Test Summary Report

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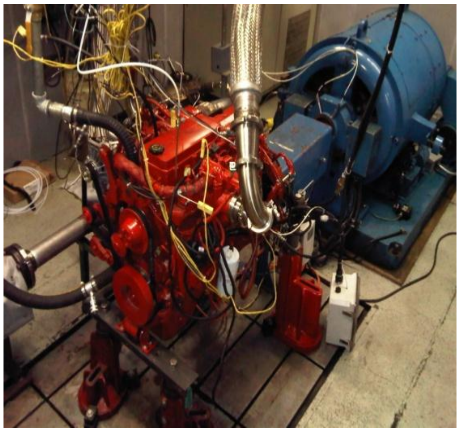
Engine Emissions Test Results
Regulated emissions measurements were performed using procedures consistent with the Code of Federal Regulations title 40, section 86, subpart N. The test setup consisted of a 2008 model year 6.7L 330 hp Cummins ISB. Properties of the test engine are shown in Figure 1. The engine employs cooled high-pressure exhaust gas recirculation (EGR), a variable geometry turbocharger, electronic control, and high-pressure common rail direct fuel injection. The engine, designed and calibrated to meet the 2007 U.S. heavy-duty emissions standards, also uses an actively regenerated diesel particulate filter (DPF) for reduction of particulate matter (PM) emissions.

Testing was conducted with four fuels. The baseline diesel fuel was a 2007 Certification Ultra Low Sulfur Diesel (ULSD) supplied by Haltermann Products (Channelview, TX). This fuel was used for baseline comparison as well as the diesel blend stock for fuel blending. The second fuel was vegetable oil that had been hydrotreated using Neste oil's NExBTL PROCESS. Neat Neste renewable diesel is referred to as N100. The third and fourth fuels were 5% and 20% blends by volume of N100 into certification ULSD, and are referred to as N5 and N20 respectively.

Testing was conducted over the heavy duty transient (HDT) cycle in accordance with the federal test procedure. Four consecutive hot-start repeats were conducted with the N5 and N100 test fuels. Five repeats were conducted with the N20 test fuel. Over the course of four separate days, eleven total hot-start repeats of this test were conducted with the certification ULSD. This data provides a measure of the day-to-day variability of engine emissions. In addition, an 8-mode steady state test was conducted to measure engine-out smoke number emissions. Following the FTP transient cycle, two hot-start repeats of this test were conducted with the N20 and N100 test fuels. Four hot-start repeats were conducted with the certification ULSD over the course of two separate days. A thorough fuel swap procedure was carried out between experiments with each test fuel. This includes flushing three times the volumetric capacity of the entire fueling system, including fuel lines, the fuel meter and the engine. As a check, the fuel density measured by the fuel meter, is an indication of the fuel being delivered to the engine.

Measurement of NO_x, PM, THC, CO and CO_2 emissions were collected as well as fuel consumption. NO_x emissions are determined by chemiluminescence detection, THC by flame ionization detection and CO and CO_2 by non-dispersive infrared spectrophotometer. Mass emissions levels are determined through dilute constant volume sampling with critical flow venturis. Background and humidity corrections are applied to all emission data. Fuel consumption is measured with a Pierburg fuel metering system, which measures volumetric fuel flow and density with an accuracy of +/- 0.5% of reading. An AVL smoke meter was used to measure smoke number at the inlet to the DPF (engine-out). Because this engine is equipped with a DPF which results in nearly undetectable tailpipe PM emission levels, all measurements are made at the inlet to the DPF (engine-out). The smoke number is not an approximation of g/bhp-h PM emissions, but provides a value that is proportional to PM emissions and allows us to quantify changes to engine out smoke for different fuels. Thus, the smoke number emissions reported here do not represent changes in tailpipe emissions compared to the base fuel. However, these reductions may have implications on the overall performance of the DPF.



