3,000 ekW, 60 Hz Generator Set: Diesel & HVO Test

ABSTRACT

This paper provides details and summary conclusions of the evaluation in a factory test cell of a Cat® 3516E, 3,000 ekW, 60 Hz generator set using diesel and hydrotreated vegetable oil (HVO) fuel.

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Executive Summary

This paper describes back-to-back tests performed at Caterpillar's Large Engine Center on a Cat® 3516E, 3,000 ekW, 60 Hz diesel generator set running on diesel and hydrotreated vegetable oil (HVO). The findings of the tests, which are detailed in this paper, can be summarized as follows:

Positive Impact Using HVO

- Compared with diesel, smoke and soot emissions were lower.
- Start-up time was faster than diesel, but the time to reach steady state speed was almost equal.

Additional Observations (the following results were expected; they do not preclude the use of HVO as a fuel)

- HVO density limited the injector delivery; that means at an equivalent fuel delivery setting, as used for diesel fuel, the engine lost 3.6% of power when using HVO.
  However, the engine will automatically increase fuelling until it reaches the fuel delivery limit. For most 3500 Series engines that means less than a 2% power derate, without modifications to the engine hardware or software.
- On average, transient response tests showed a 1.3% greater frequency droop.
- NOx (Nitrogen Oxide) emissions were not significantly different with HVO compared with diesel.

Introduction

Caterpillar is a world leader in the development and production of heavy-duty diesel engines.

Caterpillar has been following the development of renewable and alternative fuels for decades, and the company is involved in the development of appropriate specifications to ensure the successful application of these fuels in Cat® engines. The most common liquid renewable fuels are derived from renewable resources such as planted crops (soy, palm, rapeseed, etc.), used cooking oil, animal fat, biomass, algae, and others. Renewable fuels reduce the carbon footprint of the fuels on a Life Cycle Analysis basis. One form of renewable fuel, hydrotreated vegetable oil (HVO) — also called renewable diesel (RD) — is derived from fats and oils through a hydrotreating process.

To better understand the performance and environmental impact of using HVO as fuel in a diesel engine, Caterpillar performed a back-to-back study of diesel and HVO fuel in a Cat 3516E, 3,000 ekW, 60Hz generator set.

Fuels Tested

For the test, a comparison of engine performance was conducted using diesel fuel and HVO, referred to as neat or R100, no blending.

Details on the composition of the diesel fuel and HVO used in the test are shown in Figure 1.

		Ultra-Low Sulfur Diesel (ULSD)	Hydrotreated Vegetable Oil (HVO)
T90	°C	320	302
Density@15°C	g/mL	0.8492	0.7814*
Cetane Index, Calculated		44.7	69.8*
Sulfur	ppm	13.8	5.0
Viscosity @ 40°C	cSt	2.46	3.095*
Lubricity (maximum)	mm	0.45*	0.46*
Cloud Point	°C	-12*	-10*
Aromatics (by weight)	%	35*	1.1*
Flashpoint	°C	54*	55*

*values based on characteristics listed in the fuel certificate of analysis or in fuel specification; other values in the table represent results of fuels analysis conducted in Caterpillar Tech Center labs.

Note: Fuel specifications (e.g., ASTM D975 and EN 15940) indicate ranges or maximum/minimum for the various fuel characteristics

Figure 1

Test Set Up

The generator set was evaluated in test cell #525 at the Caterpillar Large Engine Center in Lafayette, Indiana. The test cell is normally used for production testing of generator sets and is equipped with a reactive load bank.

Pictures of the generator set installed in the test cell are shown in Figure 2.

Figure 2

The diesel fuel used for the test came from a common tank that supplies the facility test cells, while a temporary tank for the HVO was installed in an adjacent test cell.

A picture of the temporary tank for the HVO is shown in Figure 3.

Figure 3

To measure the NOx emissions and smoke, automotive-style NOx sensors and smoke sensors were installed in the exhaust stack. The installation of these sensors and the required analysis equipment are shown in Figure 4.

