

Impact of Biodiesel on Ash Emissions and Lubricant Properties Affecting Fuel Economy and Engine Wear: Comparison with Conventional Diesel Fuel

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ABSTRACT

The increased use of biodiesel fuels has raised concerns over the fuel's impact on engine performance and hardware compatibility. While these issues have received much attention in recent years, less well-known are the effects of biodiesel on engine-out ash emissions and lubricant properties. Significant differences in composition between biodiesel and petroleum diesel fuels have the potential to influence ash emissions, thereby affecting aftertreatment system performance. Further, the fuel also interacts directly with the lubricant through fuel dilution, and may impact lubricant properties.

In this study, a 5.9L, 6 cylinder, Cummins ISB 300 diesel engine was outfitted with a specially designed rapid lubricant aging system and subjected to a set of steady-state engine operating conditions. The lubricant aging system allows for the investigation of the interactions of emissions and combustion products, as well as fuel dilution, on lubricant properties in an accelerated manner. Neat soy-derived biodiesel and a conventional ultra-low sulfur diesel were employed, and both gaseous and particulate emissions were sampled and characterized. The two lubricants used in this study consisted of a conventional CI-4 diesel engine lubricant as well as a CJ-4 oil. Both the fuels and lubricants were subjected to detailed chemical and physical analyses. Following the lubricant aging procedure, changes in lubricant properties were measured and accounted for. Additionally, total ash emissions for each of these fuels were measured and characterized. This study, thus, presents a first step in investigating differences and potential interactions of biodiesel fuels on lubricant properties as well as total engine-out ash emissions. Based on differences in lubricant properties and ash emissions, explanations for the observed results were developed and implications for the compatibility of biodiesel fuels with conventional lubricants and aftertreatment systems presented.

INTRODUCTION

The performance of modern diesel engines equipped with advanced exhaust aftertreatment systems is highly sensitive to both lubricant and fuel properties. In order to enable the use of catalyzed aftertreatment systems, the United States Environmental Protection Agency (EPA) mandated a reduction in on-highway diesel fuel sulfur content to no more than 15 ppm, effective June 1, 2006 [1]. Further, the extreme sensitivity of diesel particulate filters (DPF) to lubricant-derived ash resulted in the recent CJ-4 diesel lubricant specification, limiting total sulfated ash content to no more than 1.0% of the lubricant [2]. While some progress related to increasing understanding of lubricant-derived ash and fuel effects on aftertreatment systems has been made over the past few years, even less is known about the interactions of newer and less conventional fuels, such as biodiesels.

Produced from a variety of renewable sources, biodiesel fuels are finding increased use as a blending agent with conventional petroleum diesel. Typical blending levels for biodiesel range between 5% (B5) and 20% (B20) by volume in most commercial applications in the United States. While the term, biodiesel, is often loosely used to describe a wide range of renewable diesel fuels, the American Society for Testing of Materials (ASTM) defines biodiesel as mono alkyl esters of long chain fatty acids [3]. This definition restricts the class of biodiesel fuels to processed oxygenated fuels and rules out the use of un-processed oils and fats.

Biodiesel is produced via the transesterification of vegetable oils and animal fats with an alcohol in the presence of a catalyst. In the transesterification process triacyl glycerides, of which most fats and oils are composed, are reacted with either ethanol or methanol to produce mono alkyl esters (biodiesel) and glycerol, a byproduct. The resulting fuel is either termed a methyl ester or ethyl ester, depending on the alcohol used in the reaction, methanol or ethanol, respectively. The most common catalysts used in the transesterification reaction

are sodium and potassium hydroxide. Following the reaction, residual glycerin, catalyst, alcohols, and free fatty acids must be removed from the finished fuel [4].

Commercial biodiesel must meet ASTM D6751 specifications in the United States and the EN14214 specification in Europe [5]. ASTM D6751 is the current specification for B100 fuels used as blending agents up to the B20 level. In addition to the fuel specifications, a voluntary accreditation program, BQ-9000, for fuel producers and marketers exists to promote the production and distribution of high quality biodiesel fuels meeting the current ASTM standards [3].

