CRC Report No. E-117

Combustion and Engine-Out Emissions Characteristics of a Light Duty Vehicle Operating on a Hydrogenated Vegetable Oil Renewable Diesel

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Final Report

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Executive Summary

In recent years, government agencies around the world have implemented legislation to increase the use of renewable fuels in the transportation sector. In the U.S., the Energy Independence and Security Act of 2007 mandates the use of 36 billion gallons of biofuels in the transportation fuel market by 2022. Additionally, the European Union (EU) has implemented several government mandates, such as the EU Renewable Energy Directive (2009/28/EC), which requires at least 10% (on an energy basis) of each Member State's transport fuel use to come from renewable sources (including biofuels). In California, the low carbon fuel standard (LCFS) was implemented in 2011 to promote the reduction of greenhouse gas emissions by targeting a 10% reduction in the carbon intensity of transportation fuels by 2020.

Hydrogenated vegetable oil (HVO) is a promising biofuel that can be produced by means of a refinery-based process that converts animal fats and vegetable oils into paraffinic hydrocarbons. Most HVO is characterized by a high cetane number with virtually no sulfur or aromatic compounds. The advantages of HVO fuel, including the attractive fuel properties and environmental characteristics, as well as California government mandates, have led to its expanded use over the last several years in many California cities, including San Francisco, Oakland, San Diego, and Los Angeles, as well as other cities across the country. The purpose of this project is to investigate the engine-out emissions and combustion characteristics of HVO from a current technology diesel vehicle to better understand the emissions performance of HVO as a drop-in fuel.

Two fuels were used in this study, including an Ultra Low Sulfur Diesel (ULSD) and a neat HVO to evaluate one light-duty diesel truck equipped with common rail direct injection. The HVO fuel contained 98.5 vol % of HVO and 1.5 vol % petroleum; and is hereinafter, the fuel denoted as

HVO. Although the vehicle was equipped with a diesel particle filter (DPF) and selective catalytic reduction (SCR) aftertreatment systems, all emissions sampling occurred before the catalyst. The vehicle was tested at least twice on each fuel using the LA-92 drive cycle and at steady-state conditions at 30 miles per hour (mph) and 50 mph at different loads. The test vehicle was preconditioned using a procedure that included multiple fuel drain and fills (40% of the fuel tank volume) and an LA-4 drive cycle. Engine-out emissions measurements were made for total hydrocarbons (THC), oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM) mass, soot mass, solid particle number (SPN), and fuel economy. Combustion pressure measurements were made over the LA-92 drive cycle and the steady-state conditions using a dSpace data acquisition system. The engine noise was characterized through the combustion sound level. Combustion noise measurements were made during steady-state conditions at each load point.

Overall, the use of HVO fuel in a modern light-duty diesel vehicle led to reductions in the engine-out THC, CO, NOx, and particulate emissions over the LA-92 cycle compared to ULSD. The reductions in most engine-out emissions with HVO were either statistically significant and/or marginally significant. The reductions in engine-out gaseous and particulate emissions with HVO compared to ULSD were attributed to the lower volatility and absence of sulfur and aromatic compounds. More specifically, the reductions in particulate emissions for HVO relative to ULSD can be attributed to the absence of aromatic and polyaromatic hydrocarbon compounds, as well as sulfur species, which are known precursors of soot formation, in the HVO. In addition, the higher cetane number and lower distillation profile (particularly the back-end of distillation temperature) of HVO led to reduced particulate emissions. Volumetric fuel economy, calculated based on the carbon balance method, did not show statistically significant differences between the fuels. The similar fuel economy values for the two fuels under the present test conditions indicates that this modern diesel vehicle is not calibrated to account for the differences in fuel properties (i.e., cetane number, density) when operated with HVO fuels. Steady-state testing at 30 mph and 50 mph revealed reductions in engine-out THC emissions with HVO, but mixed results for CO emissions. The use of HVO showed higher NOx and soot mass emissions for the higher load points compared to USLD.

Results reported here are for the test conditions used in this project (i.e., test fuels, vehicle, and driving cycle). Other trends may be observed under different conditions.

List of Acronyms

CAD Crank Angle Degrees

CARB California Air Resources Board

CE-CERT College of Engineering-Center for Environmental Research and Technology

CLD Chemiluminescence Detector

CO Carbon Monoxide

CO_2 Carbon Dioxide

COV Coefficient of Variability

CRC Coordinating Research Council

CSL Combustion Sound Level

DOC Diesel Oxidation Catalyst

DPF Diesel Particulate Filter

EGR Exhaust Gas Recirculation

EFM Exhaust Flow Meter

EU European Union

FAME Fatty Acid Methyl Ester

FID Flame Ionization Detector

FTP-75 Federal Test Procedure

HVO Hydrotreated Vegetable Oil

IMEP Indicated Mean Effective Pressure

LCFS Low Carbon Fuel Standard

MFB Mass Fraction Burned

MSS Micro Soot Sensor

NDIR Non Dispersive Infrared

NO Nitric Oxide

NOx Nitrogen Oxides

PM Particulate Matter

SCR Selective Catalytic Reduction

SPN Solid Particle Number

THC Total Hydrocarbon

UC Unified Cycle

ULSD Ultra Low Sulfur Diesel

VERL Vehicle Emissions Research Laboratory

1. Introduction

As global demand continues to increase consumption of traditional petroleum-derived transportation fuels, biofuels have gained interest as a viable alternative to supplement existing petroleum supplies. In addition, low carbon fuel legislation efforts promoting biofuel use have expanded globally. For example, alternative fuels such as fatty acid methyl esters (FAME) and hydrogenated vegetable oils (HVO) are being considered as viable solutions for compression ignition (i.e., diesel) engine applications. FAME (commonly known as biodiesel) is the most widely used biofuel for diesel engines. It is produced from the transesterification of vegetable oils, animal fats, and waste cooking oils. The ester group of biodiesel provides superior lubricity compared to ultra-low sulfur petroleum diesel (ULSD), but is more susceptible to poor oxidative and storage stability (Hoekman et al., 2011).

Another way to process vegetable oil is to remove the oxygen from the structure and hydrogenate the double bonds in the triglyceride molecule. This is a popular pathway to produce HVO (also known as renewable diesel), which is a second-generation biofuel that could address the stability problems associated with conventional biodiesel described above. Similar to biodiesel, HVO is derived from vegetable oils, animal fats, waste cooking oils, and forest/biomass residues. A catalytic hydrogenation process converts triglycerides into alkanes by hydro-deoxygenation. Isomerization may also be incorporated in order to improve the low temperature operability or cold flow properties. HVO properties, including high cetane number, narrow distillation, high heating value on a mass basis, low aromatics, ultra-low sulfur content, and excellent oxidation stability, collectively contribute to lower emissions and better engine performance (Singh et al., 2018a; Erkkilä et al., 2011; Gomez et al., 2016; Rantanen et al., 2005).

For completeness, this section discusses studies of both engine-out and tailpipe emissions. However, it should be noted that fuel effects may be significantly different for engine-out compared to tailpipe emissions because of the effect of vehicle emission control devices. A number of studies have shown that the use of neat or blended HVO with diesel fuel can reduce gaseous and particulate emissions compared to regular diesel and biodiesel fuels (Singer et al., 2015; Bhardwaj et al., 2013; No, 2014; Lehto et al., 2011; Na et al., 2015). Pflaum et al. (2010) reported that HVO can reduce particulate matter (PM) emissions up to 50% compared to diesel fuel due to the absence of aromatics, when using a 2-liter, 4-cylinder diesel engine and a vehicle with the same engine over the New European Driving Cycle. They also found reductions in both total hydrocarbon (THC) and carbon monoxide (CO) emissions with HVO compared to diesel, but no significant variations in nitrogen oxide (NOx) emissions. Wu et al. (2017) tested HVO fuel and regular diesel using a Euro 5 direct injection diesel engine equipped with exhaust gas recirculation (EGR), an integrated diesel oxidation catalyst (DOC), and a diesel particle filter (DPF) aftertreatment system. They found significantly lower (50% or more) particle number (PN) emissions from HVO at a sampling location upstream of the exhaust aftertreatment system (engine out) due to no aromatics. They also showed lower THC and NO emissions with the HVO compared to diesel. The ignition delay of the HVO was shorter than the diesel fuel at lower engine speeds because of the high cetane number of HVO. Omari et al. (2017) showed that HVO as a drop-in fuel will likely result in an increased volumetric fuel consumption of about 2% due to the lower density of HVO. They also showed that NOx emissions were comparable to diesel, but CO, THC, and PM emissions were reduced by more than 50%. Bohl et al. (2018) showed no reductions in NOx emissions with HVO, but reductions in particle number emissions. They also showed lower

CO and THC emissions with HVO due to better fuel-air mixing, absence of aromatics, and low boiling range components of HVO compared to diesel fuel.

In the near future, the employment of low carbon fuels (i.e., alternative fuels that result in less carbon pollution compared to petroleum-based fuels), such as HVO, for Tier 3 type of vehicles is likely to grow. As diesel powertrain systems become more complex, expensive, and sensitive to fuel quality; however, it is important to understand how new fuels might impact their emissions and performance. The purpose of the CRC Project E-117 is to investigate the engine-out emissions of pure HVO and ultra-low sulfur diesel (ULSD) from a Tier 2 compliant diesel vehicle. This report presents the experimental finding of this program and its implications in terms of the broader literature.

One of the objectives of this program was to measure and characterize the combustion parameters, including combustion noise for each test fuel. For this task, CE-CERT employed the dSPACE MicroAutoBox system and glow plug sensors designed to measure combustion control parameters. The glow plug piezoresistive sensors were provided in-kind by CRC. Combustion parameter results from this program revealed the lack of high resolution for the in-cylinder pressure signals and relatively high amounts of noise in the signal. These effects ultimately influenced the calculation of the heat release rates and combustion noise. As a result, the combustion analysis and related discussion was omitted.

2. Experimental Procedures

2.1 Test Fuels

Two fuels were used in this study. An Ultra Low Sulfur Diesel (ULSD) was used as the baseline fuel that was supplied by Gage Products Company. In addition, a hydrogenated vegetable oil (HVO) or renewable diesel, blended with 1.5% volume of petroleum diesel – i.e., R98.5, was supplied by Neste US, Inc. The ULSD was selected to have properties typical of those found in most automotive diesel fuels across the country. HVO is generally paraffinic in nature and typically has a cetane number greater than 70. HVO generally contains very low concentrations of sulfur and aromatic compounds. However, HVO has poor lubricity and a low volumetric energy content (Hartikka et al., 2012). It is standard industry practice to correct poor fuel lubricity by the use of lubricity additives. A comparison of the test fuels is listed in Table 2-1. Figure 2-1 shows the distillation profiles for the ULSD and HVO.

Table 2-1: Properties of the Test Fuels

Properties	Method	ULSD	HVO
Cetane Index	ASTM D976	44.6	77.1
Cetane Index, Procedure A	ASTM D4737	44.5	95.0
Carbon Content (wt. %)	ASTM D5291	86.0	84.8
Hydrogen Content (wt. %)	ASTM D5291	13.2	14.9
Nitrogen Content (ppm)	ASTM D4629_5762	1.1	2.3
Sulfur (mg/kg)	ASTM D2622	6	< 3
Gross Heat of Combustion (MJ/kg)	ASTM D4809	47.20	48.45
Net Heat of Combustion (MJ/kg)	ASTM D4809	44.32	45.18
Cold Filter Plugging Point (CFPP)°C	ASTM D6371	-34	-22
Density @ 15°C (g/cm3)	ASTM D4052	0.8536	0.7794
API Gravity at 60 deg F	ASTM D4052	34.3	50
Corrected Flash Point °F	ASTM D93	147	151
Kinematic Viscosity @ 104ºF/ 40ºC (mm^2/s)	ASTM D445	2.8	3.006
Cloud Point°C	ASTM D2500	-29.2	-21
Monoaromatics by SFC (wt. %)	ASTM D5186	22.4	0
Polynuclear Aromatics by SFC (wt. %)	ASTM D5186	2.9	0
Total Aromatics by SFC (wt. %)	ASTM D5186	25.3	0
Initial Boiling Point (°C)	ASTM D86	174	131.6
5% Recovery (°C)	ASTM D86	202.9	254.8
10% Recovery (°C)	ASTM D86	215.5	265.6
20% Recovery (°C)	ASTM D86	231.4	273.7
30% Recovery (°C)	ASTM D86	243.8	277.3
40% Recovery (°C)	ASTM D86	255.9	280
50% Recovery (°C)	ASTM D86	266.2	282.2
60% Recovery (°C)	ASTM D86	276.9	284.3
70% Recovery (°C)	ASTM D86	288.4	286.7
80% Recovery (°C)	ASTM D86	301.6	289.6
90% Recovery (°C)	ASTM D86	320.4	293.7
95% Recovery (°C)	ASTM D86	337.4	298.3
Final Boiling Point (°C)	ASTM D86	345.2	308.6
Recovery %Volume	ASTM D86	97.7	97.7
Residual %Volume	ASTM D86	1.4	1.3
Loss %Volume	ASTM D86	0.9	1
IQT Derived Cetane Number	ASTM D6890	43.8	84.1