Cummins ISB	
Serial Number	49891045
Displacement, L	6.7
Cylinders	6
Rated Power, kW	244 at 2800 rpm
Rated Torque, N-m	895
Bore x Stroke, cm	10.7 x 12.4
Compression Ratio	17.3 : 1
Fuel System	Common Rail

Figure 1. Cummins ISB Test Engine

Results are shown graphically in Figures 2, 3 and 4, and tabulated in Tables 1 through 4. N5 resulted in a 2.6% decrease in NO_x emissions with no significant change in fuel consumption over the FTP transient test cycle, when compared to the certification ULSD. N20 resulted in a 4.0% decrease in NO_x emissions and a 0.9% decrease in fuel consumption. N100 resulted in a 9.5% decrease in NO_x emissions and a 3.9% decrease in gravimetric fuel consumption. Because of the DOC and DPF, tailpipe emissions of PM, THC and CO were near or below detection limits for all fuels. However, measurement of engine-out smoke number emissions with N100 did show a 34.2% reduction in emissions compared to the certification ULSD. There was no significant change in smoke number emissions for N20.

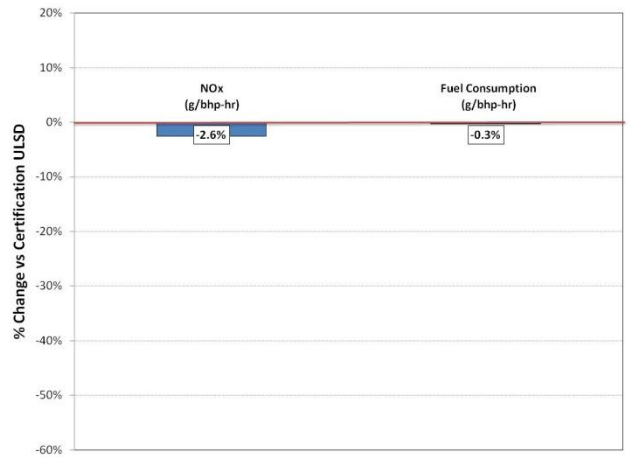


Figure 2. Changes in tailpipe brake specific NO_x emissions, engine out smoke number emissions, and brake specific fuel consumption for N5

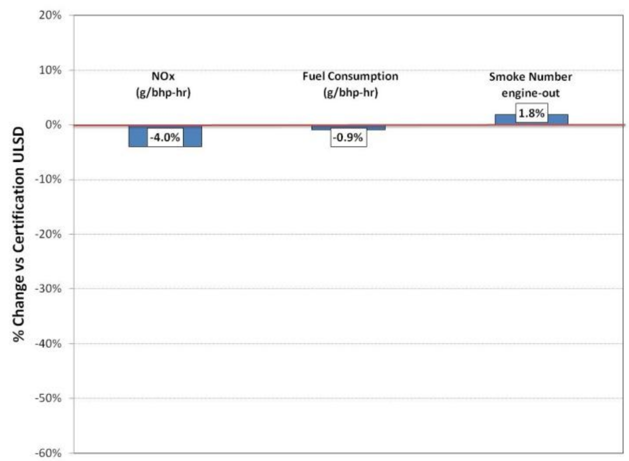


Figure 3. Changes in tailpipe brake specific NO_x emissions, engine out smoke number emissions, and brake specific fuel consumption for N20

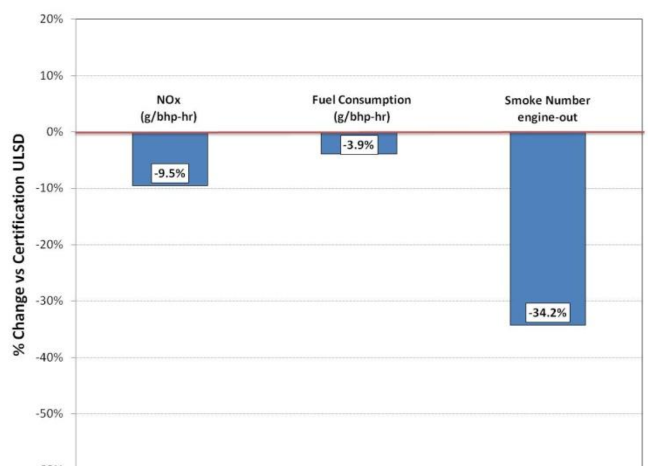


Figure 4. Changes in tailpipe brake specific NO_x emissions, engine out smoke number emissions, and brake specific fuel consumption for N100