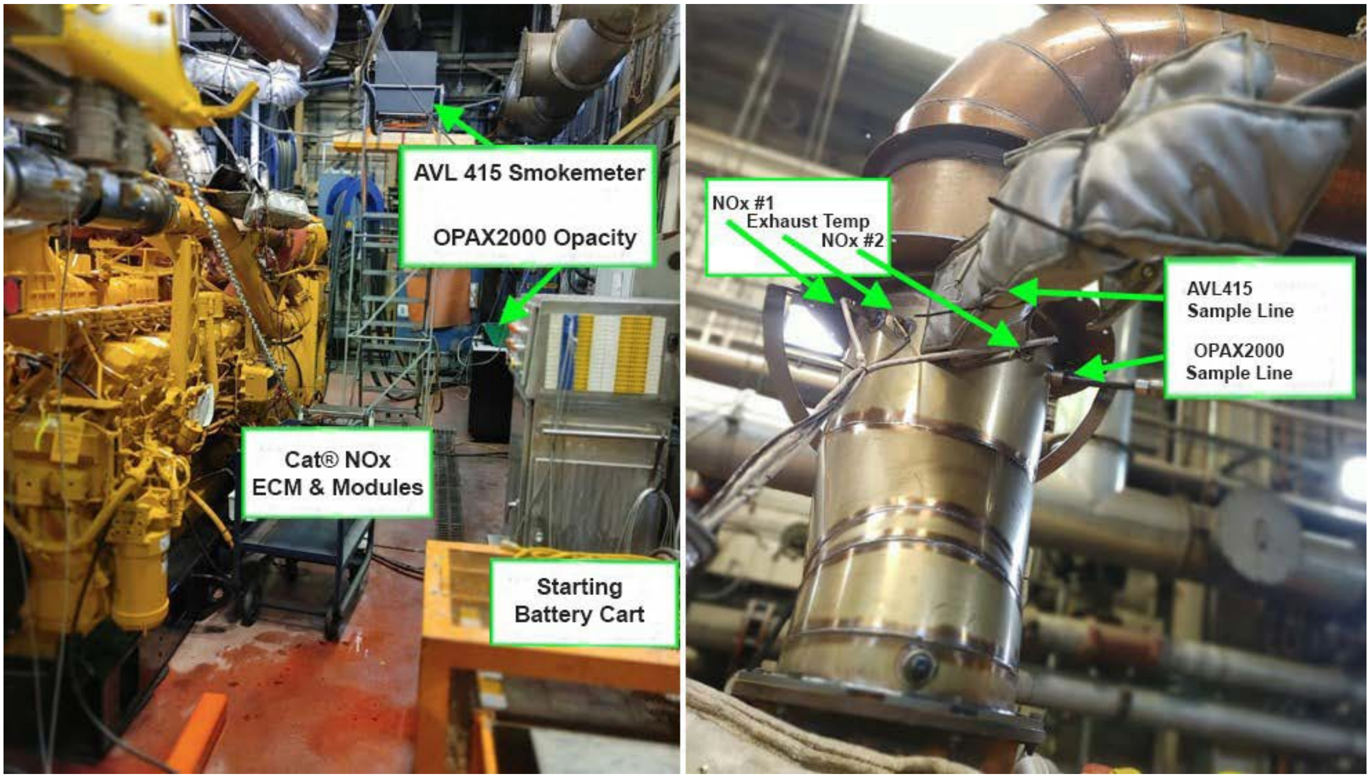

Figure 4

Test Procedure

The testing was completed in four days with a total of 18 hours of run time on the generator set. The test plan was as follows:

1. Install the generator set and perform any test cell debug with diesel fuel.
2. Perform and record 12 steady-state performance points with diesel fuel.
3. Perform and record three NFPA start-up tests with diesel fuel.
4. Perform and record four ISO 8528-5 tests with diesel fuel.
5. Perform and record four SpecSizer tests with diesel fuel.
6. Change fuel filters for the engine and test cell.
7. Purge the system of diesel fuel by running engine with 100 gallons of HVO.
8. Perform and record 12 steady-state performance points with HVO.
9. Perform and record three NFPA start-up tests with HVO.
10. Perform and record four ISO 8528-5 tests with HVO.
11. Perform and record four SpecSizer tests with HVO.
12. Change fuel filters for the engine and test cell.
13. Purge the system of HVO by running engine with 100 gallons of diesel fuel.
14. Check the generator set power with diesel fuel, inspect the generator set, and remove to prepare for shipping.

For the start-up tests, the jacket water was forced to 60°C. These tests were repeated three times to ensure consistent results. Each transient test (ISO 8528-5 and SpecSizer tests) was run at two voltage regulator settings (2 V/Hz and 3 V/Hz) as well as two power factor settings (0.8 and 1).

Test Results

The generator set was expected to lose 2% to 5% of power based on the literature as well as Caterpillar's own simulations. At all the tested part-load points, the engine was run to the same power. The engine governor modified the fuel injector duration for these points. To document the power loss at the full load point, the fuel delivery was held constant at the rated power for both the diesel and HVO tests. The test found the engine power to be 3.6% less with HVO at the same fuelling as diesel (shown in Figure 5). The engine will be able to increase fuelling until reaching the fuel delivery limit. Caterpillar expects most 3500 Series engines to experience less than a 2% power derate without any modification to the engine or software.

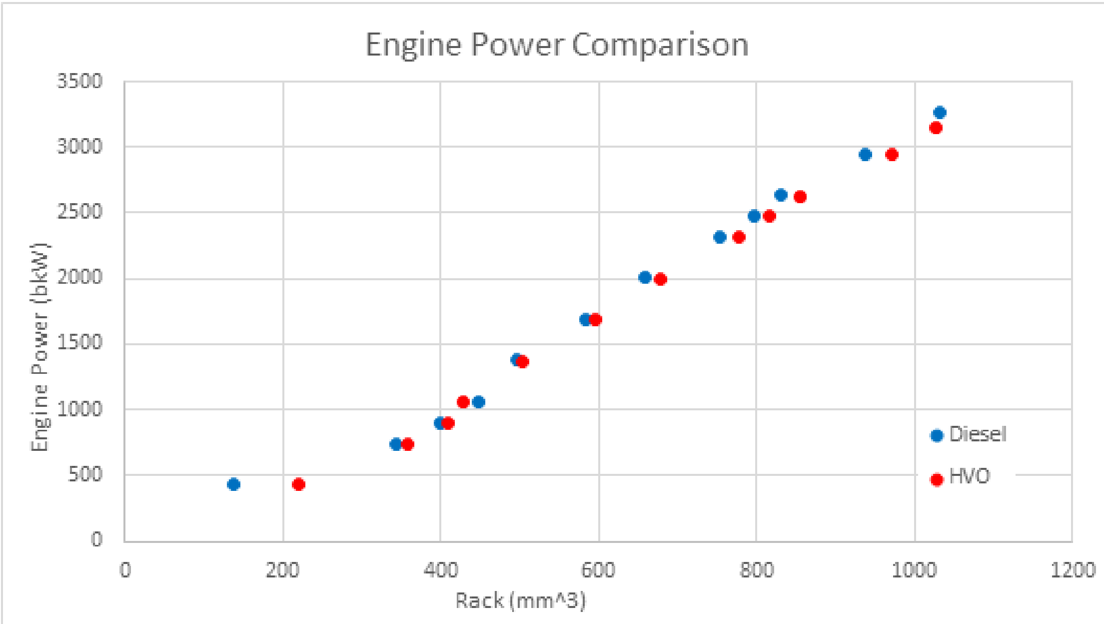

Figure 5

The fuel consumed in gallons/hr was also recorded for these 12 steady-state points, as shown in Figure 6.