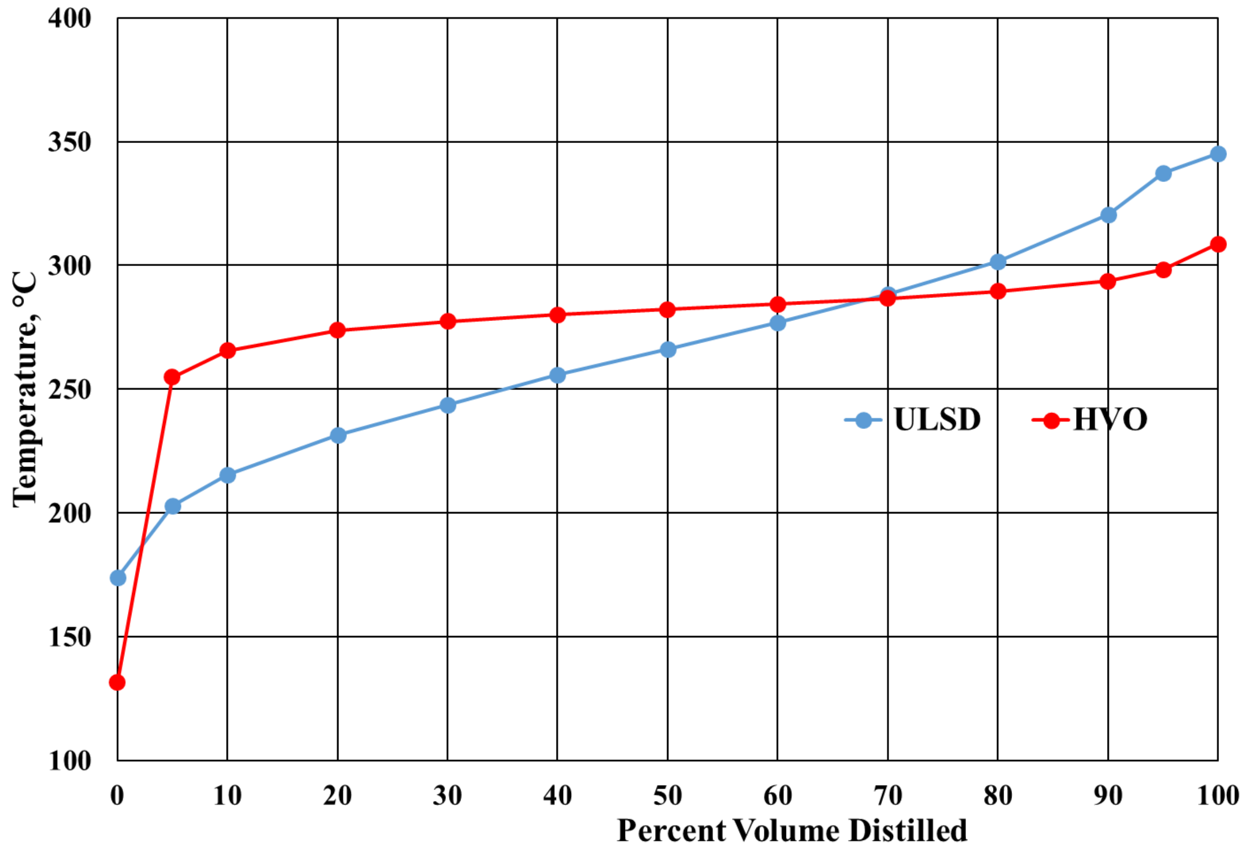


Figure 2-1: Distillation characteristics of the ULSD and HVO fuel using the ASTM D86 method

2.2 Test Vehicle

For this project, a 2012 model year Chevrolet Silverado 2500HD was chosen as the test vehicle. The 2012 Chevrolet Silverado 2500HD Duramax is a pickup truck that is widely available in the U.S. market. It is considered to be a light-duty diesel vehicle. Vehicle specifications are summarized in Table 2-2. The recommended fuel for this vehicle was ULSD that may contain up to 20 vol% biodiesel (B20) according to the owner's manual.

Prior to the start of testing, the engine lubricating oil and oil filter on the test vehicle were replaced at a local dealership according to manufacturer's recommendations. Specifically, fresh Mobil 1 SAE 5W-30 was used.

For the purpose of this project, the vehicle was tested using the original OEM engine calibration. The vehicle was not re-calibrated for testing with HVO.

Table 2-2: Technical specifications of the test vehicle

Engine	**6.6L Turbo-diesel V8**
Power	397 hp at 3,000 rpm
Fuel injection	Common-rail direct fuel injection
Torque	765 lb-ft at 1,600 rpm
Compression ratio	16.8:1
Aftertreatment	DOC/DPF/SCR
Miles at start of testing	53,866
Emissions Standards	Tier 2 Bin5/LEVII

2.3 Test Sequence and Fuel Conditioning

The vehicle was tested using each fuel at least twice over the LA-92 emissions test cycle. The LA-92 test cycle is shown in Figure 2-2. The LA-92 test cycle or the California Unified Cycle (UC) is a dynamometer driving schedule for light-duty vehicles developed by the California Air Resources Board (CARB). The LA-92 test has a similar three-bag structure, but is a more aggressive driving cycle than the Federal Test Procedure (FTP-75) cycle, which is used for certification of passenger cars and light-duty trucks in the U.S. The LA-92 test is characterized by higher speeds, higher accelerations, fewer stops per mile, and less idle time. As shown in Figure 2-2, the LA-92 cycle has three phases; namely, the cold-start phase or Bag 1, the hot-running/transient phase or Bag 2, and the hot-start phase or Bag 3.

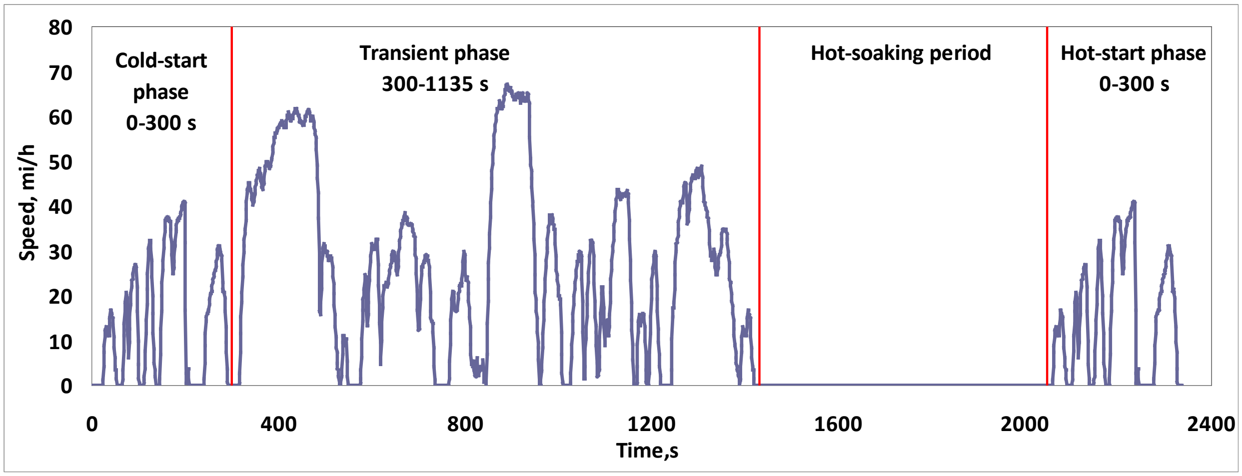


Figure 2-2: LA-92 Driving Cycle

After completing the initial duplicate LA-92 tests on each fuel, the data were evaluated to determine whether additional testing was required. A third test was performed if differences in LA-92 regulated emissions exceeded a predefined limit. This limit was defined using the same criteria as used in previous CRC projects, such as the E-60, E-67, E-83, AVFL-17b, and other older programs (Durbin et al., 2004; Painter and Rutherford 1992). Specifically, a third test was performed if the difference between the LA-92 regulated emissions measurements exceeded the following repeatability criteria: THC 30%, NO_x 50%, CO 50%, provided the absolute difference of the measurements was greater than 5 mg/mi. The emissions measurements for the third test also included particulate emissions measurements (soot mass, PM mass, and particle number).

Prior to testing, the vehicle was put through an oil conditioning procedure that included performing two US06 test cycles followed by an LA-4, followed by another US06 test cycle repeated twice on the ULSD fuel, as illustrated in Figure 2-3. The existing fuel was drained from the vehicle and the tank flushed with the test fuel. The tank was filled to 40% capacity with the test fuel. Vehicle preconditioning was performed as specified in Figure 2-3 and included driving on an LA-4 cycle and two additional drain and fills at 40%. During the prep procedure, side fan cooling was applied to the fuel tank. Following the last prep cycle, the vehicle was idled for two minutes, then shut down in preparation for the soak.

After the 12 hour soak, the first LA-92 test cycle was performed. For the LA-92 test cycle, all specified engine-out gaseous emissions were collected along with instantaneous particulate number emissions. The test matrix was designed for the ULSD fuel to be tested first followed by the HVO fuel. Duplicates were run back to back. If an additional test for each test condition/fuel combination was needed, then a third test was applied immediately following. The data were evaluated after each set of replicate tests to determine whether a third test was required.

After completing the LA-92 tests on each vehicle/fuel combination, each fuel was evaluated at steady-state conditions at 30 miles per hour (mph) and 50 mph, at loads of 0, 25%, 50%, 75%, and 100%. For each test condition/fuel combination, combustion characteristics were monitored and recorded over the LA-92 and steady-state testing. Combustion noise measurements were made during the steady-state testing only. These steps were repeated for each test fuel to verify the results of the testing after the fuel preconditioning was performed.

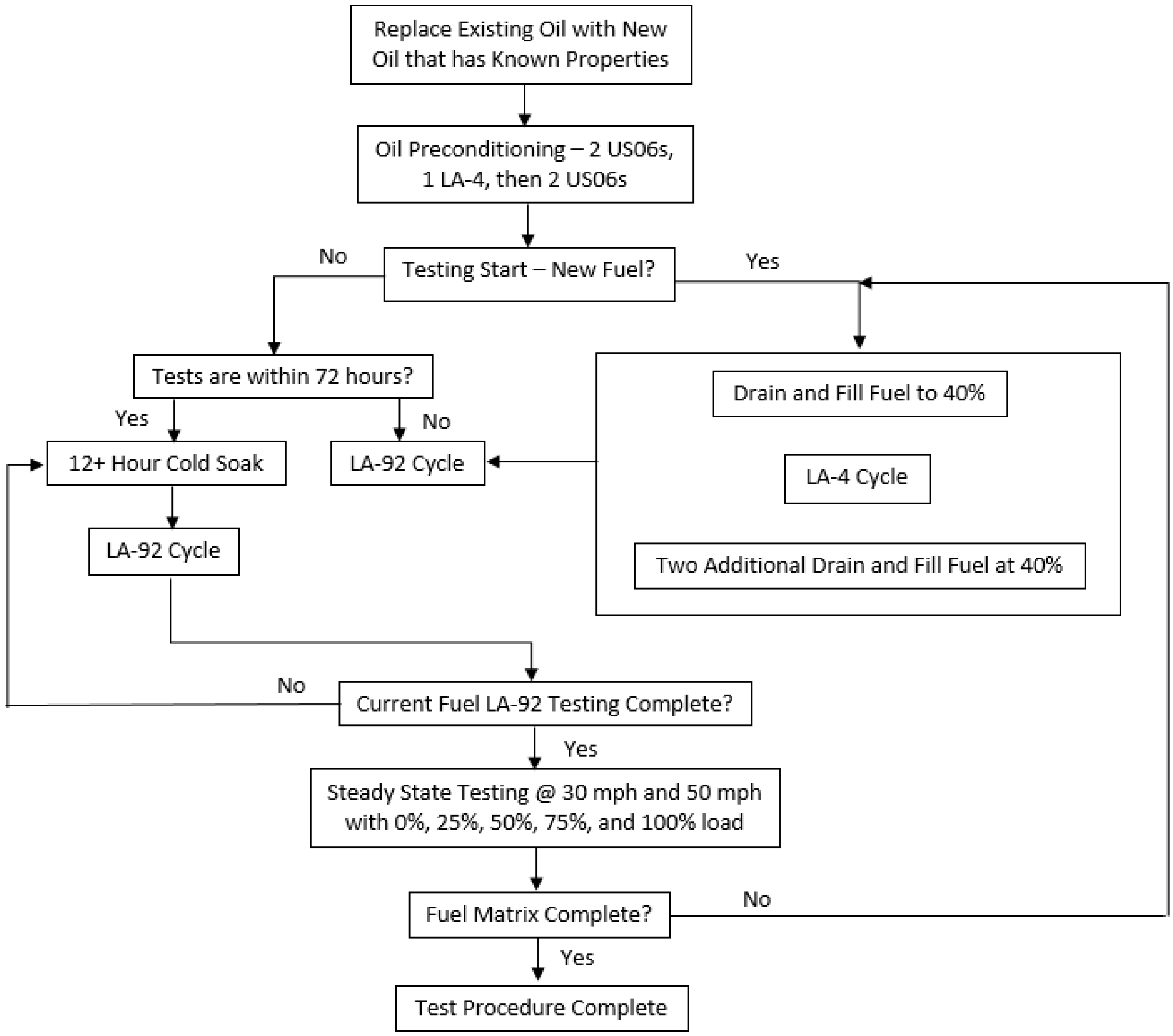


Figure 2-3: Test sequence for fuel change procedure and oil conditioning

2.4 Emissions Testing

Vehicle emissions measurements were conducted in CE-CERT's Vehicle Emissions Research Laboratory (VERL). The VERL utilizes a 48-inch Burke E. Porter single-roll electric chassis dynamometer, capable of testing vehicles weighing up to 12,000 lbs. Figure 2.4 shows a schematic of the experimental set up.