Table 1. Certification ULSD Emissions Data

Cycle	NO_x (g/bhp-hr)	Fuel Cons. (g/bhp-hr)	Cycle Energy (bhp-hr)	Smoke Number engine-out
HDT	2.34	211	17.6	-
HDT	2.43	211	17.7	-
HDT	2.34	212	17.6	-
HDT	2.42	213	17.7	-
HDT	2.40	210	17.7	-
HDT	2.40	209	17.7	-
HDT	2.37	213	17.5	-
HDT	2.27	211	17.7	-
HDT	2.32	211	17.6	-
HDT	2.35	210	17.6	-
HDT	2.34	209	17.7	-
8-mode	-	-	-	0.250
8-mode	-	-	-	0.243
8-mode	-	-	-	0.240
8-mode	-	-	-	0.253
avg.	**2.36**	**211**	**17.6**	**0.246**
std dev	*0.05*	*1*	*0.1*	*0.006*
cov	*2.0%*	*0.6%*	*0.3%*	*2.4%*

Table 2. N5 Emissions Data

Cycle	NO_x (g/bhp-hr)	Fuel Cons. (g/bhp-hr)	Cycle Energy (bhp-hr)
HDT	2.32	210	17.7
HDT	2.29	210	17.7
HDT	2.30	210	17.7
HDT	2.29	211	17.6
avg.	**2.30**	**210**	**17.7**
std dev	*0.01*	*1*	*0.0*
cov	*0.5%*	*0.3%*	*0.1%*
vs ULSD	**-2.6%**	**-0.3%**	**0.1%**
p-value	**<0.01**	**0.28**	**0.38**

Table 3. N20 Emissions Data

Cycle	NO_x (g/bhp-hr)	Fuel Cons. (g/bhp-hr)	Cycle Energy (bhp-hr)	Smoke Number engine-out
HDT	2.27	209	17.6	-
HDT	2.25	208	17.6	-
HDT	2.26	209	17.7	-
HDT	2.28	209	17.6	-
HDT	2.27	209	17.6	-
8-mode	-	-	-	0.262
8-mode	-	-	-	0.239
avg.	**2.27**	**209**	**17.6**	**0.251**
std dev	*0.01*	*1*	*0.0*	*0.016*
cov	*0.6%*	*0.3%*	*0.1%*	*6.5%*
vs ULSD	**-4.0%**	**-0.9%**	**0.0%**	**1.8%**
p-value	**<0.01**	**<0.01**	**0.41**	**--**

Table 4. N100 Emissions Data

Cycle	NO_x (g/bhp-hr)	Fuel Cons. (g/bhp-hr)	Cycle Energy (bhp-hr)	Smoke Number engine-out
HDT	2.14	203	17.6	-
HDT	2.12	202	17.6	-
HDT	nm	203	17.6	-
HDT	2.14	203	17.6	-
8-mode	-	-	-	0.163
8-mode	-	-	-	0.161
avg.	**2.14**	**203**	**17.6**	**0.162**
std dev	*0.01*	*1*	*0.0*	*0.001*
cov	*0.5%*	*0.3%*	*0.2%*	*0.9%*
vs ULSD	**-9.5%**	**-3.9%**	**-0.2%**	**-34.2%**
p-value	**<0.01**	**<0.01**	**0.18**	**--**

Steady state engine combustion and emissions were studied using a 9.3L 2008 International MaxxForce 10 engine rated at 246 kW. This engine was calibrated for use in a school bus and met the 2007 U.S. heavy-duty emission standards. The engine design employs cooled high-pressure EGR, a variable geometry turbocharger, and high-pressure common-rail direct fuel injection. Engine operation is controlled using a production engine control unit (ECU). An actively regenerated diesel particulate filter (DPF) was used to reduce PM emissions. For in-cylinder combustion and heat release analysis, one of the engine cylinders was instrumented with a Kistler piezoelectric pressure transducer type 6125C. Intake manifold pressure was measured using Kistler pressure transducer types 4005BA5FA2. Fuel injection signal was measured with a Tektronix current probe (Model A622). The engine crank angle position was identified using an AVL encoder type 365C01. Crank angle-based high-speed data acquisition (DAQ) was performed using an AVL IndiMODUL system with resolution of 0.2 crank angle degrees (CAD).