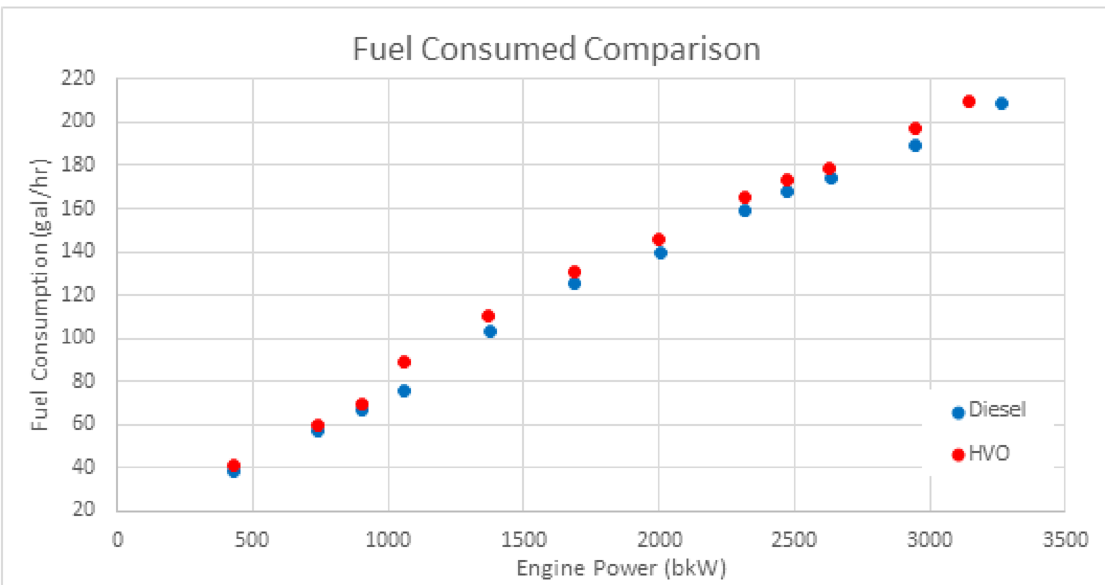

Figure 6

Since this test was not performed in a development/certification test cell, automotive NOx sensors and smoke sensors were installed and recorded to document changes with the different fuels.

For the NOx sensors, a 5% error bar has been added to all measured test points and shows there is no significant difference at high loads. At a 50% load and lower, the HVO shows a NOx reduction of up to approximately 40%. The NOx test results for 12 steady-state points are shown in Figure 7.

