation on a mileage-accumulation dynamometer (MAD) using the U.S. Environmental Protection Agency's Highway Fuel Economy Cycle because of the relatively low engine oil and exhaust temperatures, and high DPF regeneration frequency of this cycle relative to other cycles examined. Comparison of the lube oil dilution analysis methods suggests that D3524 does not measure dilution by biodiesel. The new back-flush GC method provided analysis for both diesel and biodiesel, in a shorter time and with lower detection limit. Thus all lube oil dilution results in this paper are based on this method.

Analysis of the HD lube-oil samples showed only 1.5% to 1.6% fuel dilution for both fuels during continuous operation under DPF regeneration events. During the second stage of HD testing, the ULSD lube-oil dilution levels fell from 1.5% to 0.8%, while for B20, lube-oil dilution levels fell from 1.6% to 1.0%, but the fuel in the oil was 36% biodiesel. For the LD vehicle tests, the frequency of DPF regeneration events was observed to be the same for both ULSD and B20. No significant difference between the two fuels' estimated soot loading was detected by the engine control unit (ECU), although a 23% slower rate of increase in differential pressure across DPF was observed with B20. It appears that the ECU estimated soot loading is based on the engine map, not taking advantage of the lower engine-out particulate matter from the use of biodiesel. After 4,000 miles of LD vehicle operation with ULSD, fuel dilution in the lube-oil samples showed total dilution levels of 4.1% diesel. After 4,000 miles of operation with B20, total fuel in oil dilution levels were 6.7% consisting of 3.6% diesel fuel and 3.1% biodiesel. Extrapolation to the 10,000-mile oil drain interval with B20 suggests that the total fuel content in the oil could reach 12%, compared to 5% for operation on ULSD. Analysis of the oil samples also included measurement of total acid number, total base number, viscosity, soot, metals and wear scar; however, little difference in these parameters was noted.

INTRODUCTION

Modern diesel engines utilize advanced aftertreatment (AT) systems for pollutant emissions control. For example, diesel particle filters (DPFs) are used for control of particulate emissions and must be periodically regenerated by heating to temperatures high enough for soot combustion or oxidation by nitrogen dioxide (NO₂). Two different catalytic technologies are used to reduce nitric oxides (NO_x). Selective

catalytic reduction (SCR) employs injection of urea into the exhaust for continuous reduction of NO_x. NO_x storage catalysts (NSCs) accumulate NO_x during normal, lean-burn operation but require lean-rich modulation of the exhaust stream to activate the catalytic reduction of stored NO_x. One of the approaches for both DPF and NSC regeneration is to use late in-cylinder injection, known as post-injection, to deliver fuel into the exhaust [1,2,3]. Since post-injection occurs late in the expansion stroke, the ambient in-cylinder densities are relatively low, which could increase the likelihood of liquid fuel impingement on the cylinder wall, known as wall wetting. Wall wetting by late-cycle post-injection was observed by Bozic *et al.* [4]. Liquid fuel on the cylinder wall can make its way past the oil rings and accumulate in the engine oil crankcase. It is expected that post-injection will lead to increased dilution of the engine lubricant by fuel.

Biodiesel has drawn a lot of attention in recent years as an alternative fuel to mitigate green house gas emissions and reduce the nation's dependence on foreign oil. It is generally agreed that biodiesel reduces engine-out hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM) compared to petro-diesel [5]. However, one of the major concerns of using biodiesel is the increased fuel oil dilution in engines that use post injection for DPF and NSC regeneration. Due to the lower volatility of biodiesel, the fuel injection spray liquid length of biodiesel is approximately 20%-30% longer than ultra low sulfur diesel (ULSD) [6, 7], which increases the severity of wall wetting [4]. Also, biodiesel that enters into the crankcase is less likely to evaporate out of the lube oil [8], potentially causing higher levels of oil dilution.

