

# Impacts of Biodiesel Fuel Blends Oil Dilution on Light-Duty Diesel Engine Operation

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## ABSTRACT

Increasing interest in biofuels—specifically, biodiesel as a pathway to energy diversity and security—have necessitated the need for research on the performance and utilization of these fuels and fuel blends in current and future vehicle fleets. One critical research area is related to achieving a full understanding of the impact of biodiesel fuel blends on advanced emission control systems. In addition, the use of biodiesel fuel blends can degrade diesel engine oil performance and impact the oil drain interval requirements.

There is limited information related to the impact of biodiesel fuel blends on oil dilution. This paper assesses the oil dilution impacts on an engine operating in conjunction with a diesel particle filter (DPF), oxides of nitrogen ( $\text{NO}_x$ ) storage, a selective catalytic reduction (SCR) emission control system, and a 20% biodiesel (soy-derived) fuel blend. The main focus was on the biodiesel oil dilution levels observed during an accelerated aging protocol and an assessment of the potential impacts on the engine and emissions control systems. For the  $\text{NO}_x$  storage system (which requires a late in-cylinder fuel injection for regeneration), biodiesel oil dilution levels ranged from 5%-10%. For the SCR system (which used a urea solution as a reductant and late in-cylinder fuel injection for diesel particle filter regeneration), biodiesel oil dilution ranged from <4%-8%. These observations were made over typical oil drain intervals. Despite these observed biodiesel oil dilution levels, there were no observed impacts on performance of the engine or the emission control systems.

## INTRODUCTION

Biodiesel fuel blends are one option currently being researched as a pathway to energy diversity and reduced petroleum dependence in the transportation sector. One of the key factors related to the success of biodiesel fuel blends is their compatibility with vehicle components such as fuel systems, combustion parts, and advanced emission control systems. However, one way that biodiesel fuel blends can create potential problems affecting vehicle operation is through accelerated dilution of the oil by the fuel. This is particularly important for vehicles utilizing advanced emissions control systems that require late in-cylinder fuel injection. Excessive oil dilution has the potential to lead to several problems, such as reduced oil performance and durability (e.g., decreased viscosity or the development of oil sludge) and catalyst poisoning. At a minimum, oil dilution could impact the interval requirements for oil changes, the effectiveness of additive packages, and sump capacity. Acceptable oil dilution limits for original equipment manufacturers (OEMs) range up to 50% [1], but most OEMs want limits to be much lower.

Biodiesel is a renewable fuel derived from vegetable oil, animal fat, or waste cooking oil, and it consists of the methyl esters of fatty acids. It is typically used as a diesel blending component at levels up to 20% by volume. Life-cycle analysis indicates that the use of biodiesel can help displace imported petroleum in the United States and resource assessments have indicated that biodiesel has the potential to displace 5% or more of petroleum diesel over the next decade [2, 3]. However,

because biodiesel has a relatively higher distillation temperature and boiling point, when it is present in post-injected fuel it tends to dilute the oil on a level disproportionate to its blend ratio in the fuel [4, 5, 6]. This leads to a concern about oil dilution.

Current research at the National Renewable Energy Laboratory (NREL) on the impacts of biodiesel on emission control systems has provided an opportunity to also evaluate the impact of biodiesel fuel blends on oil dilution and its associated impacts on the performance of the engine and emission control system. As a corollary to a larger research project at NREL on biodiesel impacts on selective catalytic reduction (SCR) with urea and oxides of nitrogen (NO<sub>x</sub>) adsorber catalyst (NAC) systems [7, 8], researchers assessed biodiesel's impacts on oil dilution. The purpose of this paper is to document the oil dilution observed in this research project and assess any potential engine or emission control system impacts.

## HARDWARE DESCRIPTION

The following sections provide an overview of the hardware components used during the project. The test vehicle and test engines were procured by the U.S. department of energy in direct support of this project. All the catalyst hardware, as well as the urea dosing system, was supplied by the manufacturers of emissions controls association (MECA).

**ENGINE HARDWARE** - The engine used for this project in the test cell as well as in the vehicle was a 4-cylinder 2.15 l high-speed direct injection (HSDI) diesel engine. The original engine calibration complied with euro 4 emission standards. The engine utilized a conventional high-pressure exhaust gas recirculation (EGR) loop, a second-generation common-rail fuel injection system (1600 bar maximum injection pressure, solenoid injectors) with all actuators electrically controlled. Table 1 lists the main parameters of the test engine.