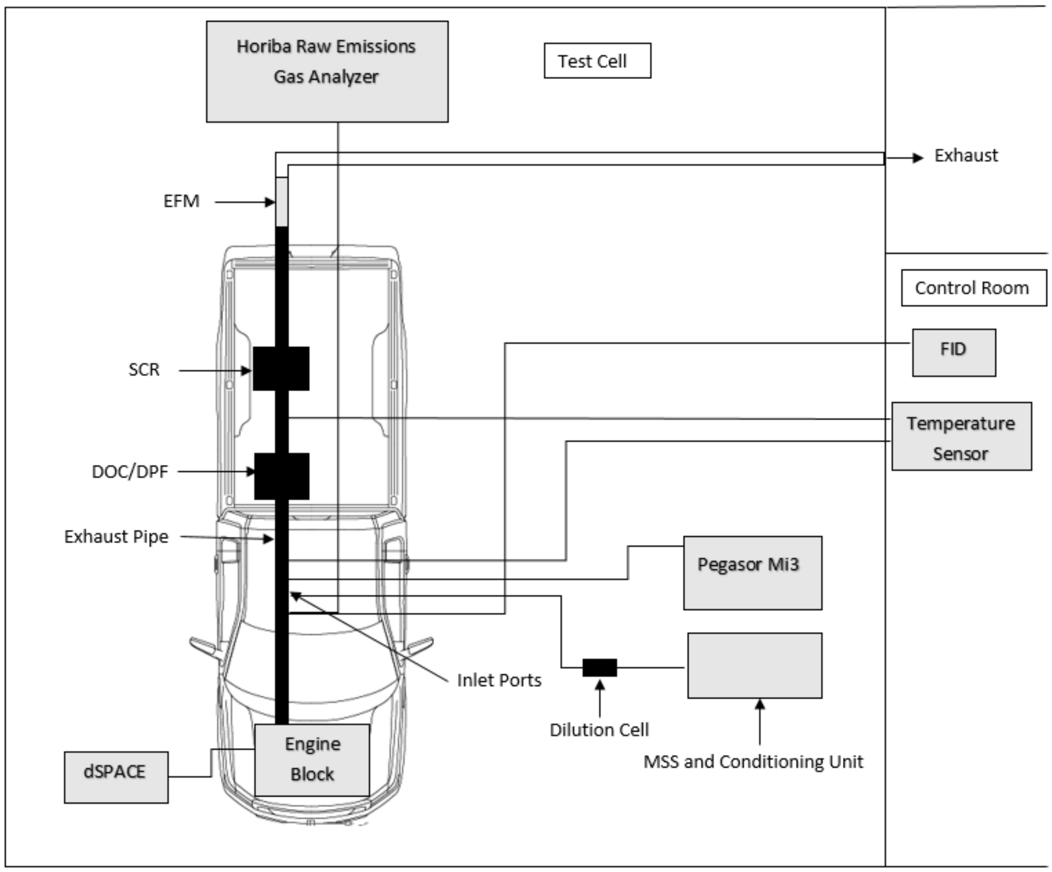


Figure 2-4: Experimental setup

For this project, emissions and fuel economy measurements were made only for the engine-out exhaust. The engine-out samples were collected inside the 4-inch exhaust pipe, prior to the catalyst and 16 inches downstream of a bend from the engine manifold. Since no modifications to the exhaust pipe were made, the length between the engine manifold bend and DOC is only 24 inches. This area was selected to be most representative of a well-mixed exhaust sample. Insulated ¼ diameter sample probes were inserted into stainless steel half coupling pipe threads with stainless steel Swagelok fittings used to secure the probes. The gaseous sample probe was designed with a single hole and the PM sample probe was designed with an upstream facing sample and was inserted into the exhaust flow stream in such a manner that it was away from all other probes and away from boundary conditions where surface wall effects could impact sample quality.

An AVL Micro Soot Sensor 483 (MSS) with an AVL Exhaust Conditioning unit were used to measure real-time soot mass emissions. The MSS is an instrument that measures soot mass concentration at a frequency of one Hertz (Hz). The MSS uses a photo acoustic detection technique where the light-absorbing PM components (such as soot particles) are exposed to laser light that is periodically modulated at the acoustical resonant frequency. The instrument is designed to measure soot concentrations down to approximately 5 $\mu g/m^3$, and operates at a flow rate of 2 L/min. The exhaust conditioning unit uses mass flow controllers to supply a constant dilution ratio to the MSS. Insulated ¼ inch stainless steel piping connected the sample probe to the dilution cell, which coupled the conditioning unit and MSS inlet.

A Pegasor Mi3 unit was used to measure PM mass and solid particle number (SPN) emissions. The Pegasor Mi3 utilizes electrical detection of particles using an ionization chamber to charge the particles, which are then measured with a sensitive electrometer. A heated sample line connected the exhaust inlet port directly to the inlet of the Pegasor Mi3 instrument.

For the gaseous emissions, including CO, CO_2 and NOx, a Horiba series 200 analyzer raw emissions unit was used. CO and CO_2 were measured using a non-dispersive infrared (NDIR) analyzer while a chemiluminescence (CLD) detector was used to measure NOx. A separate California Analytical Instruments Model 300-HFID HC analyzer was used to measure THC. A ¼ inch stainless steel tubing was used to connect the Horiba series 200 gas analyzer and flame ionization detector (FID) to the exhaust probes. A Sensors exhaust flow meter (EFM) was attached at the tailpipe and used to measure the mass flow rate of the exhaust gases. Two type K thermocouples were placed inside the exhaust pipe, one before the DOC/DPF and one after the aftertreatment system.

This program was conducted in two phases: Phase 1 included at least duplicate testing over the LA-92 cycle on both the ULSD and HVO fuels, followed by steady-state testing, while Phase 2 was a repeat of Phase 1 through the same procedure to verify the results of the testing. Testing between the two test phases spaced apart 8 days. The test vehicle remained on the chassis dynamometer room in a temperature controlled enviromment. No testing was conducted between the two test phases. Prior testing for Phase 2, the vehicle was prepped over LA-4 and US06 cycles.

3. Emissions Testing Results

This section presents and discusses figures for the engine-out gaseous and particulate emissions results over the LA-92 test cycle for the light-duty diesel vehicle tested on ULSD and HVO. The results for each test fuel represent the average of all test runs completed on that particular fuel. The weighted LA-92 cycle results were calculated using the same weighting factors utilized in determining the weighted FTP emissions using the cold-start transient, stabilized, and hot-start transient phases from the LA-92 cycle. For all figures, emission results represent the arithmetic average of the four tests on a given fuel. For the steady-state tests, values presented in figures represent the arithmetic average for two tests on a given fuel for each load point and speed conditions. The error bars represent one standard deviation on the average values for each test point. Statistical analyses were performed using a 2-tailed, 2-sample, equal-variance *t*-test. For the purpose of this discussion, results are considered to be statistically significant for p values ≤ 0.05 and marginally statistically significant for $0.05 \leq p < 0.1$.

This section also presents the emission results for the steady-state conditions at 30 mph and 50 mph. This program was conducted in two phases: Phase 1 included at least duplicate testing over the LA-92 cycle on both the ULSD and HVO fuels, followed by steady-state testing, while Phase 2 was a repeat of Phase 1 through the same procedure to verify the results of the testing. Emissions data from both phases of the program over the LA-92 cycle and the steady-state conditions at different loads are provided in Appendix A.

3.1 THC and CO Emissions

The cold-start, hot-running transient phase, hot-start, and weighted LA-92 THC and CO emissions results are presented in Figure 3-1 and Figure 3-2, respectively. Engine-out THC emissions were found in lower concentrations for the HVO compared to the ULSD. For the weighted engine-out THC emissions, HVO showed a reduction of 29.6% relative to ULSD. The use of HVO also showed a statistically significant reduction of 41.3% (p=0.048) in engine-out THC emissions for the cold-start segment of LA-92 relative to ULSD. For the engine-out CO emissions, the use of HVO resulted in statistically significant reductions on the order of 41.4% (p=0.002), 24.9% (p=0.004), and 28.3% (p=0.005), respectively, for the cold-start, hot-running, and weighted LA-92 compared to ULSD.

Our results are in line with previous projects that have shown reductions in THC and CO emissions with the use of either neat or blended HVO fuels compared to petroleum diesel (Napolitano et al., 2015; Kousoulidou et al., 2014; Aatola et al., 2008; Millo et al., 2013; Pellegrini et al., 2015). It has been reported that the very high cetane number and the absence of aromatic compounds in HVO are the main factors leading to reductions in CO and THC emissions (Napolitano et al., 2015; Pflaum et al., 2010). Aromatics are expected to affect CO and THC formation as they have a lower reactivity (leading to a longer ignition delay) as compared to paraffins. The shorter ignition delay of HVO originating from its molecular composition reduces the severity of overleaning during combustion. Differences in fuel cetane number may, in a similar way, also contribute to the observed differences in emissions.