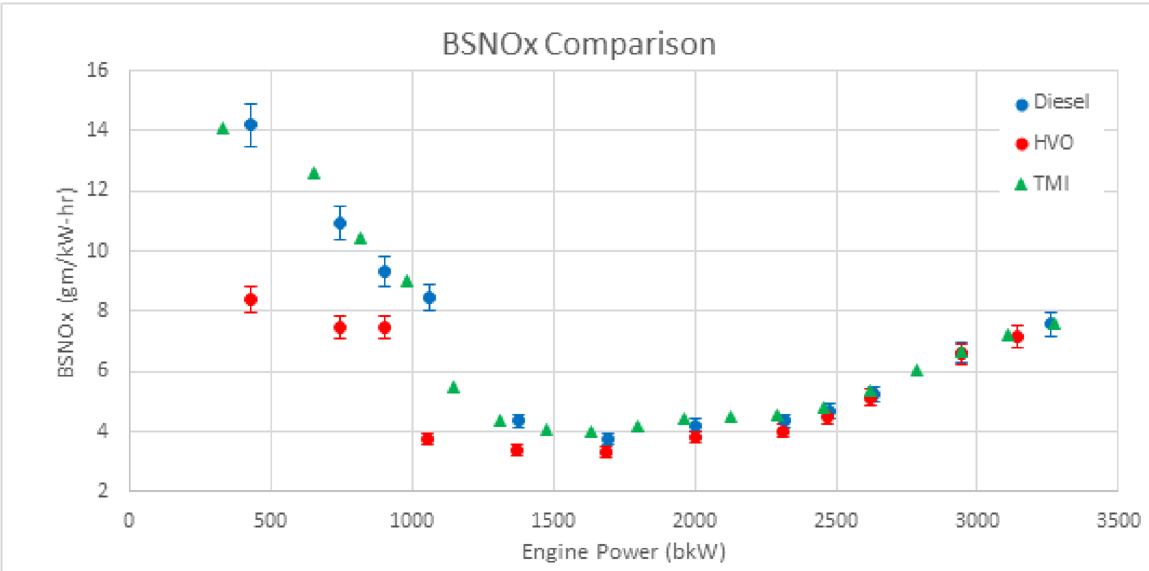

Figure 7

An AVL 415 smoke meter was used to measure the filter smoke number (FSN) for the 12 steady-state points. The FSN values for HVO were up to approximately 60% lower than the diesel values down to approximately 28% load. The FSN values for diesel were lower than the HVO values by up to approximately 80% at approximately 23% load and below. These results are shown in Figure 8.

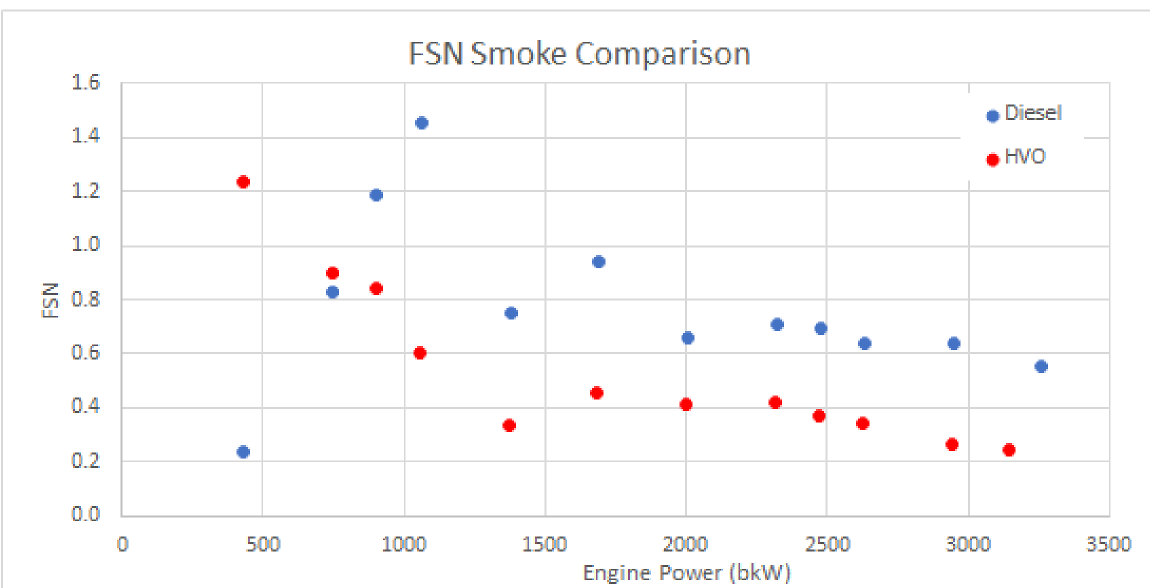

Figure 8

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The peak smoke opacity was captured for the SpecSizer test also. These results correspond with the steady-state results, showing the smoke produced with HVO is approximately 50% of the diesel value. This is shown in Figure 9.