The certification ULSD and N100 were studied at 13 steady-state engine modes shown in Table 5. The engine was warmed up by running at 1000 rpm and 600 N·m for 20 minutes before being tuned to the desired speed and load conditions. At each condition, the engine was stabilized for at least 3 minutes before collecting engine-out regulated emissions and high-speed data. The intake CO_2 concentration was also measured to calculate exhaust gas recirculation (EGR) rate. The emission data reported in this study were averaged over 30 seconds. Apparent heat release rate (AHRR) was calculated based on the cycle-averaged pressure using 50 cycles.

Table 5. 13-mode International Engine Operating Points

Mode	**Speed (rpm)**	**Torque (N·m)**
1	700	0
2	1288	1600
3	1575	769
4	1575	1153
5	1288	800
6	1288	1200
7	1288	400
8	1575	1538
9	1575	384
10	1863	1298
11	1863	324
12	1863	973
13	1863	649

During the test, the engine speed was controlled by the AC dynamometer and the engine load was controlled by the accelerator pedal position (APP). Since renewable hydrocarbon fuels have different volumetric energy density, the APP was close-loop controlled to meet the desired engine load. All other engine operating parameters were automatically selected based on the ECU calibration, which means that differences in APP cause differences in other engine operating parameters such as EGR valve position and fuel injection timing, etc.

Figure 5 shows the AHRR curves of the ULSD and N100 at low speed (1288 rpm) and low load (400 N·m) conditions. The engine uses about 28% EGR and the same start of injection (SOI) of about 6 crank angle degrees before top dead center is observed for both fuels. Since intake manifold pressure (IMP) and intake manifold temperature (IMT) are relatively low, the combustion ignition delay is relatively long. A two-phase heat release is observed in Figure 5. The first phase is due to the combustion of the partially premixed fuel air mixture formed during ignition delay, shown as the first peak on the heat release curve. The second phase is the diffusion combustion of the rest of the fuel injected into the cylinder, shown as the second peak on the heat release curve.

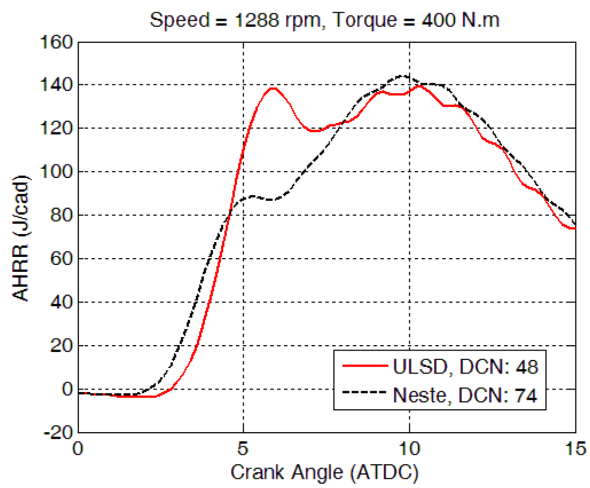


Figure 5. Apparent heat release curves. Conditions: Speed = 1288 rpm, Torque = 400 N·m, EGR ≈ 27%, IMP = 1.5 bar, IMT = 50 °C.

Figure 6 shows the AHRR curves at intermediate speed (1575 rpm) and high load (1153 N·m) condition. At this condition, the engine IMP (2.54 bar) and IMT (58 °C) are higher than those at low speed and low load condition. Both fuels exhibit very short ignition delay. The heat release curve exhibits only one peak representing diffusion combustion. No obvious premixed combustion is observed. As a consequence, no significant difference in combustion heat release is observed.