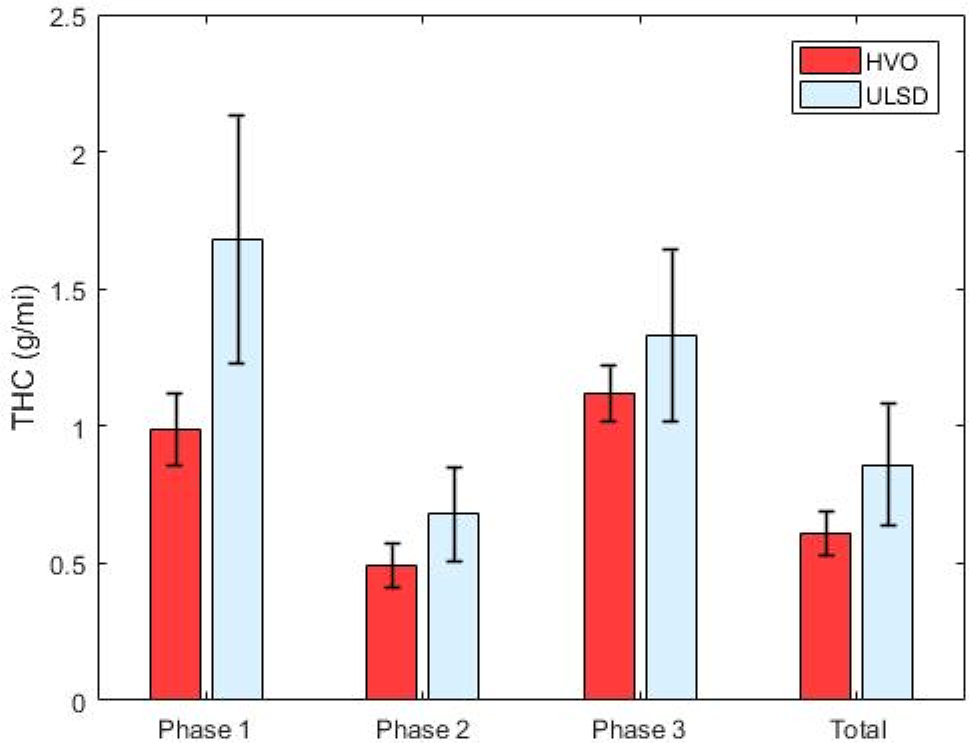


Figure 3-1: THC emissions over the LA-92

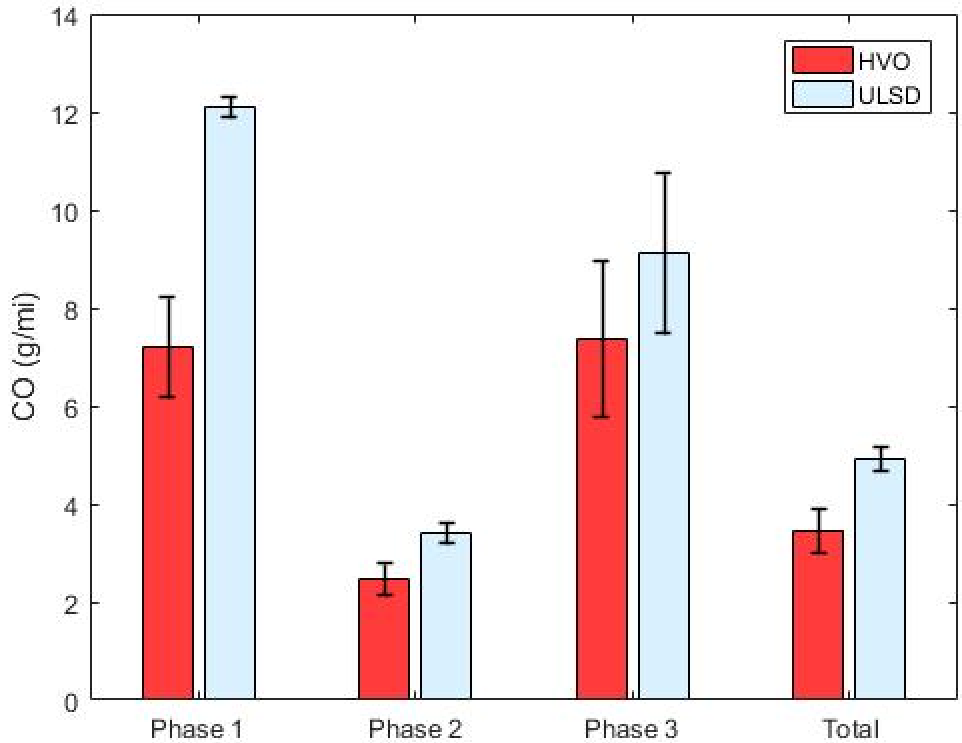


Figure 3-2: CO emissions over the LA-92

3.2 NOx Emissions

Nitrogen oxides (NOx) are one of the toughest pollutants to control in a diesel engine. They consist mostly of nitric oxide (NO) and nitrogen dioxide (NO_2), and play an important role in ground-level ozone formation. Formation of NOx in an internal combustion engine is strongly dependent on combustion temperatures (thermal NOx), residence times of the mixture at high temperatures, and local concentrations of oxygen. NOx may also be formed in the primary reaction zone of fuel rich flames when molecular nitrogen reacts with hydrocarbon radicals leading to formation of NOx (Sun et al., 2010).

NOx emissions are shown in Figure 3-3. The use of HVO showed statistically significant reductions in engine-out NOx of 14.8% ($p=0.028$) and 14.6% ($p=0.048$), respectively, for the hot-running and weighted LA-92 compared to ULSD. HVO contains straight chain and branched hydrocarbons in the range of C10-C22. In addition to paraffins, a typical petroleum-derived ULSD also contains cyclic molecules (aromatics and naphthenes) that may boil over a wider temperature range. Due to the increased volumetric energy density, ULSD is expected to have higher in-cylinder temperatures and pressures during combustion, leading to higher NOx formation. Previous studies have shown that HVO combustion can lead to lower NOx emissions due to the shorter ignition delay period characteristic of its higher cetane number (Happonen et al., 2012; Heikkila et al., 2012; Wu et al., 2017; Kuronen et al., 2007; Murtonen et al., 2009).

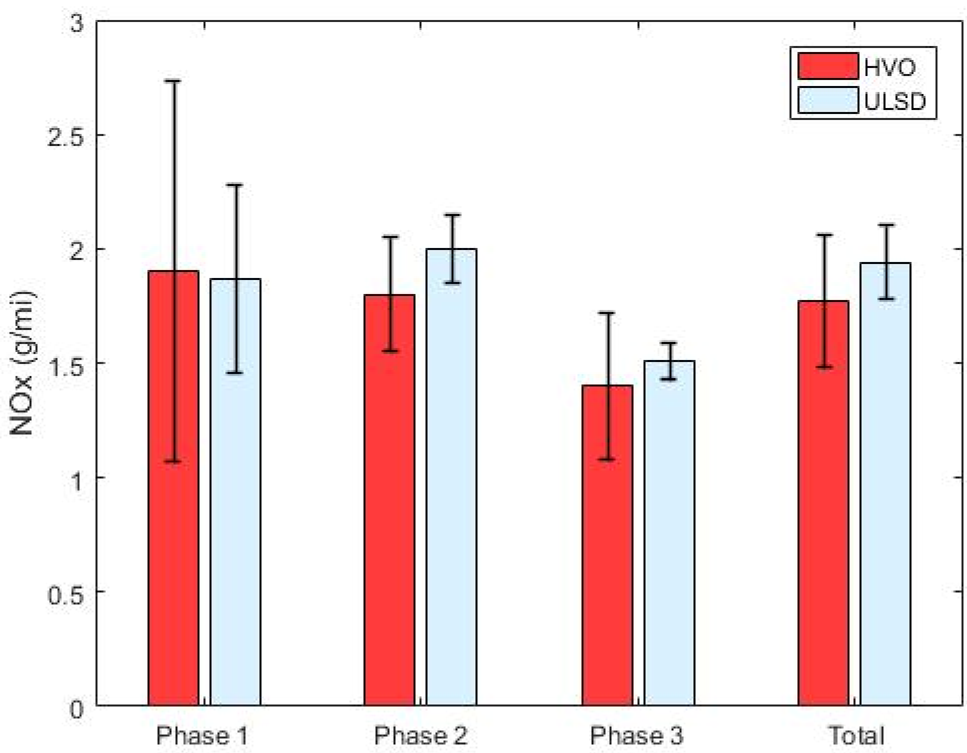


Figure 3-3: NOx emissions over the LA-92

3.3 CO_2 Emissions and Fuel Economy

Carbon dioxide emissions are shown in Figure 3.4. Engine-out CO_2 emissions did not show statistically significant fuel effects over either the weighted LA-92 cycle or its individual phases. Previous studies have shown that CO_2 emission levels decrease with HVO compared to the petroleum diesel due to a lower carbon content and lower C/H ratio of HVO (Singh et al., 2018b; Kuronen et al., 2007; Napolitano et al., 2015; Napolitano et al., 2018; Murtonen et al., 2009).

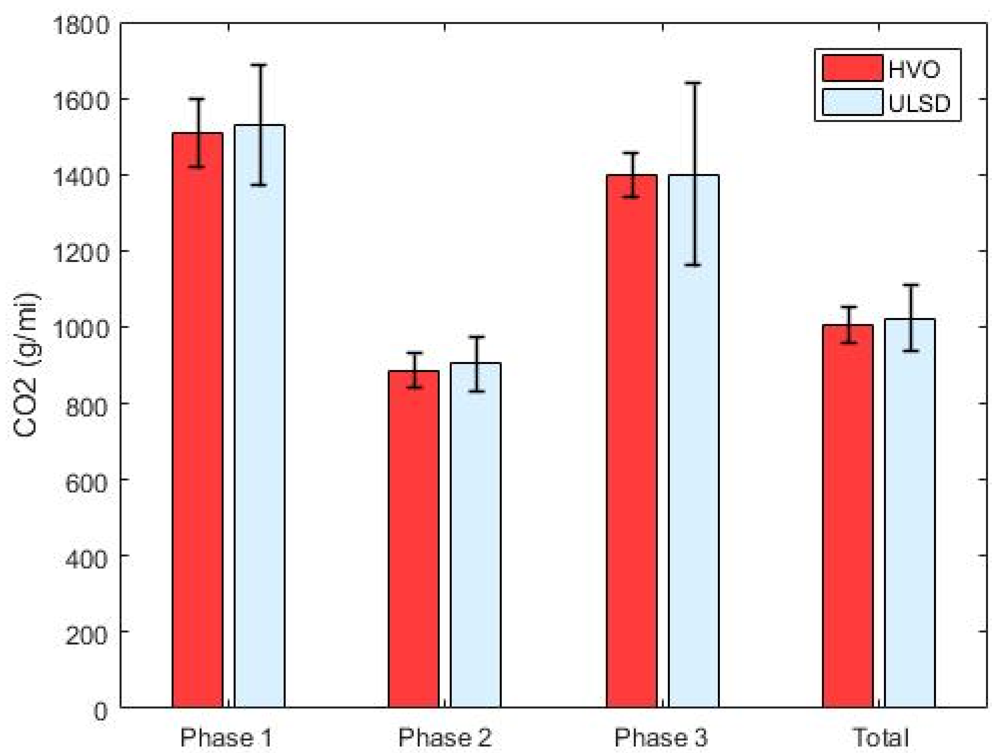


Figure 3-4: CO_2 emissions over the LA-92

Fuel economy results are shown in Figure 3-5. For this project, fuel economy was calculated based on the carbon balance method and the unique properties for each different test fuel, rather than the standard EPA equation. The carbon balance equation (shown below) more directly accounts for the differences in energy content between different fuels, which are normalized out in the standard EPA fuel economy equation.

$$Fuel\ Economy\ via\ Carbon\ Balance = \frac{CWF \times sp.gr \times 3781.8}{(CWF \times THC\left(\frac{g}{mile}\right)) + (0.429 \times CO\left(\frac{g}{mile}\right)) + (0.273 \times CO2\left(\frac{g}{mile}\right))}$$

Where:

3781.8: Density of water at 60 ˚F in g/gals

THC: THC emission rate (g/mile)

CO: CO emission rate (g/mile)

CO_2: CO_2 emission rate (g/mile)

CWF: Carbon weight fraction of the test fuel

sp.gr: Specific gravity of the test fuel (g/cm^3)

Although fuel economy trended lower for the HVO fuel, the differences in carbon balance fuel economy for the weighted LA-92 cycle and each individual phase were not statistically significant. Previous studies have reported lower volumetric fuel economy with HVO due to its lower density compared to petroleum diesel (Kuronen et al., 2007; Napolitano et al., 2018; Kousoulidou et al., 2014). The insignificant differences in fuel economy under the present test conditions may indicate that modern diesel vehicles are not calibrated to account for the differences in fuel properties (i.e., cetane number, density) when operated with HVO.

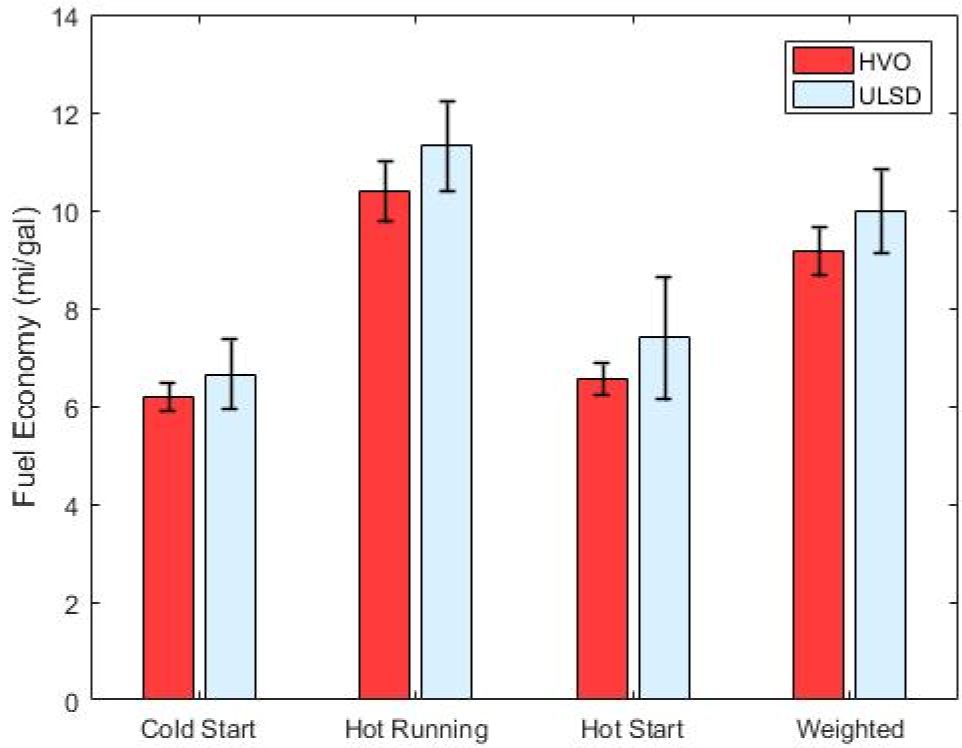


Figure 3-5: Carbon balance fuel economy over the LA-92

3.4 Particulate Emissions

Soot mass or black carbon emissions are shown in Figure 3-6. The ULSD resulted in a statistically significant difference in the weighted engine-out soot mass emissions compared to HVO. The reduction in weighted engine-out soot mass emissions for the HVO was 27.6% (marginally statistically significant p=0.057). No significant fuel effects were observed for soot mass emissions during the cold-start and hot-start phases, except for the hot-running phase where HVO led to lower soot mass emissions than ULSD. For the hot-running phase, HVO showed a statistically significant reduction in soot mass emissions of 30.7% (p=0.044).