Table 1: Engine specifications

|                       |                                        |
|-----------------------|----------------------------------------|
| Engine Power          | 113 kW at 4000 rpm                     |
| Peak Torque           | 360 Nm at 2000 rpm                     |
| Maximum Engine Speed  | 4700 rpm                               |
| Maximum BMEP          | 21 bar                                 |
| Cylinder Arrangement  | 4-Cylinder Inline                      |
| Firing Order          | 1 – 3 – 4 – 2                          |
| Valve Train           | 4 Valve DOHC                           |
| Bore to Stroke Ratio  | 1.0034                                 |
| Displacement          | 2.15 l                                 |
| Compression Ratio     | 18:1                                   |
| Fuel Injection System | 2 <sup>nd</sup> Generation Common Rail |

The test vehicle was a conventional four-door sedan vehicle in the 1,700 kg class. It met the EURO 4 emission standards and was equipped with a catalyzed

diesel particle filter (DPF) as a standard feature. Table 2 lists the relevant vehicle features.

Table 2: Vehicle specifications

| Criteria                | Unit            | Value              |
|-------------------------|-----------------|--------------------|
| Vehicle Mass            | kg              | 1,700              |
| Air Drag Coefficient    | -               | 0.29               |
| Frontal Surface Area    | m <sup>2</sup>  | 2.20               |
| Transmission Gear Ratio | 1 <sup>st</sup> | 4.99               |
|                         | 2 <sup>nd</sup> | 2.82               |
|                         | 3 <sup>rd</sup> | 1.78               |
|                         | 4 <sup>th</sup> | 1.25               |
|                         | 5 <sup>th</sup> | 1.00               |
|                         | 6 <sup>th</sup> | 0.82               |
|                         | Axle            | 2.65               |
| Tires                   | Rear            | 205 / 55 R 16 91 H |
|                         | Front           | 205 / 55 R 16 91 H |

**CATALYST SPECIFICATIONS** - Two emission control systems (ECS) were developed and tested separately as part of this project. These included an NAC/DPF system and a SCR/DPF system. The NAC was located in a close-coupled position, directly after the turbine exit with minimal distance to the catalyst to allow for rapid heat-up of this NO<sub>x</sub> treatment unit; the DPF was located under the floor. The SCR catalyst was also located under the floor and was followed by the DPF in the same can, with a close-coupled diesel oxidation catalyst (doc). All the piping between the doc exit and the SCR inlet was made of dual-wall exhaust pipe to increase heat preservation during operation. MECA provided all the ECS components. Table 3 lists all the catalyst specifications for this project.

Table 3: Catalyst specifications for each component

| Component System |              | Volume [L] | Cell Density [cps] | PGM loading [g/ft <sup>3</sup> ] |
|------------------|--------------|------------|--------------------|----------------------------------|
| NAC System       | DOC          | 0.8        | 400                | 150                              |
|                  | DPF          | 3.3        | 300                | 60                               |
|                  | NAC          | 4.1        | 400                | 120                              |
| SCR System       | DOC          | 1.23       | 400                | 150                              |
|                  | DPF          | 4.1        | 300                | 60                               |
|                  | SCR Fe-ZSM-5 | 4.43       | 300                | N/A                              |

**FUEL AND OIL SPECIFICATIONS** - An ultra-low-sulfur diesel fuel (ULSD), also referred to as the base fuel, was used to blend the 20% by volume soy-derived methyl ester. Table 4 lists the fuel specifications for each tested fuel type. The effects on the fuel specifications as a result of the increased amount of methyl ester become particularly noticeable in the heating value, the cetane number, and the oxygen content. The base lube oil used for this study was CJ-4 oil.