Laboratory bench tests [9,10,11,12,13] and engine tests fueled with different levels of biodiesel-diesel blends [8,11,14,15,16,17,18,19] were conducted by other researchers to demonstrate the impacts of biodiesel on the engine oil. Under some conditions biodiesel could cause negative impacts on engine oil such as increased fuel dilution [8,15,16], reduced oil viscosity [15], increased oil degradation [15,16,17,18], increased lead corrosion [11,12,15,17,18], accelerated total base number (TBN) depletion [12] and total acid number (TAN) increase [12, 16], reduced oil deposit resistance performance and anti-wear performance [16]. Although the negative impacts of biodiesel in the oil may support a reduced oil drain interval, no excessive engine wear has been observed by using biodiesel [15,17,19]. The primary cause of wear of heavy-duty (HD) diesel engines is the abrasive nature of primary soot particles [20]. Few differences on soot particle size and hardness in engine oil were observed between ULSD and B20 [17]. Fresh biodiesel might actually decrease engine wear due to its higher intrinsic lubricity and reduced formation of PM. The PM surfaces generated from biodiesel are generally more

polar than those generated by ULSD, which interact more strongly with dispersant, resulting in a more effective suspension of soot in the oil [10].

Although some original engine manufacturers have approved using B20 on their newer model year vehicles [21], there is still a significant number of vehicles not approved for B20. Only a few vehicle tests on the biodiesel impacts on engine oil have been reported [15,19]. Thornton *et al.* [19] studied the impacts of B20 on engine oil using a four-door sedan equipped with either a NSC/DPF or a SCR/DPF emission control system. The vehicle was calibrated to meet the Euro 4 emission standards. However, no direct comparison to ULSD was made in this study. The most comprehensive study was conducted by Zdrodowski *et al.* [15] using six prototype medium-duty trucks equipped with V8 diesel engines. The vehicles were equipped with urea-SCR and used a post-injection strategy for active DPF regeneration. In the United States, urea-SCR is more widely used than NSC as a NO_x control strategy for medium- and heavy-duty engines. NSCs, with fewer service and maintenance requirements, are common for light duty (LD) applications. Very limited information has been published on the impact of biodiesel on oil dilution for Tier 2 Bin 5-certified vehicles equipped with both NSCs and DPFs that use post injection for AT system regeneration.

This paper reports on experiments that were conducted by running a HD engine and a LD vehicle on ULSD and B20 to determine the effect of biodiesel on lubricant dilution. The study consisted of two parts: 1) a HD engine dynamometer test using a 2008 6.7L Cummins ISB engine, and 2) a LD vehicle test using a 2010 VW Jetta. Both engines use late fuel injection for AT system regeneration. The first part is a fundamental study of the fuel dilution and evaporation behavior of ULSD and biodiesel in the HD engine lubricant. The second part is to test the impact of biodiesel on engine lubricant oil dilution for a Tier 2 Bin 5-certified LD vehicle equipped with both a NSC and DPF. Oil samples were collected at certain intervals during the test. Dilution of fuel in the lubricant was measured using a novel method developed by Perkin Elmer, Inc. [22], which combines rapid measurement and differentiation of diesel and biodiesel fuel dilution with a high degree of sensitivity.

EXPERIMENTAL SETUP AND TEST PROCEDURE

HEAVY-DUTY ENGINE TEST

The HD engine portion of this test was performed on a 2008 Cummins ISB340. It has a displacement of 6.7 L and a power output of 254 kW. The engine was calibrated for use in an emergency vehicle application. The engine implements cooled high-pressure exhaust gas recirculation, a variable geometry turbocharger, high-pressure common-rail direct fuel

injection, a diesel oxidation catalyst (DOC), and an actively regenerated DPF. Additional information can be found in [Table 1](#).