Despite recent progress in defining fuel specifications and quality assurance protocols, a number of inherent differences in fuel properties and composition exist between biodiesel and conventional petroleum-derived diesel fuels. The effects of these inherent differences in fuel properties on potential interactions between the fuel and lubricant through fuel dilution, as well as the impact of biodiesel combustion products on advanced aftertreatment system performance are not well known.

AFTERTREATMENT SYSTEM IMPACT

Several studies in the literature have attempted to investigate the performance of diesel particulate filters on engines fueled with both neat biodiesel and blends. A 2006 study investigating the effects of a B5, B20, and a neat soy-derived biodiesel on catalyzed DPF performance noted reductions in balance point temperatures of 45 °C and 112 °C with the B20 and B100, respectively. Filter regeneration rates were also considerably faster even at the B5 level, with the increase in regeneration rate attributed to elevated soot reactivity for the neat biodiesel and blends [6]. An added benefit of biodiesel fuels is a reduction in engine-out particulate matter (PM) emissions from 14% to over 70% for neat biodiesel fuels, depending on fuel type [4, 7].

While the studies mentioned above highlight a number of important effects of biodiesel on the operating characteristics of diesel particulate filters, little is known about the potential long-term effects on the performance and service life of these systems. The most significant factor affecting the long-term service life of diesel particulate filters is irreversible plugging due to ash accumulation. Past studies on ash emissions have focused primarily on diesel lubricants, generally the largest source of engine-out ash, with little attention paid to fuel properties.

The oil consumption of typical heavy-duty diesel engines ranges between 0.1% and 0.2% of total fuel consumption [8]. Calculations based on data from a recent benchmarking study of seven modern heavy-duty diesel engines showed lubricant consumption for these engines to be less than 0.2% of total fuel consumption [9]. Assuming oil consumption to be 0.1% of fuel consumption, 1,000 ppm_w of additive elements in lubricant oil is equivalent to 1 ppm_w of trace elements in

the fuel. To put these numbers in perspective, representative low ash CJ-4 diesel engine oils typically contain slightly more than 1,000 ppm_w of Zn, and P each [2]. Therefore, it is quite obvious that the potential exists for even low ppm levels of trace elements in diesel fuels to contribute significantly to engine-out ash emissions with a CJ-4 oil.

In contrast to conventional diesel fuels, the potential for biodiesel to contain trace metals is due to the manner in which the fuel is produced. Sodium and potassium are used as catalysts in the esterification reaction and are found in small quantities in the finished fuel. Further, magnesium and calcium may be used as absorbents in biodiesel production or enter the fuel if hard water is used in washing to remove the spent catalyst [4, 10, 11]. ASTM D6751 limits the combined levels of sodium and potassium as well as calcium and magnesium to 10 ppm_w [12]. However, even below the current ASTM limits, trace metals in the fuel at single digit ppm levels can contribute significantly to engine-out ash emissions, as demonstrated above.

Aside from residual alkali and alkaline metals, sulfur and phosphorous in fuels are well known catalyst poisons. While conventional petroleum diesel fuels are naturally high in sulfur, new U.S. on-highway fuel standards have limited the sulfur content to no more than 15 ppm to enable the use of catalyzed aftertreatment systems [1]. On the other hand, neat biodiesels are typically low in sulfur or sulfur free, but may contain low levels of phosphorous. Phosphorous in biodiesel fuels originates in the feedstock, with phosphorous levels highly dependent upon feedstock type [4, 10]. Studies in the literature show the detrimental effects of phosphorous, sulfur, and specific ash species on the performance of diesel oxidation catalysts (DOC), catalyzed diesel particulate filters, and some NOx aftertreatment systems [13-16]. In this study, differences in trace metal, sulfur, and phosphorous emissions were measured and characterized for conventional and biodiesel fuels, with the aim of understanding their potential impacts on diesel aftertreatment system performance.