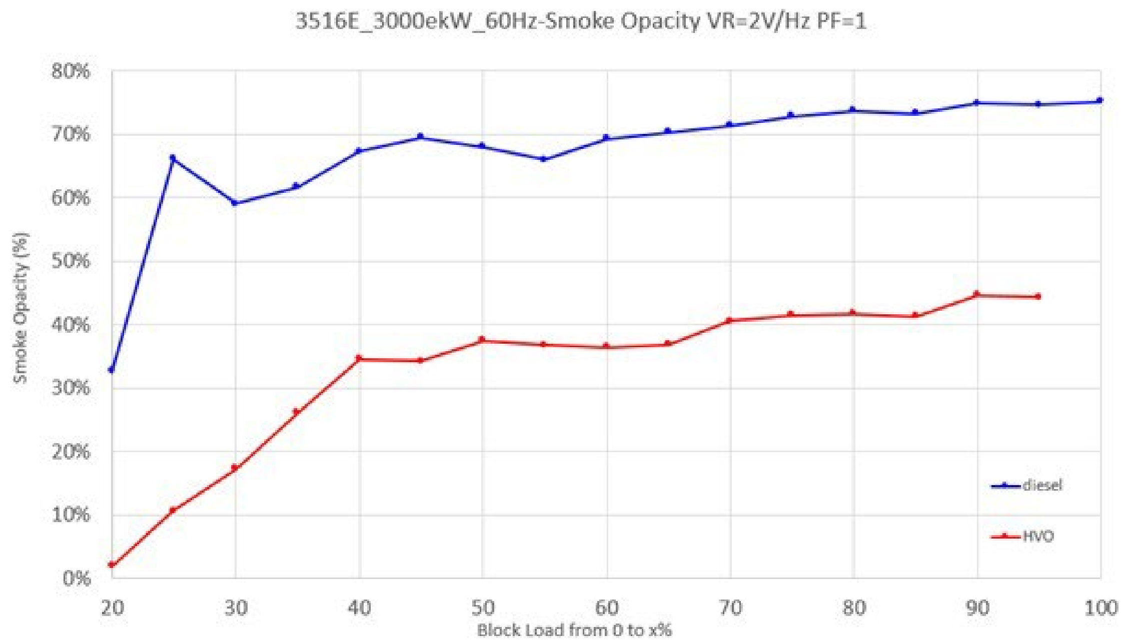

Figure 9

Transient response tests with a 2:1 slope voltage regulator and at a 1.0 PF resulted in the frequency droop crossing the G3 limit at approximately 41% with HVO and 43% with diesel. The G2 limit was crossed at approximately 48% with HVO and 51% with diesel. These test results are shown in Figure 10.