Table 1. Engine specifications for HD engine test

Cummins ISB 340	
Serial number	49891045
Displacement, L	6.7
Cylinders	6
Rated Power, kW	254 at 2,800 rpm
Rated Torque, N-m	895 at 1,600 rpm
Bore x Stroke, cm	10.7 x 12.4
Compression Ratio	17.3 : 1
Fuel System	Common Rail
NOx Cert Level, g/bhp-hr	1.95
PM Cert Level, g/bhp-hr	0.01

Two fuels were used for the HD engine testing: ULSD and a soy-based B20 volumetrically blended with ULSD. Testing was conducted in two stages: 1) continuous forced regeneration events, followed by 2) normal transient engine operation. Through use of an engine control unit (ECU) tool (Cummins Insite), the engine can be forced to conduct an active regeneration event. This is referred to as “parked regeneration” and is typically used for DPF maintenance. These parked regeneration events create DPF temperatures up to 650°C, under idle conditions, and last approximately 40 minutes. Stage one of testing consisted of 10 consecutive repeats of the parked regeneration event, with a 5- to 10-minute idling period between. All 10 parked regeneration events were run in the same day. An oil sample was collected following every two regeneration events. This continuous operation with late in-cylinder fuel injection creates an accelerated condition for lube-oil dilution. Stage two of testing consisted of 16 hours of normal engine operation over a transient test cycle. No active regeneration events were experienced over this period of operation, which created an opportunity for any accumulated fuel in the oil sump to boil out. Oil samples were collected after every four hours of operation. The transient test cycle used in this stage of testing was developed under the Coordinating Research Council (CRC) ACES program and is referred to as the 16-hour cycle [23]. It consists of four repetitions of a 4-hour sub-cycle which is a combination of both urban and rural transient operation.

A petcock valve was installed halfway up the side of the engine oil pan to facilitate sampling engine oil. A total of 200 mL of oil was purged from the valve and put back into the top of the engine prior to taking samples to ensure the oil

sample represented the oil in the pan and not the residuals in the petcock valve.

LIGHT-DUTY VEHICLE TEST

LD vehicle testing was conducted on a 2010 Volkswagen (VW) Jetta powered by a 2.0 L diesel engine. The vehicle was certified to meet the U.S. Tier 2 Bin 5 emission regulations. It uses cooled low-pressure exhaust gas recirculation (exhaust gases are drawn downstream of DPF and circulated back into the intake) for engine-out NO_x emission control. The engine AT included a close coupled DOC, a DPF, a NSC, and a hydrogen sulfide (H₂S) catalytic converter. The vehicle uses in-cylinder post fuel injection to either increase the exhaust gas temperature for DPF regenerations or generate intermittent rich excursions for NSC regeneration. The recommended oil drain interval for the 2010 VW Jetta is 10,000 miles when using synthetic oil. The odometer reading of the vehicle was 38,000 miles at the start of the test, thus the vehicle was well broken-in.

The engine and AT system were instrumented with K-type thermocouples to monitor engine operation and identify regeneration events. The temperatures at the following locations are monitored, including: engine oil, coolant, intake air, post air compressor, engine exhaust, pre-DOC, pre-DPF, post-DPF, pre-NSC, and post-NSC. The engine out and tail-pipe emissions were measured by running the engine on a chassis AC dynamometer. Emission tests were conducted with ULSD and B20 to study the fuel impacts on PM emissions.

Experiments were conducted using a Mileage Accumulation Dynamometer (MAD). An important element of this study was to select the proper driving cycle to be used for fuel oil dilution testing. The selected cycle should not only represent real world driving conditions, creating realistic opportunities for DPF and NSC regeneration events but must also be safe to operate on the MAD. Prior to MAD testing, five driving cycles were evaluated, including FTP72, US06, highway fuel economy (HWFET), Approved Mileage Accumulation (AMA) driving cycle, and New European Driving cycle (NEDC). [Table 2](#) summarizes DPF regeneration performance of the five cycles using ULSD. The US06 is a very aggressive driving cycle with rapid accelerations and extended high speed cruises. Actions were taken to prevent engine overheating by installing a high velocity fan and lowering the test site's ambient temperature. Despite the pre-emptive actions, the average vehicle oil temperature was about 116°C with temperatures frequently spiking above 120°C during the cycle. Because the oil temperature was on the edge of safe engine operation, US06 was not selected for fuel oil dilution testing. A series of engine PM emission tests showed that the majority of PM emissions were generated during engine transient operation. The many constant speed cruise periods in the AMA and the NEDC cycles lead to low soot loading of