LUBRICANT EFFECTS

Besides affecting aftertreatment system performance, fuels also interact directly with the engine lubricant through fuel dilution, and indirectly through the formation of combustion products (soot) and gasses which may become entrained or dissolved in the oil. Fuel dilution occurs when liquid fuel impinges on the cylinder walls, mixes with the lubricant, and slowly accumulates in the oil sump. The rate of fuel dilution in the lubricant is determined by a number of factors including fuel properties, injection parameters, and combustion strategies. Generally accepted maximum fuel dilution limits are 5% wt. in heavy-duty diesel engines [9].

A number of studies have investigated the effects of specific fuel properties on lubricant fuel dilution. The boiling range of most biodiesel fuels, between 330 °C

and 360 °C, is considerably higher than that of petroleum diesel [4, 12]. This higher boiling range reduces the rate at which the fuel vaporizes upon injection, and can lead to increased amounts of liquid fuel impinging on the cylinder walls and mixing with the lubricant. Additionally, the higher boiling range for biodiesel also reduces the rate of evaporative losses once it enters the lubricant [17]. Aside from differences in fuel properties, engines employing late post-injection for the regeneration of diesel particulate filter systems are also susceptible to increased fuel dilution [17,18].

Once the fuel enters the lubricant, it may affect both the lubricant’s physical properties, most notably viscosity, and, in some cases, also interact with specific lubricant additives. A recent study examining the effects of biodiesel fuel dilution showed an initial decrease followed by an increase in lubricant viscosity due to oxidation and polymerization of the fuel constituents [19]. Further, the polar nature of some methyl esters has been shown to react with the phosphorous in a common anti-wear additive, ZDDP, forming stable complexes preventing this additive from coating and protecting metal surfaces. The greatest effect on reducing ZDDP functionality was attributed to partial esters containing hydroxyl groups, which result from mono- and di-glyceride impurities in the fuel or partially oxidized biodiesel [20]. Additionally, some of these polar species may also destabilize over-based detergents in certain additive packages as well [21]. This study attempts to systematically compare the effects of fuel dilution with biodiesel and conventional diesel fuels on changes in lubricant properties.

EXPERIMENTAL DESCRIPTION

The experiments described in this study were conducted utilizing fuels and lubricants of known composition. Bulk and individual particulate and ash emissions were sampled from the exhaust stream and extensively characterized using a number of techniques. Further, a specially designed rapid lubricant aging system was utilized to accelerate lubricant aging and simulate fuel dilution under carefully controlled conditions.

ENGINE AND INSTRUMENTATION

The engine used in this study was a pre-production Cummins development engine based on the 2002 ISB 300 engine platform. The ISB 300 is a 6 cylinder, 5.9 liter, turbocharged, direct injection diesel engine. The engine is rated at 224 kW (300 hp) at 2500 rpm and 890 N-m (660 ft-lb) at 1600 rpm. In order to meet 2002 EPA emissions standards, the engine is equipped with a high-pressure common rail fuel injection system, variable geometry turbocharger, and cooled exhaust gas recirculation (EGR). The engine and its associated subsystems are all electronically controlled, and access to Cummins control and calibration software allows for real-time monitoring and modification of engine control parameters. Table 1 contains details regarding engine specifications and geometry.

Table 1. Cummins ISB 300 engine specifications.

Model	ISB 300
Maximum Torque	890 N-m @ 1600 rpm
Maximum Power	224 kW @ 2500 rpm
Number of Cylinders	6, in-line
Combustion System	4 stroke, direct injection
Injection System	Common Rail
Aspiration	Variable geometry turbocharger and intercooler
Displaced Volume	5.9 liters
Compression Ratio	17.2:1
Cylinder Head Layout	4 valves/cylinder
Injection Nozzle	O.D. = 158 µm
	L = 1.00 mm
	8 sac-less nozzles per injector
Injection Pressure	800-1600 bar

The engine was heavily-instrumented with provisions for the measurement of regulated and non-regulated gaseous emissions as well as particulate matter. All gaseous emissions were sampled from the raw exhaust using heated sample lines and filters. Emissions of HC, NO, and NOx were sampled wet, while CO, CO₂, and O₂ emissions were sampled dry after first passing through a sample chiller and condenser. NOx and NO emissions were measured with a heated chemiluminescence analyzer, and hydrocarbon emissions were measured using a flame ionization detector. A non-dispersive infrared analyzer was used to measure CO, CO₂, and O₂ emissions, with the CO₂ measurements used to verify EGR fraction in the intake manifold. All dry emissions measurements were converted to a wet basis by accounting for intake humidity levels and computing the water vapor mole fractions in the exhaust. Additional details regarding the emissions measurement systems can be found in Table A-1 of the Appendix.