Table 4: Fuel specifications

| Specification     | Unit                 | ASTM Method   | ULSD  | B20   |
|-------------------|----------------------|---------------|-------|-------|
| Net Heating Value | MJ/kg                | D240          | 42.53 | 41.52 |
| Cetane Number     | -                    | D6890         | 41.4  | 45.6  |
| Density at 15°C   | kg/m <sup>3</sup>    | D4052         | 847.5 | 852.9 |
| Viscosity at 40°C | mm <sup>2</sup> /sec | D445          | 2.429 | 2.685 |
| Carbon            | wt%                  | D5291         | 87.04 | 85.01 |
| Oxygen            | wt%                  | By difference | 0.00  | 2.29  |
| Hydrogen          | wt%                  | D5291         | 12.96 | 12.70 |

## LATE IN-CYLINDER FUEL INJECTION EVENTS

Oil dilution in diesel engines will occur over time with normal operation, leading to oil degradation and the need for oil replacement. With increased use of advanced emission control devices, oil dilution impacts can also increase as a result of late in-cylinder fuel injection events used in conjunction with some of these devices [4, 6]. The late injection events are used as a regeneration strategy for DPFs as well as NACs. These late injection events increase the opportunity for unburned fuel to reach the cylinder walls and in turn enter the lubricating oil. With conventional diesel fuel it can boil out of the lube oil, minimizing long term dilution effects. However, this effect is accentuated with biodiesel because of its high boiling point relative to petroleum diesel, which can lead to a disproportionate amount of fuel being retained in the lube oil. Three main late injection events are associated with DPF and NAC operation that can accentuate the oil dilution problem. These include lean-rich modulation used for NAC regeneration, desulfurization used to liberate the NAC from accumulated fuel-borne sulfur, and DPF regeneration used to burn off accumulated soot from the DPF substrate.

**LEAN-RICH MODULATION** - NAC regeneration is a key component of meeting NO<sub>x</sub> emission standards with an NAC system. A short pulse of rich exhaust gas desorbs the NO<sub>x</sub> emissions and subsequently reduces them, following the well-known chemistry of the three-way-catalyst, described in more detail in the next section. These events occur quite frequently (e.g., every one to two minutes). The goal is to obtain the required rich exhaust conditions with a diesel engine that typically operates under lean conditions. Lean-rich modulation through late in-cylinder fuel injection is used to achieve

the rich exhaust conditions required by the NAC, but this also has the potential to lead to increased oil dilution.

**Desulfurization** - The basic principle of NAC is the adsorption of NO<sub>2</sub> during the lean operating phases of the engine. The NO<sub>2</sub> is adsorbed by alkaline earth oxides forming nitrates such as Ba (NO<sub>3</sub>)<sub>2</sub>. The nitrates become unstable and release the NO and NO<sub>2</sub> at high temperature (thermal release of NO<sub>x</sub>) or during rich exhaust conditions. The rich exhaust conditions allow the three-way-catalyst mechanism to be used to reduce the released NO<sub>x</sub> into N<sub>2</sub> and CO<sub>2</sub>. In addition to their desired functions, NACs exhibit the undesired function of adsorbing SO<sub>3</sub><sup>-2</sup> and forming BaSO<sub>4</sub>, which is a considerably more stable compound requiring high temperatures and stoichiometric operating conditions to be released. This release or desulfurization has to occur relatively frequently to avoid catalyst deactivation. The frequency of this event depends on the fuel sulfur level as well as the contribution of the engine lubricating oil. The rich operation required to create these high-temperature desulfurization conditions also requires late in-cylinder fuel injection, and that in turn creates an opportunity for increased oil dilution.

**DPF REGENERATION** - DPF regeneration is occasionally required in order to oxidize the accumulated soot that collects on the DPF during normal engine operation. As with NAC regeneration and NAC desulfurization, late in-cylinder fuel injection is used to create the high temperatures over the DPF required to burn or oxidize the accumulated soot. This provides another opportunity for increased oil dilution, and it would be the case for both NAC systems and SCR systems.

## AGING TEST CYCLE

Both systems were aged to an equivalent of 120,000 miles, or full useful life, and the oil was sampled at regular intervals during this aging. In order to simulate the appropriate aging conditions, the engine and ECS were exposed to an equivalent useful lifetime of fuel in the engine dynamometer test cell. To keep the aging time at a reasonable level, the aging duration for each ECS was set to be accomplished in approximately 700 hours. The following assumptions were used regarding fuel consumption for the system:

- Highway Fuel Economy Test (HFET) fuel economy of 55 mpg
- Urban Dynamometer Driving Schedule (UDDS) cycle fuel economy of 33 mpg
- Split of ¾ HFET and ¼ UDDS

These assumptions resulted in an average fuel economy of 49.5 mpg. At 120,000 miles, this equates to 2,424 gallons or 7,708 kg of fuel. Given the 700 hours of aging time, an average fuel consumption of approximately 3.4