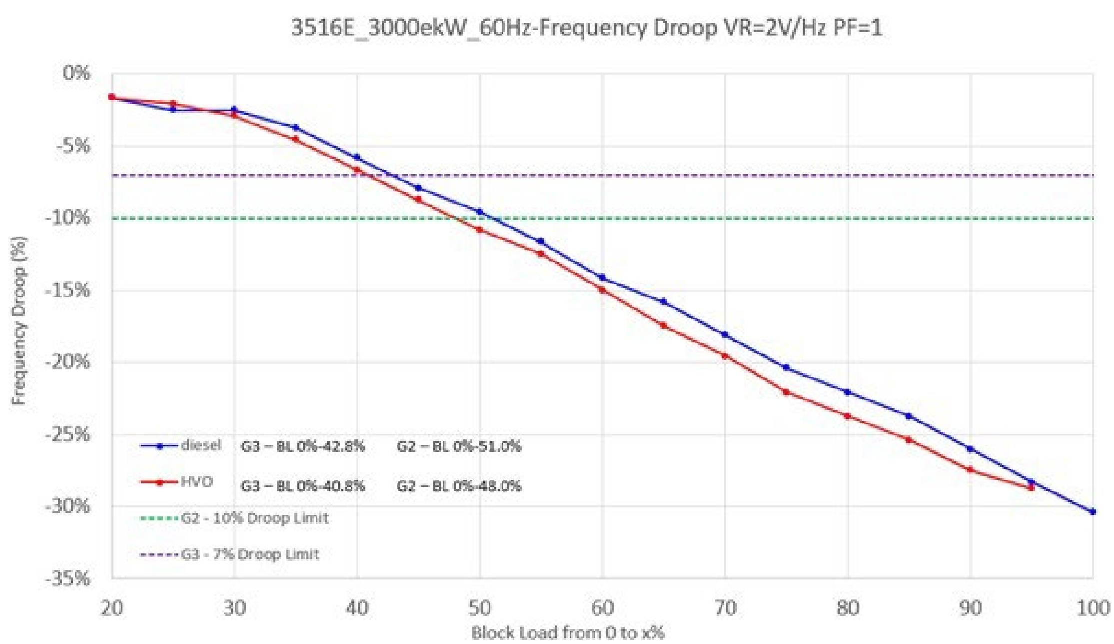

Figure 10

Figure 11 shows how the frequency behaves with diesel and HVO fuel for block loads of 0-40% to 0-60%, in 5% increments. In all cases, the frequency dip and recovery time with diesel are less than with HVO. The frequency rise is slightly higher with diesel than HVO for the load rejection of block loads in 5% increments from 40% to 60%, except in the case of the 45% load rejection.

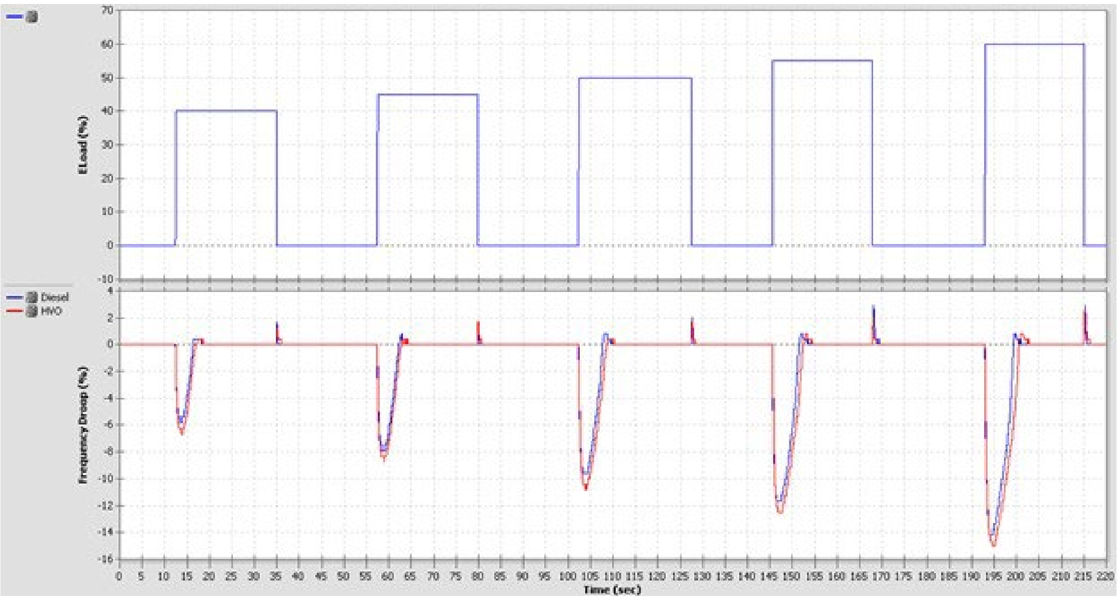

Figure 11

To test the capability of the Cat 3516E to meet NFPA 110, Type 10 requirements that stipulate power must be provided to the load terminals of the transfer switch within 10 seconds, the jacket water temperature of the engine was maintained at 60°C and a start-up test was performed with each fuel three times. Results for each of the three runs were similar, so the third run with each fuel is shown in Figure 12. As expected, based on the higher cetane number, the start-up time with HVO was slightly faster than with diesel. There was a slight overshoot in engine speed with HVO, resulting in almost identical times to reach steady state speed. In both cases, the steady state engine speed reached 1800 rpm (60 Hz) in under 7 seconds.