PARTICULATE SAMPLING AND ANALYSIS

While the engine was equipped with a diesel particulate filter as part of ongoing research into DPF/ash interactions at MIT, all particulate samples were collected from the raw exhaust upstream of the DPF. This allowed for the characterization of the particulates and ash as they exist in the raw undiluted exhaust entering the particulate filter. Bulk PM samples were collected on 47 mm glass fiber filters and the PM emission rates determined gravimetrically.

Following sample collection and gravimetric analysis, the composition of the particulates was characterized using Horiba’s MEXA 1370 PM analyzer. The MEXA 1370 measures PM sulfate fraction (SO₄), soluble organic fraction (SOF), and insoluble fraction (SOL). The insoluble fraction is primarily composed of elemental carbon and inorganic ash, while the soluble organic fraction consists of lubricant- and fuel-derived condensed hydrocarbons. The sulfate fraction contains sulfuric acid and water, with the sulfur originating in the fuel and lubricant [22]. A detailed description of the MEXA 1370 PM analysis and comparison to conventional analytical chemistry techniques is found in [23].

In addition to bulk PM sampling and analysis, individual particulate samples were also collected from the raw exhaust. The particulates were collected directly on small 3mm (0.12 inch) diameter grids, fixed to a sample probe and inserted through a sample port on the engine's exhaust system upstream of the DPF. The sample grids were composed of a fine copper mesh covered with a pure carbon film, and the sampling time was on the order of several seconds. A comparison of the grids used for individual PM sampling and conventional glass fiber filters used for bulk PM collection is shown in Figure 1.

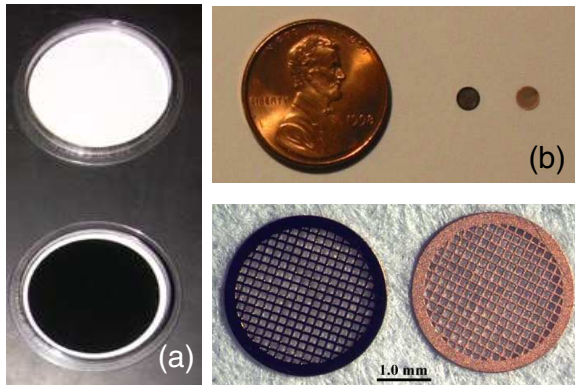


Figure 1. Conventional 47mm glass fiber filter for bulk PM collection (a) and 3mm TEM sample grid for individual PM collection (b).

The use of the small sampling grids allowed for the collection of individual particles frozen in composition and structure, as they exist in the exhaust stream entering the DPF. Further, this collection method serves as an ideal means for subsequent analysis of PM composition and morphology via electron microscopy, as the sample grids can be inserted directly into the electron microscope without additional sample preparation. The application of this technique to the characterization of ash-related species in diesel exhaust is described in [23]. A similar system has been developed and used at Argonne National Laboratories applied to the study of PM morphology, with additional details in [24-26].

ASH SAMPLING AND ANALYSIS

Ash samples were characterized in terms of their composition and distribution in the bulk particulate matter and following soot oxidation. In order to quantify the emission rates of individual ash species, a number of advanced analytical techniques were used and are described in the following section.

Electron Microscopy

Transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) were used to characterize ash morphology in the exhaust entering the DPF, as well as to provide qualitative information regarding ash composition. TEM provides high resolution images of ash and PM samples to a fraction of a nanometer. The use of commercial image processing

software enabled the determination of average primary particle and agglomerate sizes and additional morphological information.