Table 2. 2010 VW Jetta DPF regeneration preliminary comparison for five driving cycles with ULSD

	FTP72	US06	HWFET	AMA	NEDC
Cycle duration (s)	1,372	600	765	4,793	1,184
Mileage per cycle (miles)	7.44	8.00	10.26	40.49	6.84
Average speed (mph)	19.5	48.0	48.2	30.4	20.8
Average oil temperature (°C)	102	116	107	97	99
Average coolant temperature (°C)	82	92	81	74	77
Average pre-DPF T (°C)	281	426	332	313	286
Calculated mileage between regenerations based on average soot load estimator	189	365	221	459	269
Calculated time between regenerations based on average soot load estimator (hours)	9.7	7.6	4.6	15.1	13.0
MAD time needed to reach 4,000 miles (hours)	204.8	83.4	82.8	131.5	192.3

the DPF. Thus the AMA and NEDC were not selected because of the expected low opportunity for regeneration events. Of the five cycles that were evaluated, the HWFET was selected for testing. The HWFET cycle created exhaust temperatures low enough to avoid excessive levels of passive DPF regeneration and also had the lowest estimated time between regeneration events (4.6 hours).

For the MAD test, the test sequence normally comprises 10 consecutive repeats of the U.S. Environmental Protection Agency's Highway Fuel Economy Cycle followed by 2 minutes of idle and an hour of soaking. The sequence was repeated four times every day for 10 days, which resulted in approximately 4,000 miles of operation. During the test, MAD and vehicle operating data were logged. Some key information is: vehicle speed, load, MAD torque, all instrumented K-type thermocouple temperatures, and estimated soot loading by the engine control unit (ECU). The pre-DPF temperature is closely monitored because it can be used to interpret both DPF and NSC regeneration events.

During preliminary testing, the vehicle periodically experienced an extended regeneration event. These extended regeneration events were different from normal DPF regenerations, which were very predictable based on ECU estimated soot loading. The extended regeneration event, however, was not predictable and would periodically occur upon vehicle startup regardless of soot loading. The regeneration event would not end until the vehicle was keyed off. Although the purpose of the extended regeneration events was unclear, it was controlled by the engine ECU and triggered by a control algorithm unknown to the authors. Continuous operation on the MAD during one of these extended regeneration events would cause extensive oil dilution beyond what might be experienced under normal operating conditions. To prevent this from causing unacceptable levels of oil dilution, a control algorithm was

used to stop the vehicle in the event of an extended regeneration event. This was done by monitoring the pre-DPF temperature and stopping the vehicle if temperatures were above 575°C for two consecutive test cycles. The vehicle would then be restarted, and testing would resume as usual. The typical time histories of vehicle velocity, pre-DPF gas temperature, and ECU estimated soot load for two consecutive HWFET cycles with an extended regeneration are shown in [Appendix Figure A-4](#).

Oil samples were collected every day before the start of MAD testing. To minimize sampling variation, the oil samples were collected using the following procedure. First, the vehicle was started and run at idle for 10 minutes to warm up the engine oil. Then, all engine oil was drained to an oil pan, weighed, and well mixed before collecting a 50-gram oil sample. The rest of the engine oil was put back into the engine.

FUELS AND ENGINE LUBE-OIL

Fuels used in this study are No.2 ULSD and B20. A recent study conducted by Alleman *et al.* [24] showed that 55% of the B100 used in the United States was produced from soybean oil. Thus, B20 was prepared by splash blending #2 ULSD with the soy-based biodiesel purchased from Agland, Inc. Selected fuel properties are summarized in the [appendix](#). [Figure 1](#) shows the fuel distillation curves for ULSD, B20, and B100. Biodiesel exhibits significantly higher distillation temperatures. B20, although only 20% in volume, can play an important role in increasing oil dilution because of its impact on the liquid penetration length and higher boiling range, which results in less of the fuel evaporating out of the lube oil.