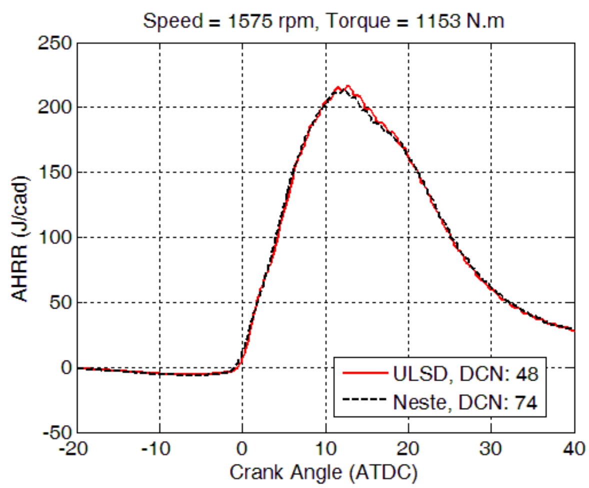


Figure 6. Apparent heat release curves. Conditions: Speed = 1575 rpm, Torque = 1153 N·m, EGR ≈ 24.5%, IMP = 2.54 bar, IMT = 58 °C.

The results of engine-out NO_x, CO and THC emissions at 1288 rpm, 400 N·m for the ULSD and N100 are listed in Table 6. As shown here the EGR rate was increased by 2.5% as a result of the increased throttle percent necessary to maintain engine load conditions with the lower volumetric energy density of N100 relative to ULSD. NO_x and CO were both decreased relative to ULSD. The NO_x reduction is attributed to the higher EGR rate, due to the resulting increase in combustion temperature. The reduction in CO is attributed to the higher cetane value of the N100 as this fuel has a shorter ignition delay time and thus less premixed combustion will occur, particularly at low load conditions as were applied during this test.

Table 6. N100 Fuel Property Data

	ULSD	**N100**	**Percent Change**
EGR rate	0.26	0.27	2.5%
NO_x (ppm)	251.83	215.83	-14.3%
CO (ppm)	67.44	58.96	-12.6%
THC (ppm)	8.79	9.85	12.1%
Throttle (%)	27.63	28.70	3.9%

Fuel Analysis Test Results

Fuel Properties

Fuel properties covering the D975 specification for diesel fuels along with several other properties were determined for the N100 sample; the results of these tests are listed in Table 7. The Neste renewable diesel fuel met the requirements for No. 2 diesel in ASTM D975. The fuel also shows excellent thermal and oxidative stability, and is essentially 100% renewable carbon. The mass-basis net heating value was measured at 3.8% higher than that of the ULSD; however the volume-basis heating value was measured at 3.3% lower due to the relatively low density of the fuel. In addition to ASTM specification properties the fuel was tested for anticorrosion properties by NACE TM0172. This test is a pipelining requirement with a minimum rating of B+. The Neste renewable diesel was found to have a NACE rating of E, the lowest rating, and would therefore require an anticorrosion additive to meet pipelining specifications.

Elemental analysis was conducted by inductively coupled plasma atomic emission spectrometry following ASTM method D5185. The results of this analysis are listed in Table 8. None of the elements included in this analysis were detected above the limit of detection for the method.

Distillation curves of the N100, N5, and N20 samples were determined by ASTM D86. A comparison of N100 to the certification ULSD is shown in Figure 7. A comparison of the N5 and N20 to ULSD is shown in Figure 8. The distillation curve of the N100 shows lower initial and final boiling points than ULSD with a higher boiling point for approximately T10 through T70. The T90 of the N5 was unchanged from the ULSD; both were 300 °C. The T90 of the N20 was decreased by 2 °C compared to the ULSD.