In addition to obtaining high-resolution images using TEM, STEM allows for the identification of specific elements on a particle-by-particle level. STEM employs a 1.0 nm diameter electron beam, scanned across the surface of the samples. X-rays excited in the sample by the high-energy electron beam are collected by an x-ray detector and used to generate a spectrum characteristic of the specific elements of which the sample is composed. Under ideal conditions, STEM can provide compositional information at a spatial resolution of 0.5 nm. This technique, thus, provides qualitative information on ash composition and distribution of the ash particles in the PM entering the aftertreatment system.

Neutron Activation Analysis

Although STEM provides qualitative information on ash composition and distribution at a microscopic level, neutron activation analysis (NAA) was used to obtain a quantitative assessment of speciated ash emission rates. NAA is a non-destructive measurement technique allowing the simultaneous quantification of multiple elements. Minimum detectable levels (MDL) for neutron activation depend upon the elements of interest, but are typically in the sub-ppm range, making the technique ideally suited for quantifying trace metals and ash-related elements in the PM.

In neutron activation analysis, the PM samples collected on 47mm quartz filters are irradiated for a specified amount of time at the MIT Nuclear Reactor Laboratory. While in the reactor, the PM sample is bombarded by neutrons causing the elements present to form various isotopes. Following irradiation, the sample is placed in a radiation detector to measure the emissions generated by the decay of the isotopes. By comparing the decay characteristics and spectra of the PM and ash samples to that of a known standard, the specific trace ash elements in the PM can be quantified.

Thermo-Gravimetric Analysis

Thermo-gravimetric analysis (TGA) was used to measure the total ash content in the PM samples, without regard to specific ash composition. TGA measures the change in weight of a sample as a function of temperature. The ash content of a particulate sample is determined as the amount of incombustible material remaining following controlled oxidation in the TGA. The Perkin Elmer TGA 7 used in this study has a maximum temperature of 1000 °C with a sensitivity of $\pm 1 \mu\text{g}$. Additional details regarding TGA measurement of ash content in PM and the specific method used in this study was presented in [23]. The ash generated from the PM samples via TGA was also subjected to additional microscopy analysis as described in the previous section.

ACCELERATED LUBRICANT DEGRADATION

Due to the long run times, on the order of several hundred hours, necessary to quantify engine oil fuel dilution, an accelerated lubricant aging system was utilized in this study. The accelerated aging system enabled multiple experiments to be carried out in a timely manner, while at the same time simulating engine oil fuel dilution under carefully-controlled conditions. A schematic of the accelerated lubricant aging and fuel dilution test system is shown in Figure 2.

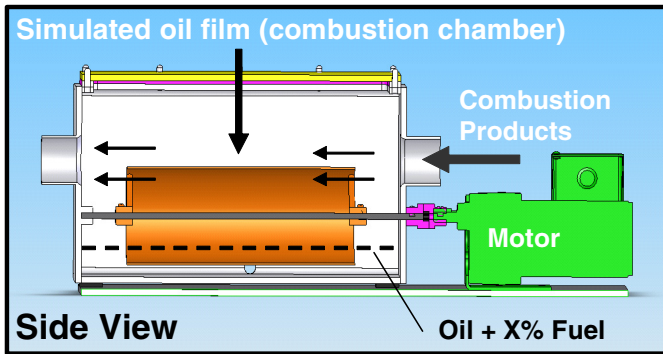


Figure 2. Accelerated lubricant aging and fuel dilution test system used on the Cummins ISB.

The accelerated aging system, shown in Figure 2, accelerates the degradation of a small volume of lubricant by exposing the lubricant to elevated temperatures and combustion products. In the present study, the lubricant aging system was filled with one liter of lubricant, pre-diluted to a specific fuel dilution level. A small portion of the exhaust from the Cummins ISB was directed through the main chamber of this system. Figure 3 shows the lubricant degradation system installed on the Cummins test bed.