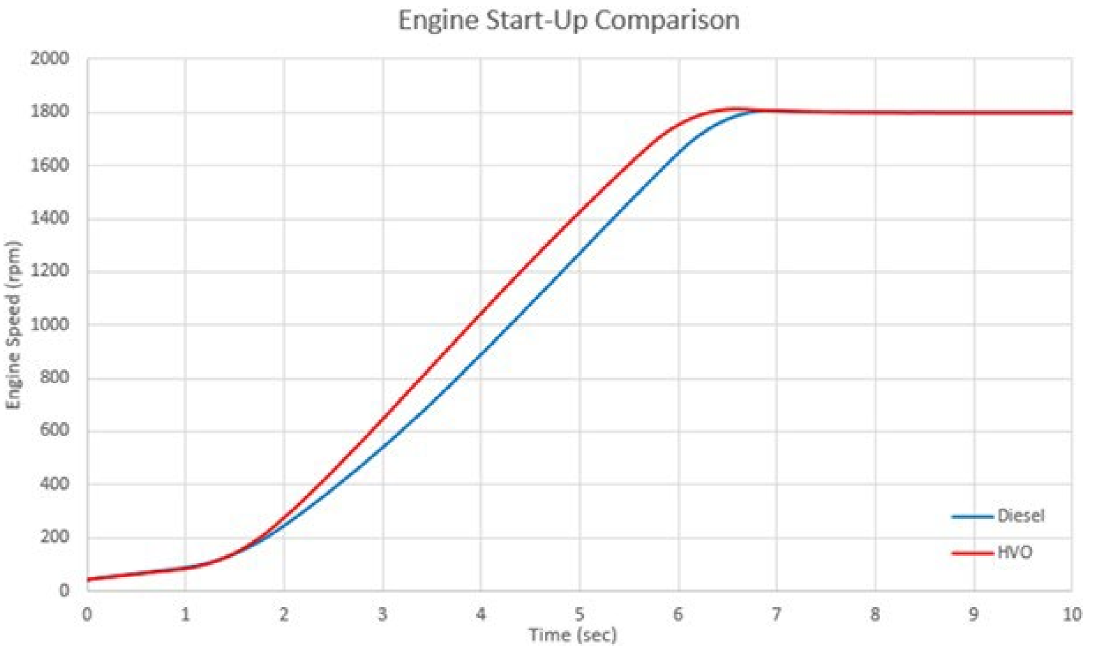

Figure 12

Caterpillar has evaluated the compatibility of elastomers used in the 3500 Series fuel system with HVO through aging testing. Cat seals and hose materials are considered compatible with HVO and all HVO-diesel blends, with no negative impact to the components.

It is recommended that the end user consult the fuel source supplier for information regarding the handling and storage of HVO.

Summary

With some trade-offs, the tests demonstrated the viability of HVO as an alternative to diesel fuel:

- HVO density limited the injector delivery, and the engine had a 3.6% power loss at equal fuelling with diesel. Most 3500 Series engines will experience less than 2% power derate from rated without any modification to the engine.
- Fuel consumption was slightly higher using HVO at all points measured.
- Overall, lower smoke and soot emissions were recorded when using HVO. For the smoke opacity test, the results using HVO were approximately 50% of diesel at all points measured. NOx emissions were not significantly different when using HVO.
- On average, transient response tests showed a 1.3% greater frequency droop with HVO.
- Start-up time using HVO was faster than diesel, but the time to reach steady state speed was almost equal.

Other 3500 Series engine ratings are expected to have the same directional impact as was seen in this test data when converting from diesel to HVO.

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