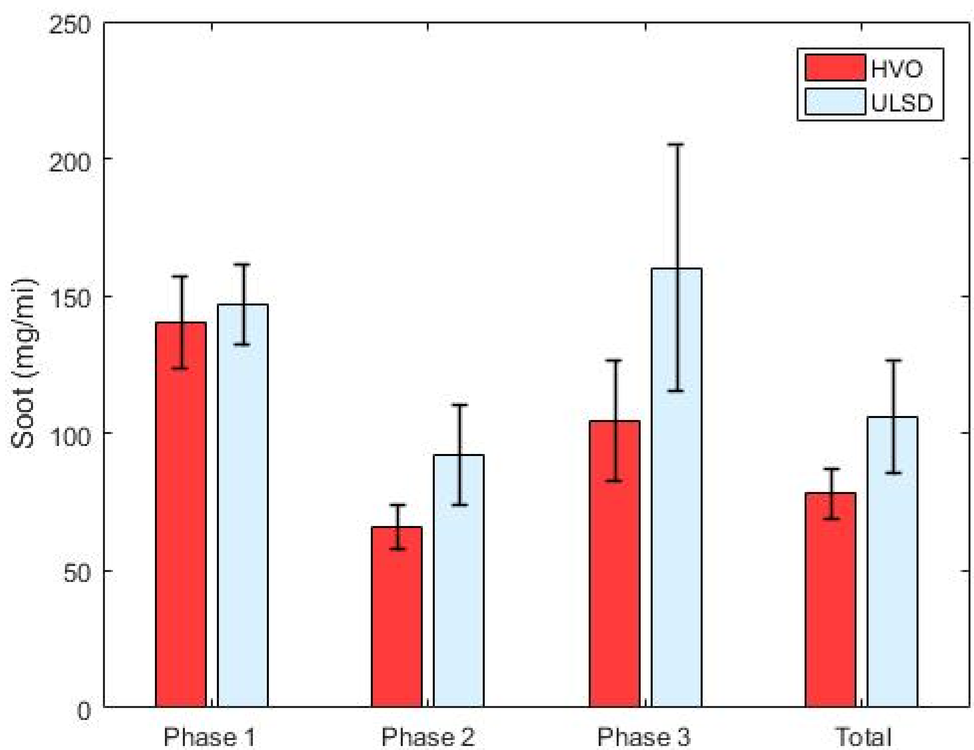


Figure 3-6: Soot mass emissions over the LA-92

Similar to the soot mass emissions, engine-out PM mass emissions showed large reductions with the HVO compared to the ULSD for the weighted LA-92, the cold-start, and hot-running phases

(Figure 3-7) that were statistically significant. The statistically significant reductions in PM mass emissions for the HVO were on the order of 31.5% (p=0.008), and 33.7% (p=0.004), respectively, for the weighted LA-92 and the hot-running phase. For the cold-start, the reduction in PM mass for HVO relative to ULSD was 30.1% (p=0.055) at a marginally statistically significant level.

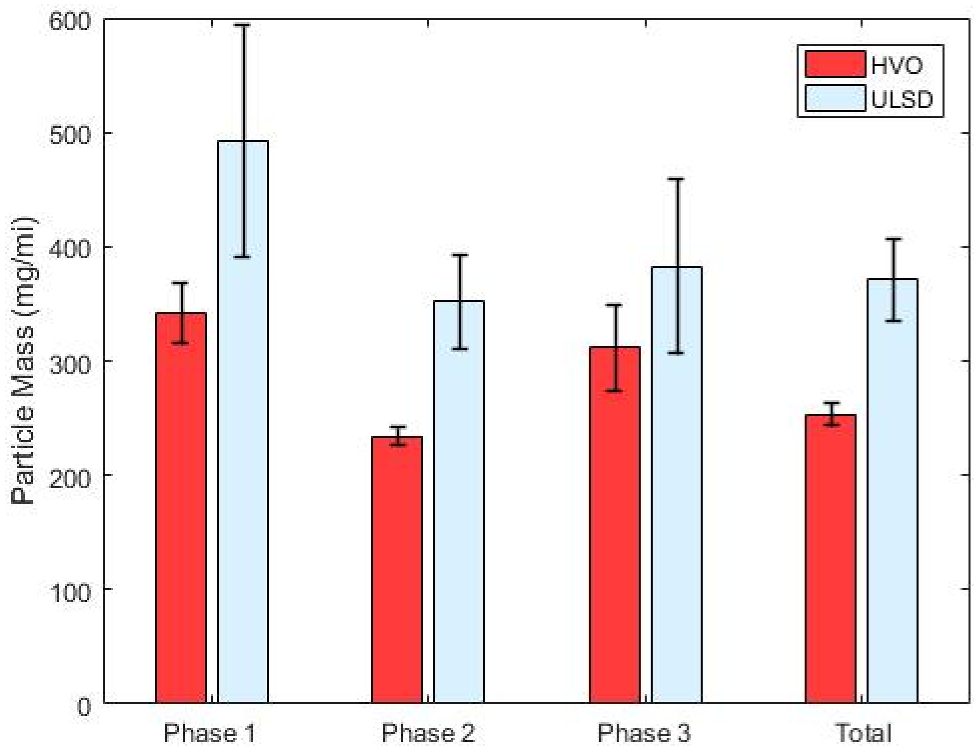


Figure 3-7: PM mass emissions over the LA-92

Engine-out solid particle number emissions followed the same pattern as PM mass emissions and showed statistically significant reductions for the HVO compared to ULSD. As shown in Figure 3-8, these reductions were 31.5% (p=0.005), 30.1% (p=0.055), and 33.7% (p=0.008), respectively, for the weighted LA-92, the cold-start, and hot-running phases. The reductions in solid particle number emissions were either statistically significant or marginally statistically significant.

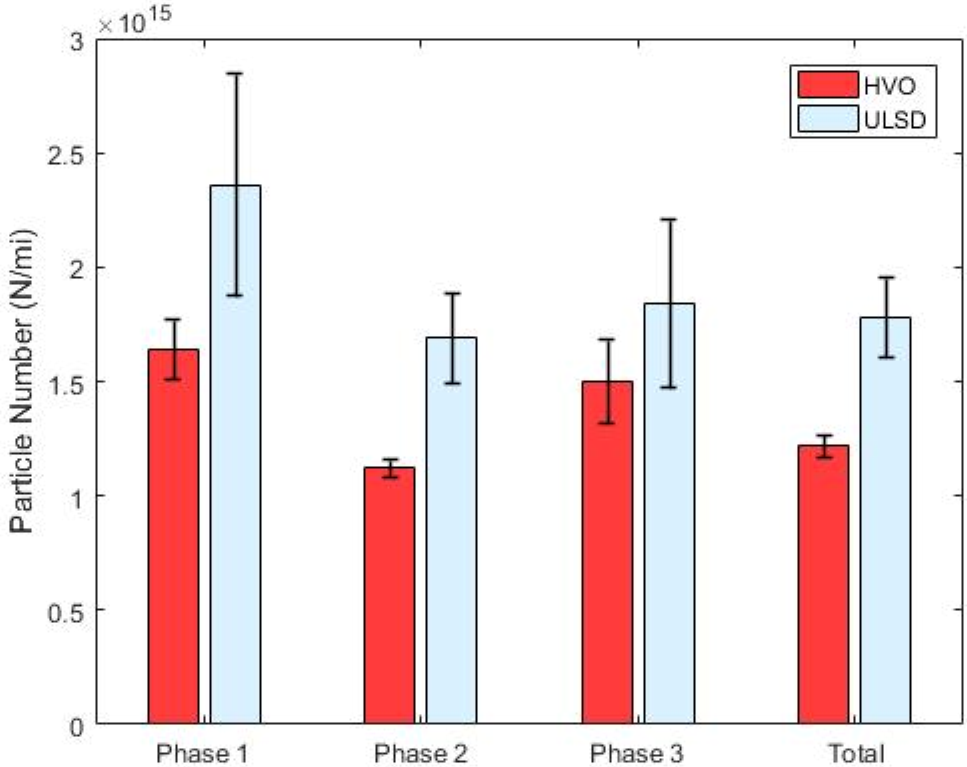


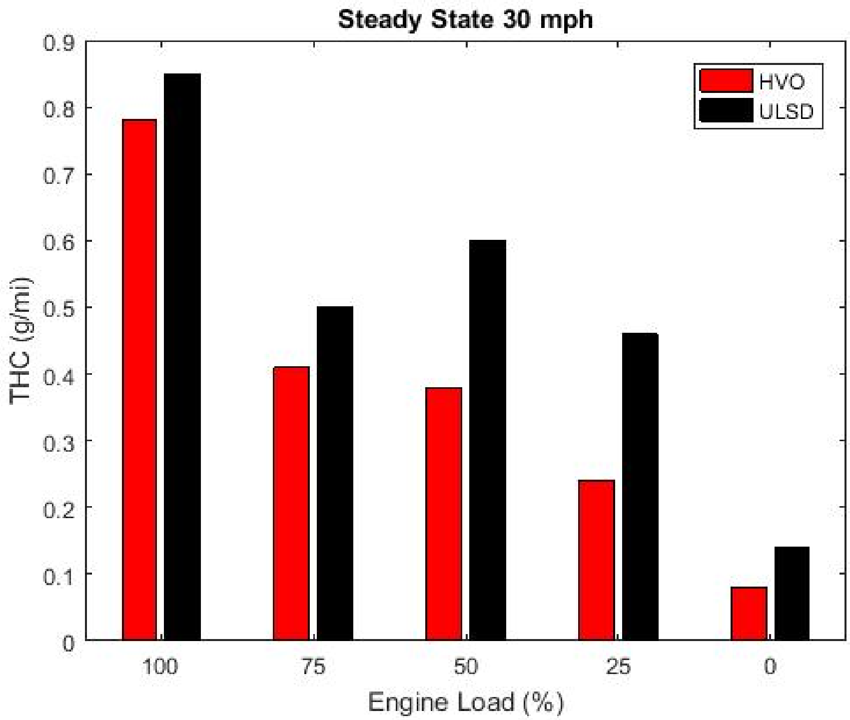
Figure 3-8: Particle number emissions over the LA-92

The results reported here agree with previous studies showing reductions in particulate emissions with HVO relative to petroleum diesel (Vo et al., 2017; Prokopowicz et al., 2015; Tan et al., 2013; Happonen et al., 2012; Singh et al., 2015; Singh et al., 2018b). Soot formation during combustion is a complex phenomenon and depends on many parameters such as fuel/air ratio, ignition delay, and fuel composition. The absence of aromatic and polyaromatic hydrocarbon molecules, as well as sulfur species in the HVO, which are considered as the main precursors of soot formation, were the main contributing factors leading to the reductions in particulate emissions relative to ULSD (Tan et al., 2013; Singh et al., 2015).

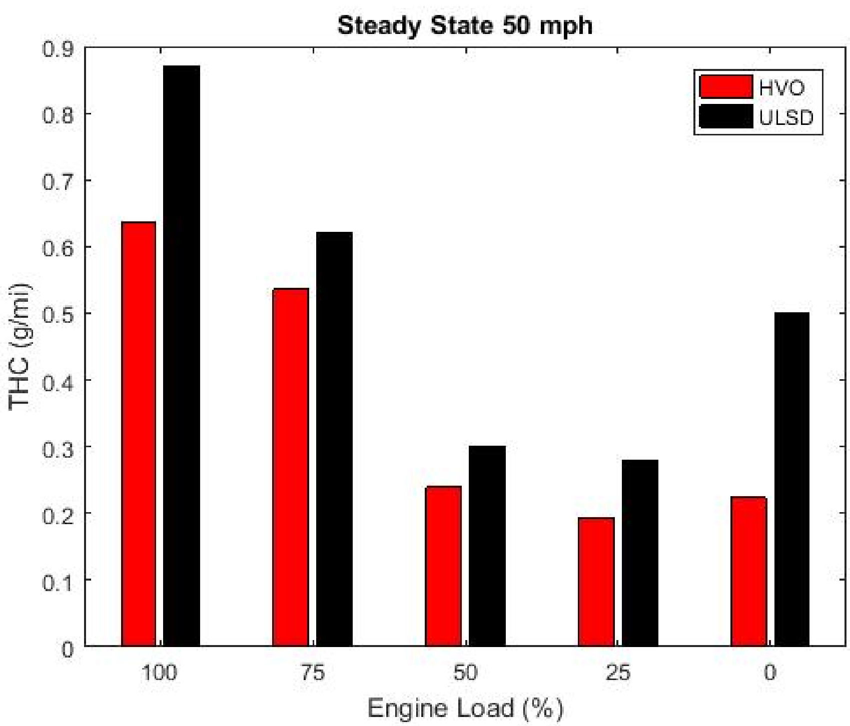
3.5 Steady-State Emissions Testing

Figure 3-9(a-b) and Figure 3-10(a-b) show the engine-out THC and CO emissions, respectively, at different engine loads over the steady-state 30 mph and 50 mph tests. For the engine-out THC emissions, the use of HVO led to reductions relative to ULSD for both steady-state conditions. As previously discussed, the absence of aromatics and the higher cetane number of HVO resulted in lower THC emissions. Also, due to fuel density differences, less HVO fuel is injected resulting in lower THC emissions.