Table 7. N100 Fuel Property Data

Property	ASTM Test Method	Units	N100	ULSD[§]	ASTM D975 Limit[*]
Derived Cetane Number	D6890	--	74	--	40 min
Cetane Number	D613	--	--	42.5	40 min
Copper Strip Corrosion	D130	--	1A	--	3 max
Aromatics	D1319	%	<0.1	33	35 max
Olefins	D1319	%	0.6	1.6	--
Saturates	D1319	%	99.4	65.4	--
Cloud Point	D2500	°C	-27	-24	Report
Cloud Point	D5773	°C	-24.8	--	Report
LTFT	D4539	°C	-24	--	--
CFPP	D6371	°C	-25	--	--
Sulfur	D5453	ppm	1.1	8	15 max
Water and Sediment	D2709	vol%	0.01	--	0.05 max
Water	D6304	ppm	15	--	--
Water Saturation	D6304	ppm	50	--	--
Kinematic Viscosity	D445 (40°C)	cSt	2.5	2.4	1.9 – 4.1
Ash	D482	wt%	<0.001	--	0.01 max
Carbon Residue	D524_10%	wt%	0.04	0.07	0.35 max
Lubricity: Wear Scar Diameter	D6079	µm	425	612	520 max
Distillation (T-90)	D86	°C	287	300	282 - 338
Flash Point	D93	°C	65	76	52 min
Conductivity	D4308	pS/m	113	106	25 min
Heating Value (Net)	D240	btu/lb	19,108	18,413	--
Heating Value (Net)	D240	btu/gallon	123,604	127,840	--
Density	D4052 (15°C)	g/mL	0.7751	0.8508	--
Carbon	D5291	%	84.6	87.01	--
Hydrogen	D5291	%	15.19	12.99	--
Oxygen	FNAA	%	<0.01	--	--
Biobased Carbon Content	D6866	%	100	--	--
Accelerated Stability	D2274	mg/100mL	0.2	--	--
Thermal Stability	D6468 (180 minutes)	% Reflectance	100	--	--
NACE Corrosion	TM0172	--	E	--	--
Acid Value	D664	mg KOH/g	0.02	--	--
FAME Content	D7371	%	<0.5	--	5 max

[*]Limits for No. 2 S15 diesel fuel
[§]Properties of the ULSD were supplied by the fuel producer

Table 8. N100 Elemental Analysis Data

Element	Result (ppm)	Element	Result (ppm)	Element	Result (ppm)
Al	<1	Mn	<1	Sr	<1
Sb	<1	Mo	<1	V	<1
Ba	<1	Ni	<1	Ti	<1
B	<1	P	<1	Cd	<1
Ca	<1	Si	<1	S	<25
Cr	<1	Ag	<1	As	<5
Cu	<1	Na	<5	Be	<5
Fe	<1	Sn	<1	Bi	<5
Pb	<1	Zn	<1	Co	<5
Mg	<1	K	<5	W	<5