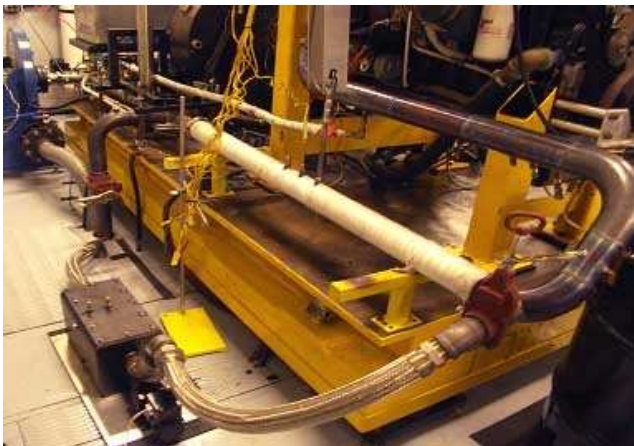


Figure 3. Accelerated lubricant aging and fuel dilution test system installed on Cummins test bed.

In order to simulate, as closely as possible, conditions inside the power cylinder, a 10.1 cm (4 inch) diameter stainless steel tube was slowly rotated through the lubricant bath, generating a thin oil film on both surfaces of the cylinder. Cylinder rotation was driven by a variable

speed gear motor, enabling rotation rates between 1 and 30 rpm. The hot exhaust combustion products from the Cummins ISB were directed to flow over the oil film on the cylinder. By varying exhaust flow rates into the accelerated aging system, temperatures and lubricant degradation rates could be controlled, thus simulating lubricant exposure to high temperatures, soot, and combustion gases found in the power cylinder.

LUBRICANT PROPERTIES ANALYSIS

Changes in lubricant properties were measured at various time intervals during the accelerated degradation procedure. The lubricant properties and associated standard test procedures used in the measurements are listed below:

- Viscosity @ 100 °C – ASTM D445
- Total Acid Number (TAN) – ASTM D664
- Total Base Number (TBN) – ASTM D2896/4739
- Trace Elements – ASTM D5185
- Pentane Insolubles – ASTM D4405
- Four-Ball Wear – ASTM D4172

Fourier transform infra-red (FTIR) analysis was also used to provide information on lubricant oxidation, anti-wear additive functionality, sulfation, nitration, water and soot levels, as well as fuel dilution.

LUBRICANT AND FUEL PROPERTIES

In order to better understand differences in emissions characteristics and fuel – lubricant interactions, as well as to evaluate changes in these properties over time, the properties of the lubricants and fuels used in this study are listed below.

Lubricant Properties

Table 2 lists the elements measured in the new CI-4 and CJ-4 oils by inductively coupled plasma (ICP), as well as the CI-4 oil run in the Cummins ISB for 220 hours.

Table 2. Elemental composition of new CI-4 and CJ-4 15W-40 diesel engine oils. The composition of the CI-4 oil aged in the Cummins ISB for 220 hours is listed for comparison.

Lubricant Condition	ASTM D5185						
	B	Ca	Fe	Mg	P	Zn	S
	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Fresh CI-4	<1	2352	2	269	1181	1398	5863
Fresh CJ-4	586	1388	2	355	985	1226	4606
Used CI-4	18	2626	20	267	1246	1464	6076

As can be seen from Table 2, the main differences in terms of elemental composition between the CI-4 and CJ-4 oils is a reduction in calcium by nearly a factor of two, with slight reductions in zinc and phosphorous.

Boron is also present in the CJ-4 oil in higher amounts. Table 3 compares specific physical and chemical properties for these lubricants.

Table 3. Properties of the new and engine-aged CI-4 oil, as well as the new CJ-4 oil.