The oil used for the HD engine test is Valvoline's VV70509 premium blue engine oil type 15W-40, which is



Documents

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recommended and endorsed by Cummins, Inc. The oil used for the LD vehicle test is Castrol SLX synthetic oil type 5W-30, which complies with VW standard “VW 507 00” for the 10,000-mile oil drain interval.

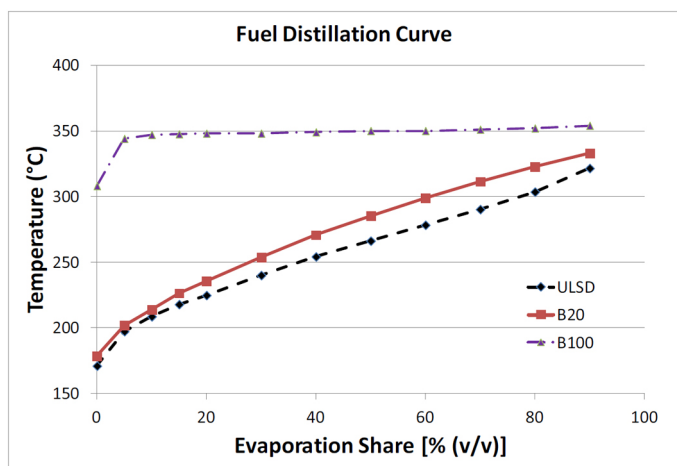


Figure 1. Distillation curve of the fuels (ULSD and B20 by D86, B100 by D1160)

OIL ANALYSIS METHODOLOGY

All samples of lube oil collected during the test campaigns were analyzed for fuel dilution by gas chromatography (GC) following ASTM test method D3524, as well as by a back-flush GC method (described below). Biodiesel content was measured by Fourier transform infrared (FTIR) spectroscopy following a modified version of ASTM test method D7371 described by Thornton and others [19] as well as by a back-flush GC method. Soot content was measured by thermogravimetric analysis following ASTM test method D5967 Annex A4.

The back-flush GC method developed by Perkin Elmer, Inc. [22] for rapid analysis of both diesel and biodiesel in lube oil was investigated and compared to ASTM methods for measurement of lube oil dilution. This method employs column back-flushing to remove lube oil from the chromatogram and minimize interference from light-end lube oil compounds in the retention time region of biodiesel. Analysis was conducted using an Agilent 7890A GC equipped with split/splitless injection port, flame ionization detector, and Deans Switch column switching valve. A 100% polydimethyl siloxane capillary column was used for compound separation; an HP-1 with dimensions of 15 m × 0.25 mm, with 0.25-μm internal coating (Agilent Technologies part # 19091Z-431). The HP-1 column was installed from the injection port to the Deans Switch and a deactivated fused silica restrictor, with dimensions of 0.45 m × 0.1 mm, was installed from the valve to the detector. The third port of the Deans Switch was plugged to maintain flow from the column to the detector. An Agilent 7683B

Automatic Liquid Sampler with a 0.5-μL syringe was used for injection of 0.1 μL of sample. The injection port temperature was set at 300°C, column head pressure was set at 49 psi, the Deans Switch pressure was set at 35 psi. Injection was made in split mode at 100:1 split ratio. The detector temperature was 250°C, and the GC oven temperature was held at 225°C isothermal for 2.5 minutes. Post run the Deans Switch pressure was raised to 58 psi, the injection port pressure was reduced to 2 psi, and the oven temperature was increased to 250°C. Post run time was set at 3 minutes.