For the engine-out CO emissions, the picture was different with both increases and decreases for HVO. At higher loads (75% and 100%) over 30 mph, the use of HVO resulted in engine-out CO emission increases relative to ULSD, but not at partial and lower load points. At 50 mph conditions, HVO showed higher engine-out CO emissions compared to ULSD only at the 75% load.

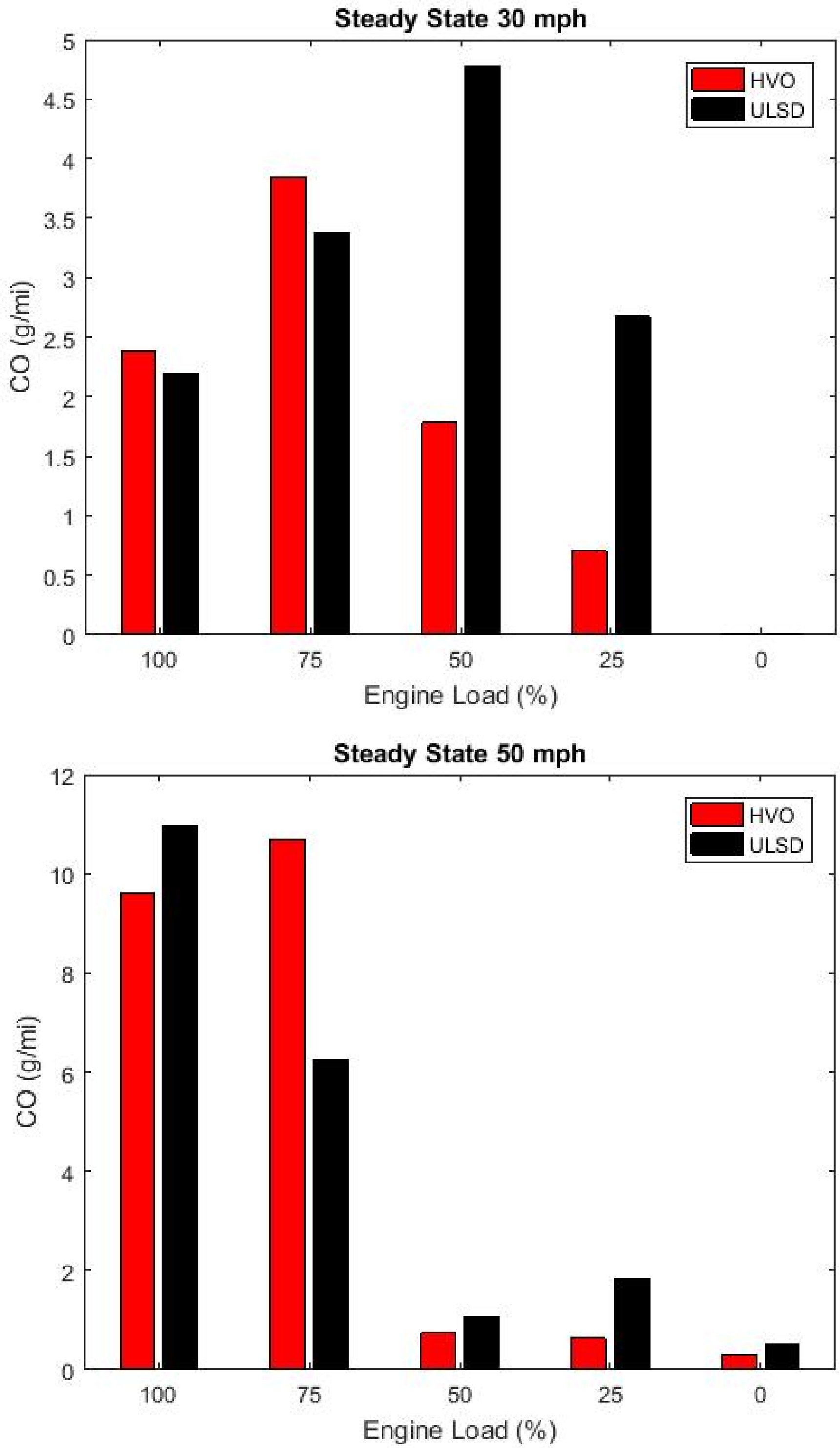


A



B

Figure 3-9 (a-b): THC emissions over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions

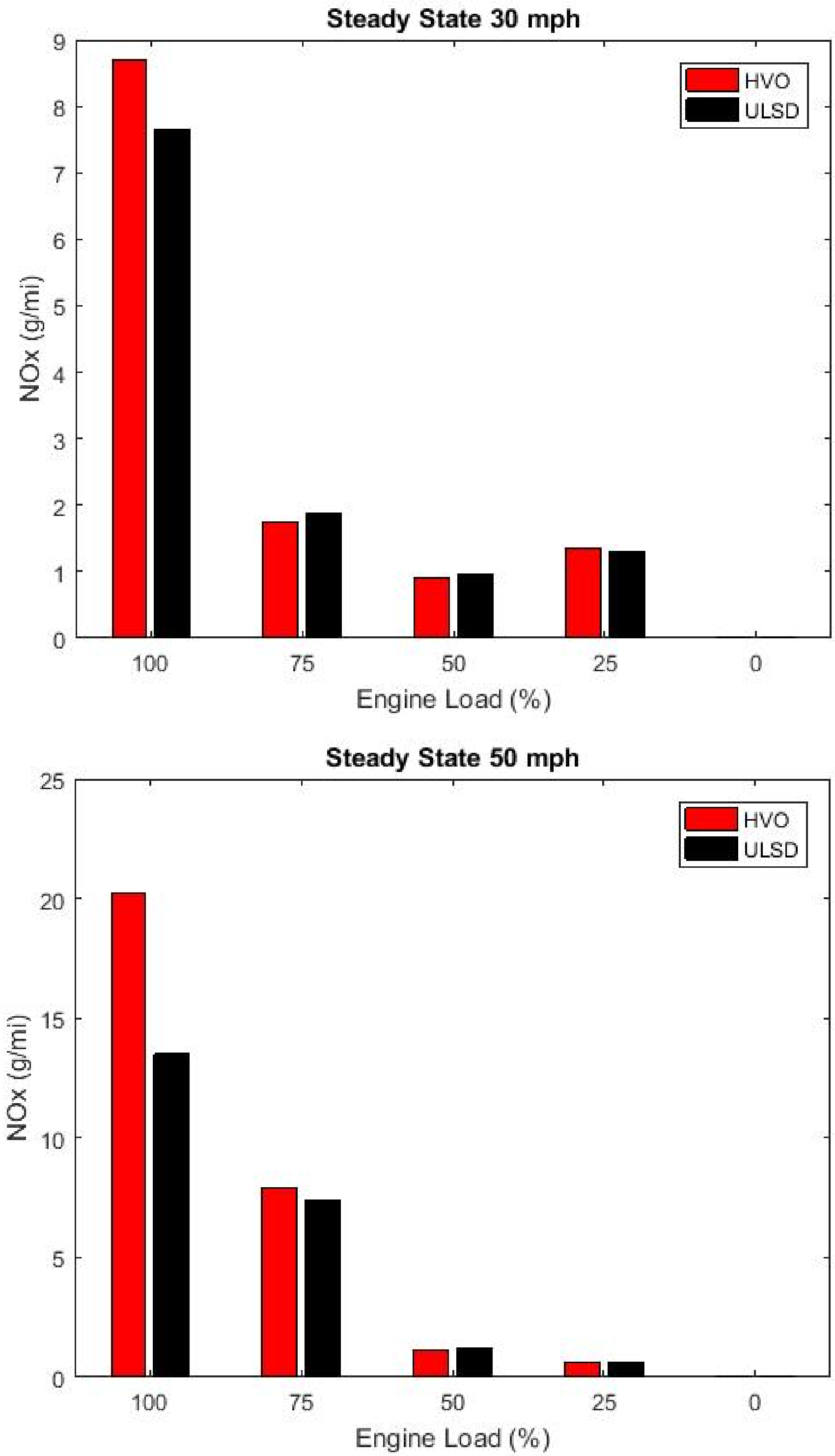


A

B

Figure 3-10 (a-b): CO emissions over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions

Figure 3-11(a-b) show the engine-out NOx emissions obtained during the steady-state conditions at 30 mph and 50 mph. Engine-out NOx emissions were generally comparable for both test fuels over the two steady-state conditions and the different engine loads, with the exception of the high load (100%) for both 30 mph and 50 mph, where an increase in engine-out NOx was measured for HVO compared to ULSD. Because the engine was not calibrated to account for a high cetane number fuel such as HVO, it is possible that at higher loads the use of HVO resulted in the injection of more fuel at sub-optimal timing. The higher amount of HVO burned along with its higher cetane number compared to ULSD, may increase the maximum temperature and in-cylinder pressure, which may result in higher NOx emissions at higher loads. Previous studies have also shown higher NOx emissions for HVO at higher engine loads (Bohl et al., 2018). Under the present test conditions, the use of HVO did not cause higher in-cylinder pressures for the higher loads over the 30 mph and 50 mph conditions (see Chapter 4).

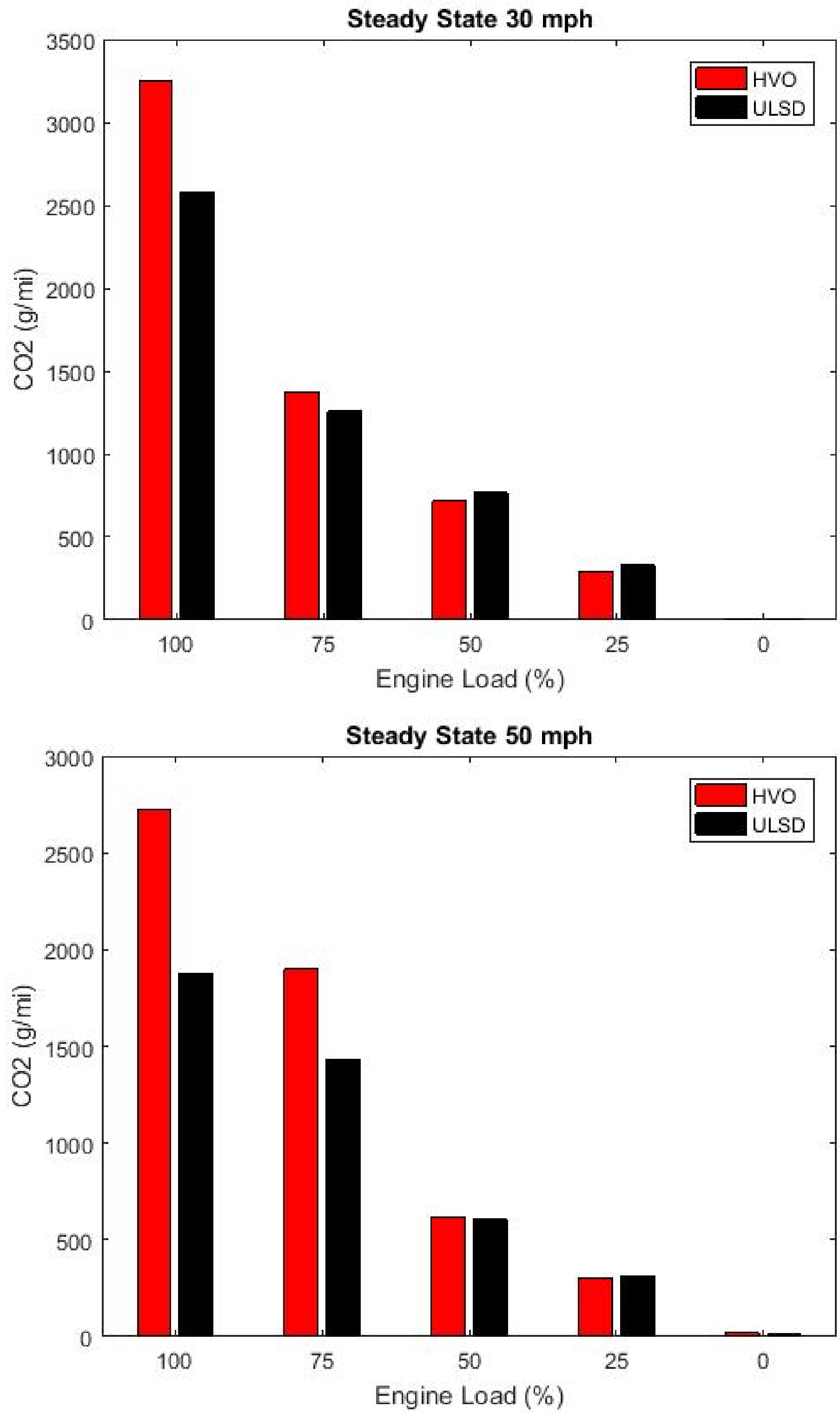


A

B

Figure 3-11 (a-b): NOx emissions over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions