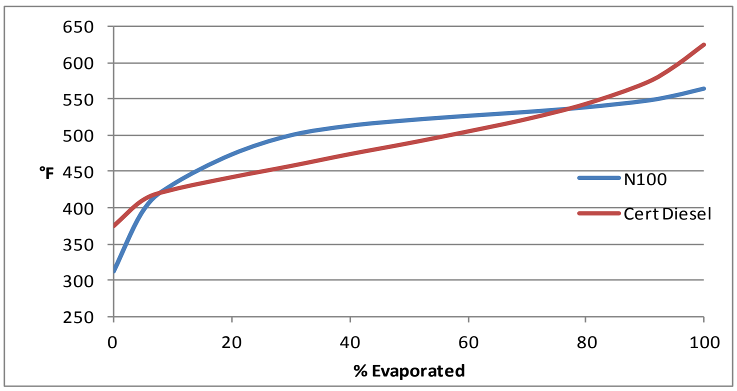


Figure 7. Distillation Curves of N100 and Cert Diesel

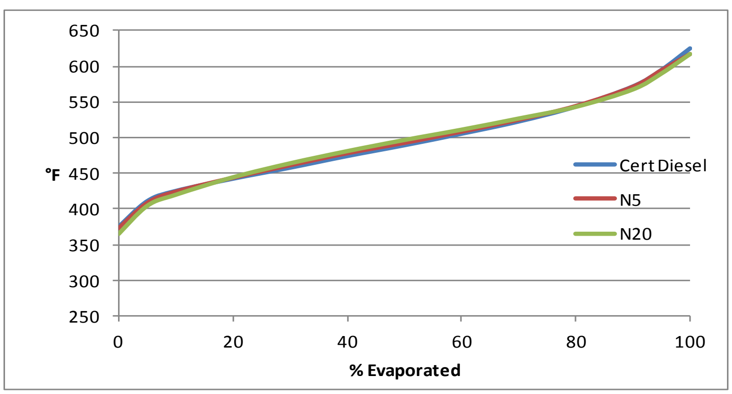


Figure 8. Distillation Curves of N5, N20 and Cert Diesel

GC-MS

The N100 was analyzed by Gas Chromatography-Mass Spectrometry (GC-MS) in order to determine its chemical composition. The sample was diluted 1:5 in methylene chloride and analyzed using an Agilent 7890GC equipped with an Agilent 5975C Mass-Selective Detector (MSD). The column used for analysis was a Supleco Equity-1, polydimethylsiloxane phase column with dimensions: 30 m x 0.25 mm and 0.25 µm internal coating. The MSD was operated in continuous scan mode from m/z 35-500. Peaks detected were tentatively identified by comparison to a NIST library of mass spectra using the NIST search program. A summary of the GC-MS results is shown graphically in Figure 9. Relative quantities of detected compounds are shown as percent of total chromatographic area.

Compounds detected were identified as hydrocarbons ranging from 8 to18 carbon atoms. Based on chromatogram area, not a quantitative calibration, the N100 is composed of approximately 87% isoparaffinic and 13% normal paraffinic hydrocarbons. The most abundant normal paraffin compounds were hexadecane (n-C16), heptadecane (n-C17), octadecane (n-C18), and pentadecane (n-C15). The most abundant isoparaffins were methylpentadecane (i-C16), methylhexadecane (i-C17), methylheptadecane (i-C18) and methyltetradecane (i-C15), with multiple di and tri methyl isomers as well. Peaks totaling about 40% of the area could not be confidently identified as a specific isomer; however the carbon number could be estimated based on the mass spectrum and elution order, and this area is included in the isoparraffin totals. It is likely that the unidentified compounds are di and tri methyl, ethyl and propyl isoparaffins with mass spectra very similar to the normal paraffin.

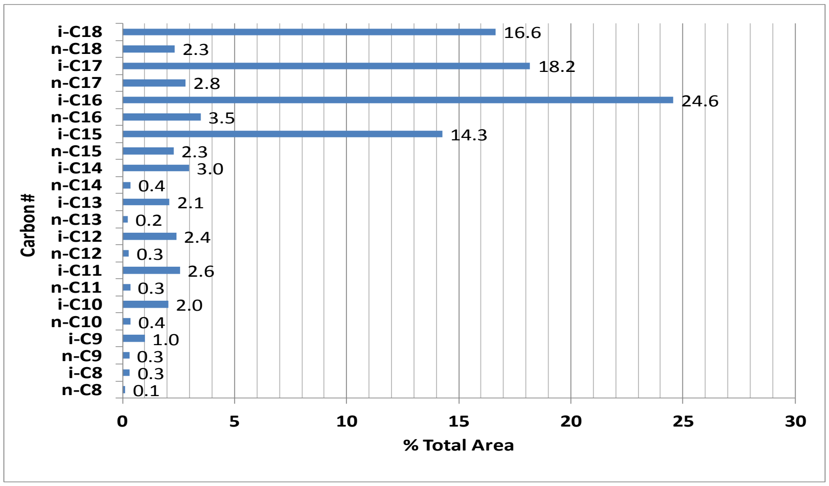


Figure 9. GC-MS Results for N100

<u>Rheology</u>

The N100 was analyzed for rheological properties at 25°C, 35°C, and 45°C. Viscosity is an important parameter when modeling fuel spray patterns for engine fuel injectors. Viscosity was measured with a TA Instruments AR 1500ex rheometer equipped with a vaned rotor. Samples were equilibrated at the proper temperature and then a continuous ramp shear rate from 0.1-500 1/s was applied over a period of 3 minutes with a delay time of 10 seconds between each measurement.