Instrument calibration was conducted with the diesel and biodiesel used for the engine test protocols. The diesel standard was prepared by ASTM D86 distillation to remove 10% volume. This is done to simulate the loss of lower molecular weight HC from exposure to peak lube oil temperatures. The biodiesel was used as received. A 50:50 by weight solution of diesel and biodiesel was prepared and diluted in 75 cSt clear mineral oil (VHG Labs Part # OIL-MIN-500) to prepare calibration standards. For the HD engine samples, the instrument was calibrated in a range of 0.05% to 2.5% diesel and biodiesel, respectively (0.1%-5% total dilution). For the LD vehicle samples, higher concentrations of fuel dilution were observed; therefore, the instrument calibration range was from 0.5% to 10% diesel and biodiesel, respectively (1%-20% total dilution). With this GC analysis, diesel fuel elutes as a grouping of peaks, and biodiesel elutes as a single peak further in the chromatogram, as illustrated in Figure 2. The diesel portion of the chromatogram is integrated as one peak for area determination.

Spike analysis was conducted with unused oil from the HD and LD testing to determine the extent of interference from the lube oil matrix. Briefly, fuel is added to samples of the unused lube oil at a concentration expected to be present in samples, and the recovery of the known spiked concentration is determined. The variation in this measurement from the known added concentration is a measure of the interference caused by the sample matrix. With the HD oil, spike recoveries were from 111%-115% for diesel and 109%-111% for biodiesel. With the LD oil, spike recoveries were from 87%-88% for diesel and 99%-102% for biodiesel. The lighter compounds in the lube oil caused interference in the analysis of spikes; however, this affected measured values of spikes by less than 20% of known values. Triplicate injection of spiked samples resulted in a coefficient of variation (standard deviation divided by the mean result multiplied by 100) of approximately 1%. Biodiesel is effectively resolved from lube oil for accurate quantification with this method.

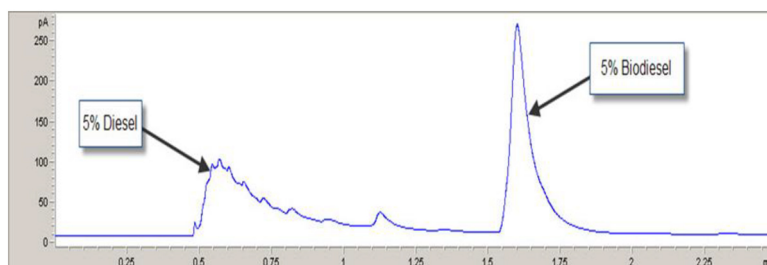


Figure 2. Example chromatogram of diesel/biodiesel standard by back-flush GC method

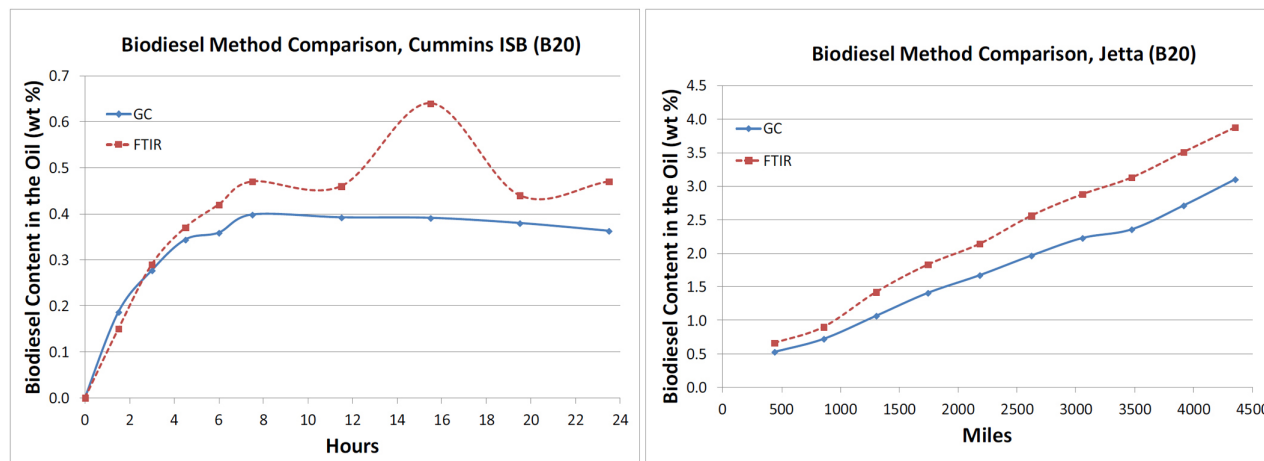


Figure 3. Comparison of biodiesel dilution determined by FTIR and back-flush GC methods for samples of LD and HD engine tests with B20.