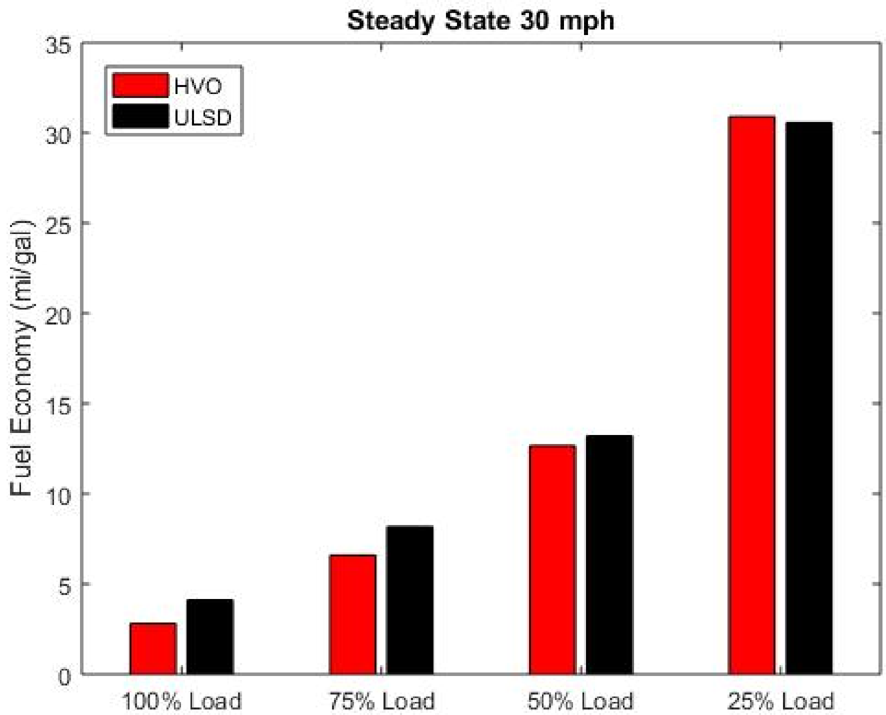
Figure 3-12(a-b) and Figure 3-13(a-b) show the engine-out CO_2 emissions and the carbon balance fuel economy, respectively, for the steady-state speeds of 30 mph and 50 mph over different engine loads. For the CO_2 emissions, at low and partial loads, the test fuels did not show any noticeable differences, however, at higher load test points (75% and 100%), a significant trend in increasing CO_2 emissions for HVO was detected at both the 30 mph and 50 mph conditions. Figure 3-12(a-b) also highlights that at higher load points, both fuels resulted in higher CO_2 values. This is expected and is mainly attributed to the lower fuel economy (higher fuel consumption) at these load points, as shown in Figure 3-.13(a-b). Although fuel economy did not show any statistically significant differences between the test fuels, it is worth noting that HVO led to lower fuel economy than ULSD for the higher load points (75% and 100%) at 30 mph and 50 mph.



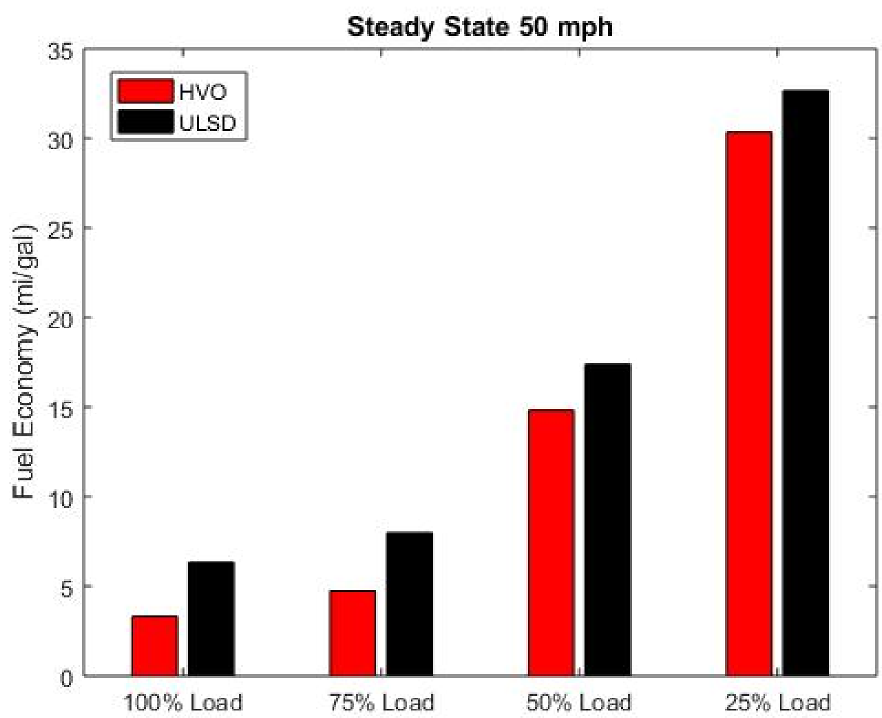
A

B

Figure 3-12 (a-b): CO_2 emissions over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions



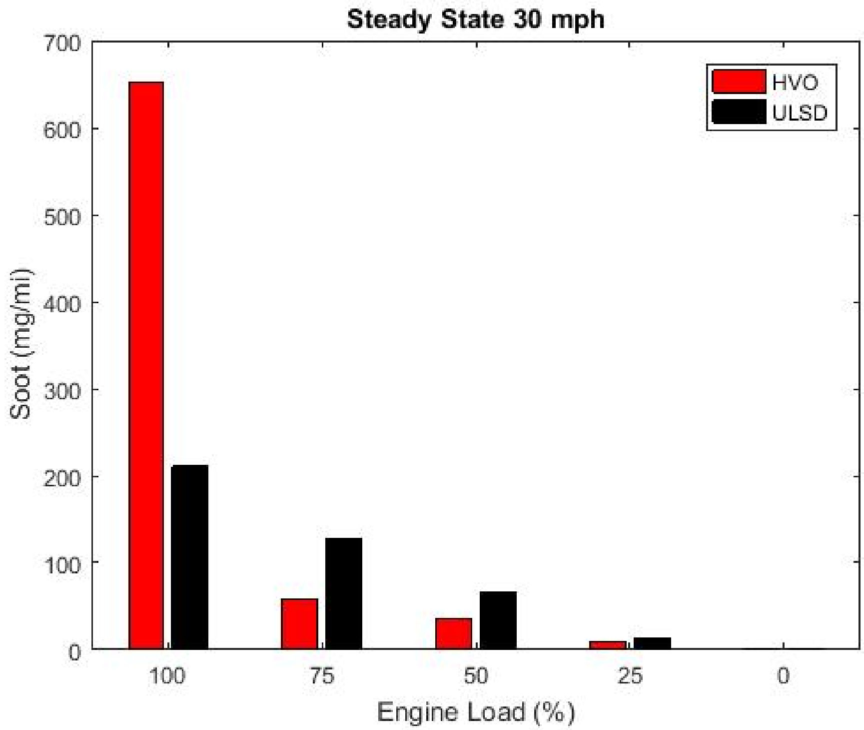
A



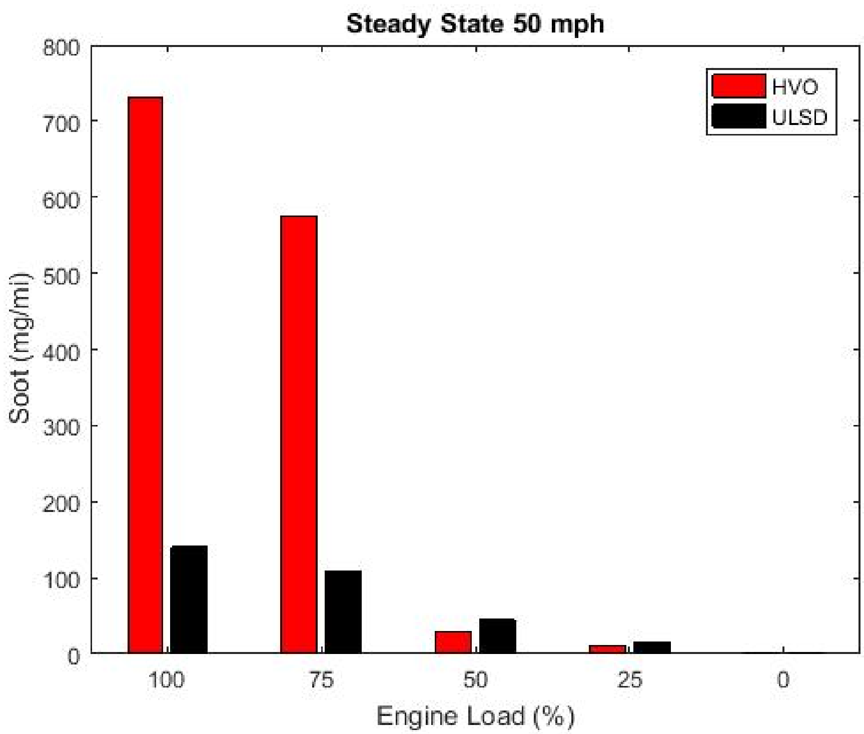
B

Figure 3-13 (a-b): Fuel economy over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions

Figure 3-14(a-b) shows the engine-out soot mass emissions for the different load points and steady-state speeds. It is evident that engine-out soot mass emissions increased for both fuels with increasing engine load. At higher engine loads, more fuel is injected into the combustion chamber, making the combustion directionally more fuel-rich and promoting the formation of soot emissions. The results reported here also show that soot mass emissions were lower for HVO than ULSD at lower and partial load points for the 50 mph conditions, but not at the higher loads (75% and 100%). At 30 mph conditions, HVO showed significantly higher soot mass emissions than ULSD only for the 100% load, but not for the other load points. Previous studies have also reported higher particulate emissions with HVO compared to petroleum diesel (Napolitano et al., 2015; Omari et al., 2017; Shukla et al., 2018). They attributed this phenomenon to the higher cetane number of HVO, which may result in more diffusive combustion; i.e., lower heat release rates (see Chapter 4) and higher soot formation, outweighing the benefits of the characteristic of the HVO being aromatic-free compared to diesel fuel.



A



B

Figure 3-14 (a-b): Soot mass emissions over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions

4. Summary

Currently, there is limited data about the impacts of HVO on engine-out emissions and combustion characteristics in modern light-duty diesel vehicles. The University of California, Riverside College of Engineering-Center for Environmental Research and Technology (CE-CERT) and the Coordinating Research Council (CRC) have undertaken a research project, aimed specifically at understanding the effects of HVO fueling on gaseous and particulate engine-out emissions from a modern technology light-duty diesel truck. The effort encompassed emissions testing on one light-duty diesel vehicle with two different fuels (HVO and ULSD) over the LA-92 cycle and steady-state conditions at 30 mph and 50 mph.

The experimental results suggest the following conclusions:

- Engine-out THC and CO emissions showed reductions with HVO over the LA-92 cycle at a statistically significant level. These reductions were attributed to fuel compositional differences, including the absence of aromatic compounds and the high cetane number of HVO.
- Engine-out hot-running and weighted NOx emissions were lower with HVO compared to ULSD, at a statistically significant level. The NOx reductions with HVO were attributed to the high cetane number of HVO, which resulted in a shorter ignition delay.
- CO_2 emissions and carbon balance fuel economy did not show any statistically significant differences between the test fuels. The insignificant differences in fuel economy suggest that modern light-duty diesel vehicles are not calibrated to account for the differences in fuel properties (i.e., cetane number, density) when operated with HVO.

- Engine-out PM mass, soot mass, and solid particle number emissions showed large, statistically significant reductions with HVO fuel compared to ULSD. The reductions in particulate emissions were due to the absence of soot precursors in the HVO; e.g., sulfur compounds and polyaromatic hydrocarbons.
- For steady-state conditions, THC emissions were lower with the use of HVO, while CO emissions showed mixed results. Engine-out NOx emissions did not show big differences between the fuels for the low and partial load points; but at 100% load, the use of HVO resulted in noticeable NOx increases compared to ULSD. Interestingly, engine-out soot mass emissions were also found to be higher with HVO for the high load points, but not for the low and partial load points. Because of the high cetane number of HVO, there was a greater tendency for diffusive combustion, which favors the growth of soot and mitigates the benefits of the aromatic-free characteristics of HVO compared to ULSD.
- In general, the chemical composition of HVO appeared relevant in respect to gaseous and particulate emissions over transient testing (LA-92 cycle), but not always for the steady-state testing. These phenomena can be explained by the fact that the engine was equipped with a common-rail system in which the physical properties of fuels had little influence on injection timing, and also the fluidity of HVO is close to diesel resulting in little differences in injection properties.

Overall, results from this project suggest that HVO can be adopted in modern technology direct injection diesel engines. The use of HVO enables appreciable reductions in engine-out NOx, THC, CO, and particulate emissions under many, but not all conditions. The potential of HVO may be further improved by optimizing the engine hardware and by implementing an HVO-specific calibration of engine operating parameters.