At low shear rates, the N100 demonstrated Newtonian behavior especially in the range of 100-200 1/s. As the shear rate was increased, the viscosity appeared to increase slightly.

This is most likely due to turbulence in the fuel rather than non-Newtonian behavior. Viscosity measurements were in the range of 2.04 x 10^{-3} to 2.80 x 10^{-3} at a shear rate of 200 1/s. The fuel showed a decrease in viscosity as the temperature was increased from 25°C to 35°C and then to 45°C as would be expected. Figure 10 shows the viscosity versus shear rate for the N100.

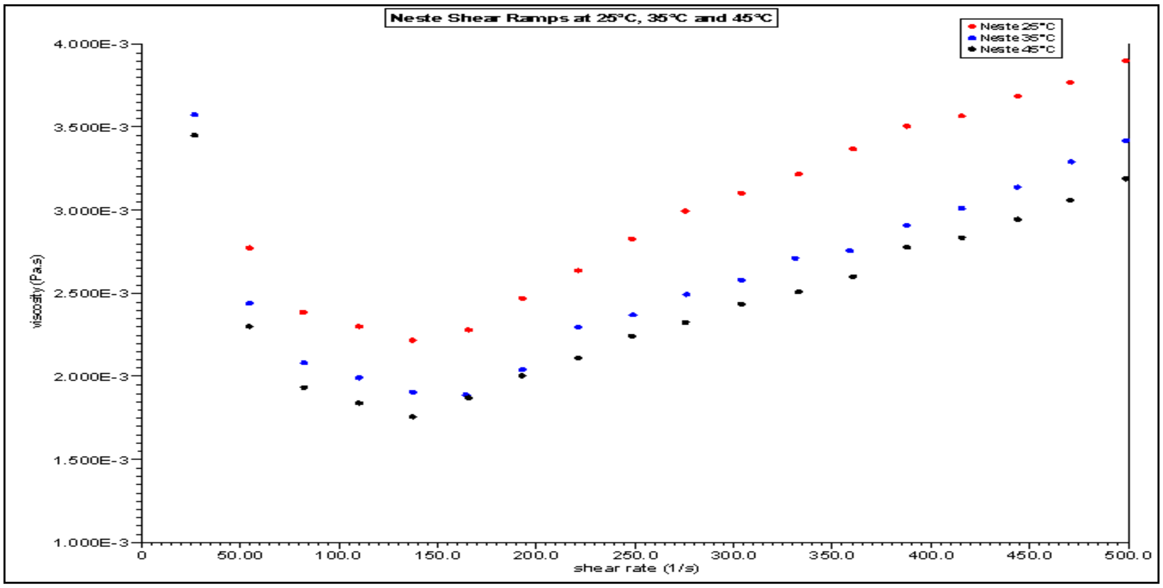


Figure 10. Viscosity versus Shear Rate for N100

Summary

Overall results show that the Neste renewable diesel was a high quality material which met or exceeded the minimum properties for ASTM D975 specification for diesel fuel oil in its neat form. ULSD blended with Neste showed decreased gravimetric fuel consumption due to the higher gravimetric heating value of N100. The mass-basis net heating value was measured at 3.8% higher than that of the ULSD, but the volume-basis heating value is 3.3% lower due to the low density of the fuel. Emission testing with a 2008 model year U.S. on-highway engine equipped with a DPF showed no effect of N5, N20, or N100 on tailpipe THC, CO, or PM. NO_x decreased by 2.6% with N5, 4.0% with N20, and 9.5% with N100. Engine out smoke number showed no significant change for N20 but was reduced by 34.2% with N100. Engine combustion studies showed a decrease in ignition delay compared to ULSD due to the higher cetane value of the N100. At steady state low-load conditions NO_x and CO emissions were decreased by 14.3% and 12.6% respectively. Percent throttle was increase by 3.9% due to the lower volumetric energy density which resulted in a 2.5% increase in EGR rate.