RESULTS AND DISCUSSION

COMPARISON OF LUBE OIL DILUTION MEASUREMENT METHODS

The results of the back-flush GC method for biodiesel dilution were compared to FTIR determination for the HD engine and the LD vehicle tests with B20. Graphs of the data are presented in Figure 3. Linear regressions comparing the data are included in the appendix, Figure A-1. The results of biodiesel dilution determined by FTIR and back-flush GC were fairly consistent with one another and had high correlations when comparing the results of the two methods: R^2 greater than 0.9. Despite the good correlation in the results, the dilution determined by FTIR was generally higher than the value determined by GC, suggesting possible interference from the lube oil with the infrared peak used to measure biodiesel content.

Total dilution determined by the back-flush GC method and ASTM D3524 was compared for all tests. Graphs of the data are presented in Figure 4. Linear regression comparisons of the results are presented in the appendix, Figures A-2 and A-3. The linear correlations of the data generated by the two test methods for the ULSD and B20 HD engine tests had R^2

of 0.5 and 0.6, respectively. The low correlation of the data between the two methods is primarily due to the fact that D3524 analysis resulted in measurements below the detection limit for some samples, although fuel dilution was detected and measured by the back-flush GC method. When the zero values are excluded from the linear regressions, R^2 is 0.8 for the ULSD test and 0.7 for the B20 test (not shown). The LD vehicle ULSD and B20 dilution determined by the back-flush GC method compared to D3524 resulted in R^2 of 0.8 and 0.9, respectively. The higher correlation between the two methods for the LD vehicle samples is due to the higher concentrations present, which did not result in any values below the detection limit of D3524. Fuel dilution results for the LD vehicle B20 test samples determined by D3524 are lower than those of the back-flush GC method by approximately the amount of biodiesel measured by FTIR or the back-flush GC method, suggesting that the biodiesel portion of the diluent was not measured by D3524.

The back-flush GC method shows good correlation with traditional methods for measuring lube oil dilution, and allows for rapid, simultaneous measurement of both diesel and biodiesel. The lube-oil dilution data presented in the rest of this paper were determined by the back-flush GC method.

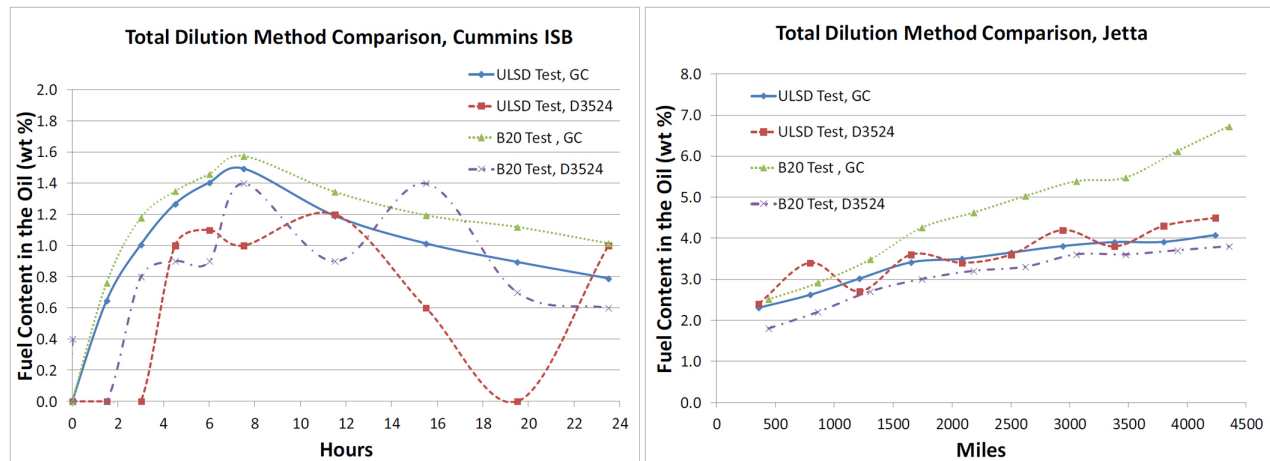


Figure 4. Comparison of total dilution determined by ASTM D3524 and back-flush GC methods for samples of HD engine tests and LD vehicle tests with ULSD and B20.