	ASTM D3524	FTIR	ASTM D445	ASTM D664	ASTM D2896	ASTM D4739
Lubricant Condition	Fuel	Soot	Visc. @ 100 C	TAN	TBN	TBN
	% Wt	% Wt	mm ² /s	mg KOH/g	mg KOH/g	mg KOH/g
Fresh CI-4	<0.1%	<0.1%	14.93	1.86	9.9	---
Fresh CJ-4	<0.1%	<0.1%	15.8	1.74	9.6*	6.66
Used CI-4	<0.1%	0.10%	13.13	2.17	10.42	---

In an effort to more accurately measure changes in detergent properties, TBN for the CJ-4 oils was measured via ASTM D4739 rather than ASTM D2896, as used for the CI-4 oils. ASTM D4739 uses hydrochloric acid, a weaker acid as compared to the perchloric acid used in ASTM D2896, and therefore measures only strong bases in the lubricant. TBN measured via ASTM D2896 is presented for the new CJ-4 oil for comparison purposes.

Fuel Properties

A comparison of the trace elements measured in the ULSD and soy-derived B100, soy methyl ester (SME), are listed in Table 4. From the table it is evident that some batch-to-batch variation does exist for the three batches of biodiesel used in this study. Batch 3 clearly does not meet the ASTM D6751 specifications for biodiesel fuels.

Table 4. Trace elements measured in the ULSD as well as individual batches of the soy-derived B100.

Element	ASTM D5185				
	Lowest Reporting Value	B100 Batch 1	B100 Batch 2	B100 Batch 3	ULSD
	ppb	ppb	ppb	ppb	ppb
Ca	97	410	140	198	<97
Mg	56	<56	<56	<56	<56
P	1,180	<1180	<1180	2,981	<1180
Na	2,010	<2010	<2010	22,587	<2010
K	2,690	<2690	<2690	<2690	<2690
Zn	155	<155	<155	<155	<155

The high levels of sodium and phosphorous measured in batch 3 indicate the presence of significant amounts of residual catalysts, the result of incomplete washing of the finished fuel. Table 5 presents additional chemical and physical properties for the biodiesel fuels.

The high acid number and low flashpoint for the biodiesel in batch 3 provides further indication of poor fuel processing, with the low flashpoint indicating the

presence of residual methanol. Additionally, the water content for this batch is at the ASTM limit. Interestingly, the high Rancimat induction time, greater than 12 hours, indicates the presence of sufficient anti-oxidants. The properties of a high-quality batch of biodiesel and the ASTM D6751 limits are listed in Table 5 as well.

Table 5. Properties of biodiesel fuels used in this study.

	ASTM D664	ASTM D3828	ASTM D6304	EN 14112
	Acid Number	Flash Point	Water	Rancimat
	mg KOH/g	°C	ppm	hr
B100 - Batch 1	0.23	>130	314	0.56
B100 - Batch 3	3.36	<130	499	>12
ASTM D6751	0.5 max	130 min	500 max	>3

All emissions measurements and fuel dilution results presented in this study were carried out using biodiesel from batches 1 and 2, which meet the current ASTM D6751 specifications. However, the observed variations in fuel properties highlight the need to ensure fuel quality meets the required specifications and standards.

TEST MATRIX AND PROCEDURES

The experiments in this study were carried out in two parts, described in detail below.

Emissions and Ash Characterization

In order to evaluate fuel effects on exhaust emissions affecting aftertreatment system performance, the engine was run using both a conventional ultra-low sulfur diesel and neat soy-derived B100 biodiesel. Particulate and gaseous emissions were measured at a low speed and load condition, 1682 rpm and 25% rated load. This operating point was chosen as representative of a typical steady-state DPF loading condition. Differences in speciated ash emission rates and ash characteristics were also measured at this condition for the two fuels.

Lubricant Fuel Dilution Analysis

Initial system testing and validation of the accelerated aging system was carried out using a commercial 15W-40 CI-4 diesel engine oil without fuel dilution. Lubricant sump temperatures within the accelerated aging system ranged from 150 °C to 165 °C, with inlet exhaust temperatures ranging from 200 °C to 220 °C, depending on the test condition. The total test duration was 12 hours per lubricant.

The lubricant properties following the accelerated test were then compared with the same oil run in the Cummins ISB for a total of 220 hours. Additional tests with the CI-4 oil were used to quantify the effects of differences in combustion products between the soy-derived B100 and ULSD fuel on changes in lubricant properties. Subsequent testing was carried out using a 15W-40 diesel engine oil, meeting the new CJ-4