HEAVY-DUTY ENGINE TEST RESULTS

Figure 5 shows the pre-DPF, post-DPF, and engine oil temperature during two repeats of a DPF “parked” regeneration. A “parked” regeneration is performed on the engine dynamometer by running the engine at idle and activating the DPF regeneration option in the Cummins Insite software. The engine controller then increases engine speed to 1,000 rpm and spools up the turbocharger to increase turbo-out exhaust temperature and flow rate. In-cylinder post injection starts when exhaust temperatures cross a set threshold, typically after about 10 minutes when starting with a cold engine. The engine will continue to run at these conditions for 40 minutes after the start of command in Insite. Figure 5 shows an example of a typical set of “parked” regenerations. Regeneration #1 post injection starts about 5 minutes after the start of command and lasts nearly 35 minutes. During regeneration #2, post injection starts at start of command and lasts the entire 40 minutes. Pre- and post-DPF temperatures reach above 550°C during a “parked” regeneration, creating a favorable environment for DPF regeneration. A peak temperature is reached at the beginning of the parked regeneration event followed by the temperature stabilizing just below 600°C. The peak temperatures reached at the beginning of the parked regeneration were approximately 30°C higher for ULSD compared to B20. The average temperature and rate of temperature rise (approximately 0.90°C/sec for ULSD and 0.83°C/sec for B20) is the same for both fuels. Also of note is that the fuel consumed during the parked regeneration events is 16% higher with B20. Additional details comparing the “parked” regeneration events for ULSD and B20 are shown in Table 3. After the engine is fully warmed up, the oil temperature stays around 92°C.

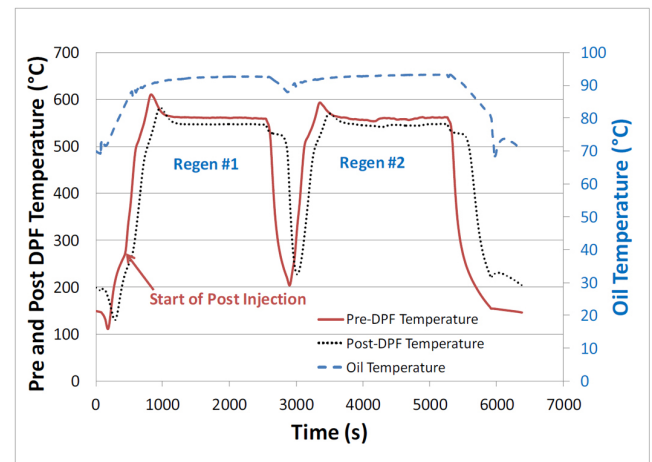


Figure 5. Typical pre-DPF, post-DPF, and oil temperature histories during two repeats of engine “parked” regeneration, (Fuel: ULSD)

Table 3. Comparison of parked regeneration events #7 and #8

	ULSD	B20
Avg Pre-DOC Temp (°C)	333	356
Avg Pre-DPF Temp (°C)	482	486
Avg Engine Oil Temp (°C)	90	91
Fuel Consumption (kg)	7.5	8.7
Total Regeneration Time (min)	66	66

Figure 6 shows the pre-DPF, post-DPF, and engine oil temperature during a 4-hour period of the 16-hour transient test cycle. Pre-DPF and post-DPF temperatures typically did not go over 450°C. No DPF regeneration was observed for both ULSD and B20 tests during the entire 16-hour CRC test cycle. On average the engine oil temperatures were higher