5. References

Aatola, H., Larmi, M., Sarjovaara, T., Mikkonen, S., “Hydrotreated vegetable oil (HVO) as a renewable diesel fuel: Trade-off between NOx, particulate emission, and fuel consumption of a heavy duty engine,” SAE Technical Paper 2008-01-2500, 2008.

Bhardwaj, O., Kolbeck, A.F., Kkoerfer, T., Honkanen, M., “Potential of hydrogenated vegetable oil (HVO) in future high efficiency combustion system,” SAE Int. J. Fuels Lubr. 6(1):2013, doi: 10.4271/2013-01-1677.

Bohl, T., Smallbone, A., Tian, G., Roskilly, A.P. Particulate number and NOx trade-off comparisons between HVO and mineral diesel in HD applications. Fuel 215, 90-101, 2018.

Durbin, T.D., Pisano J.T., Younglove T., Sauer C.G., Rhee S.H., Huai T., Miller J.W., Hochhauser A.M., et al., 2004. The Effect of Fuel Sulfur on NH_3 and Other Emissions from 2000-2001 Model Year Vehicles. Atmospheric Environment 38, 2699-2708.

Erkkilä, K., Nylund, N., Hulkkonen, T., Tilli, A. et al., "Emission performance of paraffinic HVO diesel fuel in heavy duty vehicles," SAE Technical Paper 2011-01-1966, 2011.

Gomez, A., Soriano, J.A., Armas, O. Evaluation of sooting tendency of different oxygenated and paraffinic fuels blended with diesel fuel. Fuel 184, 536-543, 2016.

Happonen, M., Heikkila, J., Murtonen, T., Lehto, K., Sarjovaara, T., et al., “Reductions in particulate and NOx emissions by diesel engine parameter adjustments with HVO fuel,” Environ. Sci. Technol. 46, 6198-6204, 2012.

Hartikka, T., Kuronen, M., Kiiski, U., 2012. Technical Performance of HVO (Hydrotreated Vegetable Oil) in diesel engines. SAE Technical Paper 2012-01-1585.

Heikkila J., Happonen M., Murtonen T., Lehto K., Sarjovaara T., Larmi M., Keskinen J., et al., 2012. Study of Miller timing on exhaust emissions of a hydrotreated vegetable oil (HVO)-fueled diesel engine. Journal of the Air & Waste Management Association 62, 1305-1312.

Hoekman S.K., Broch A., Robbins C., Ceniceros E., 2011. Investigation of Biodiesel Chemistry, Carbon Footprint and Regional Fuel Quality. CRC Project No. AVFL-17a, Final Report.

Kousoulidou, M., Dimaratos, A., Karvountzis-Kontakiotis, A., Samaras, Z., “Combustion and emissions of a common-rail diesel engine fueled with HWCO,” J. Energy Eng. 140, A4013001(9), 2014.

Kuronen, M., Mikkonen, S., Aakko, P., Murtonen, T., “Hydrotreated vegetable oil as fuel for heavy duty diesel engines,” SAE Technical Paper 2007-01-4031, 2007.

Lehto, K., Elonheimo, A., Hakkinen, K., Sarjovaara, T., Larmi, M., “Emission reduction using hydrotreated vegetable oil (HVO) with Miller timing and EGR in diesel combustion,” SAE Technical Paper 2011-01-1955, 2011.

Millo, F., Mallamo, F., Vlachos, T., Ciaravino, C., Postrioti, L., et al., “Experimental investigation of the effects on performance and emissions of an automotive Euro 5 diesel engine fueled with B30 from RME and HVO,” SAE Technical Paper 2013-01-1679, 2013.

Murtonen, T., Aakko-Saksa, P., Kuronen, M., Mikkonen S., Lehtoranta, K., “Emissions with heavy-duty diesel engines and vehicles using FAME, HVO, and GTL fuels with and without DOC+POC aftertreatment. SAE Technical Paper 2009-01-2693, 2009.

Na, K., Biswas, S., Robertson, W., Sahay, K., Okamoto, R., et al., “Impact of biodiesel and renewable diesel on emissions of regulated pollutants and greenhouse gases on a 2000 heavy duty diesel truck,” Atmospheric Environment 107, 307-314, 2015.

Napolitano, P., Beatrice, C., Guido, C., Del Giacomo, N., Pellegrini, L., et al., “Hydrocracked fossil oil and hydrotreated vegetable oil (HVO) effects on combustion and emissions performance of ‘torque-controlled’ diesel engines,” SAE Technical Paper 2015-01-2497, 2015.

Napolitano, P., Giodo, C., Beatrice, C., Pellegrini, L. Impact of hydrocracked diesel fuel and hydrotreated vegetable oil blends on the fuel consumption of automotive diesel engines. Fuel 222, 718-732, 2018.

No S.Y. Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines – A review. Fuel 115, 88-96, 2014.

Omari, A., Pischinger, S., Bhardwaj, O.P., Holderbaum, B., Nuottimaki, J., Honkanen, M. Improving engine efficiency and emission reduction potential of HVO by fuel-specific engine calibration in modern passenger car diesel applications. SAE Technical Paper 2017-01-2295, 2017.

Painter L., Rutherford J., 1992. Statistical Design and Analysis Methods for the Auto/Oil Air Quality Research Program. SAE Technical Paper 920319.

Pellegrini, L., Beatrice, C., Di Blasio, G., “Investigation of the effect of compression ratio on the combustion behavior and emission performance of HVO blended diesel fuels in a single-cylinder light-duty diesel engine,” SAE Technical Paper 2015-01-0898, 2015.

Pflaum H., Hofmann P., Geringer B., Weissel W., 2010. Potential of hydrogenated vegetable oil (HVO) in a modern diesel engine. SAE Technical Paper 2010-32-0081.

Prokopowicz, A., Zaciera, M., Sobczak, A., et al., The effects of neat biodiesel and biodiesel and HVO blends in diesel fuel on eexhaust emissions from a light duty vehicle with a diesel engine. Environ. Sci. Technol. 49, 7473-7482, 2015.

Rantanen, L., Linnaila, R., Aakko, P., Harju, T., “NExBTL – Biodiesel fuel of the second generation,” SAE Technical Paper 2005-01-3771, 2005.

Shukla, P.C., Shamun, S., Gren, L., Malmborg, V., et al. Investigation of particle number emission characteristics in a heavy-duty compression ignition engine fueled with hydrotreated vegetable oil (HVO). SAE Technical Paper 2018-01-0909, 2018.

Singer, A., Schroder, O., Pabst, C., Munack, A., Bunger, J., et al. Aging studies of biodiesl and HVO and their testing as neat fuel and blends for exhaust emissions in heavy-duty engines and passenger cars. Fuel 153, 595-603, 2015.

Singh, D., Subramanian, K.A., Garg, M.O. Comprehensive review of combustion, performance and emissions characteristics of a compression ignition engine fueled with hydroprocessed renewable diesel. Renewable and Sustainable Energy Revews 81, 2947-2954, 2018a.

Singh, D., Subramanian, K.A., Bal, R., et al. Combustion and emission characteristics of a light duty diesel engine fueled with hydro-processed renewable diesel. Energy 154, 498-507, 2018b.

Singh, D., Subramanian, K.A., Singal, S.K., "Emissions and fuel consumption characteristics of a heavy duty diesel engine fueled with hydroprocessed renewable diesel and biodiesel," Fuel 155, 440-446, 2015.

Sun J., Caton, J.A., Jacobs, T.J. Oxides of nitrogen emissions from biodiesel-fuelled diesel engines. Progress in Energy and Combustion Science 36, 677-695, 2010.

Tan, C., Xu, H., Shuai, S.-J., Ghafourian, A., Liu, D., Tian, J., "Investigation on transient emissions of a turbocharged diesel engine fueled by HVO blends," SAE Technical Paper 2013-01-1307, 2013.

Vo, C., Charoenphonphanich, C., Karin, P., Susumu, S., Hidenori, K. Effects of variable O2 concentrations and injection pressures on the combustion and emissions characteristics of the petro-diesel and hydrotreated vegetable oil-based fuels under the sumulated diesel engine condition. Journal of the Energy Institute, In Press, 1-14, 2017.

Wu, Y., Ferns, J., Li, H., Andrews, G. Investigation of combustion and emission performance of hydrogenated vegetable oil (HVO) diesel. SAE Technical Paper 2017-01-2400, 2017.

Appendix A

LA-92 Testing Results

Table A1: Gaseous and particulate emissions over the LA-92 cycle

	CO (g/mi)			
Fuel	HVO		ULSD	
Phase	Phase 1	Phase 2	Phase 1	Phase 2
Cold Start	6.82 ± 1.48	7.5 ± 0.9	11.94 ± 0.03	12.27 ± 0.18
Hot Driving	2.43 ± 0.14	2.5 ± 0.5	3.43 ± 0.07	3.38 ± 0.38
Hot Start	7.59 ± 0.13	7.22 ± 2.23	7.77 ± 0.67	10.46 ± 0.54
Weighted	3.43 ± 0.30	3.49 ± 0.60	4.84 ± 0.02	5.03 ± 0.39
	THC (g/mi)			
Cold Start	1.00 ± 0.22	0.97 ± 0.02	2.05 ± 0.24	1.31 ± 0.02
Hot Driving	0.54 ± 0.02	0.44 ± 0.10	0.83 ± 0.09	0.54 ± 0.01
Hot Start	1.08 ± 0.15	1.15 ± 0.05	1.60 ± 0.06	1.06 ± 0.02
Weighted	0.64 ± 0.06	0.57 ± 0.09	1.05 ± 0.09	0.67 ± 0.01
	CO_2 (g/mi)			
Cold Start	1426.1 ± 48.0	1531.3 ± 22.68	1409.6 ± 214.2	1650.5 ± 69.0
Hot Driving	843.7 ± 16.6	930.6 ± 19.52	853.8 ± 68.0	953.2 ± 21.6
Hot Start	1349.6 ± 31.2	1442.9 ± 63.61	1199.1 ± 68.2	1600.2 ± 79.1
Weighted	958.6 ± 16.9	1048.7 ± 21.1	955.3 ± 58.5	1090.9 ± 18.7
	NOx (g/mi)			
Cold Start	1.42 ± 0.06	1.65 ± 0.07	1.58 ± 0.17	2.17 ± 0.33
Hot Driving	1.58 ± 0.01	1.82 ± 0.06	1.92 ± 0.14	2.08 ± 0.03
Hot Start	1.18 ± 0.07	1.63 ± 0.44	1.52 ± 0.08	1.50 ± 0.07
Weighted	1.53 ± 0.03	1.79 ± 0.1	1.85 ± 0.14	2.03 ± 0.07
	Soot mass (mg/mi)			
Cold Start	125.1 ± 16.8	148.5 ± 5.2	156.1 ± 13.3	137.8 ± 11.7
Hot Driving	57.4 ± 0.4	70.8 ± 4.8	107.4 ± 8.9	77.5 ± 3.3
Hot Start	99.7 ± 0.7	120.0 ± 32.0	189.1 ± 49.8	131.5 ± 12.1
Weighted	69.0 ± 1.7	84.2 ± 7.8	122.0 ± 13.8	2.03 ± 0.07
	PM (mg/mi)			
Cold Start	336.5 ± 48.2	351.3 ± 15.2	409.5 ± 22.3	575.6 ± 50.8
Hot Driving	239.0 ± 3.6	227.8 ± 9.9	359.6 ± 5.7	344.9 ± 69.5
Hot Start	334.0 ± 4.3	313.2 ± 49.5	407.5 ± 36.4	358.4 ± 117.3
Weighted	259.2 ± 8.9	249.8 ± 14.7	371.7 ± 3.0	371.0 ± 61.6
	PN ([#/mi] * 10^{14})			
Cold Start	16.2 ± 2.3	16.9 ± 0.7	19.7 ± 1.1	27.6 ± 2.4
Hot Driving	11.5 ± 0.2	10.9 ± 0.5	17.3 ± 0.3	16.6 ± 3.3
Hot Start	16.0 ± 0.2	15.0 ± 2.4	19.6 ± 1.8	17.2 ± 5.63
Weighted	12.4 ± 0.4	12.0 ± 0.7	17.8 ± 0.1	17.8 ± 3.0

Table A2: Gaseous and particulate emissions over the 30 mph steady-state conditions

	THC (g/mi)			
Fuel	HVO		ULSD	
Phase	Phase 1	Phase 2	Phase 1	Phase 2
0% load	0.08	-	0.11	0.18
25% load	0.24	-	0.47	0.45
50% load	0.38	-	0.59	0.62
75% load	0.41	-	0.35	0.65
100% load	0.78	-	0.33	1.38
	CO (g/mi)			
0% load	0.01	0.01	0	0.01
25% load	0.74	0.66	3.14	2.2
50% load	1.87	1.7	5.39	4.18
75% load	2.05	5.62	3.53	3.22
100% load	2.39	-	2.09	2.32
	CO_2 (g/mi)			
0% load	3.16	4.2	2.17	4.93
25% load	289.73	296.27	334.75	325.1
50% load	721.69	708.84	759.2	774.49
75% load	1324.82	1423.55	1153.77	1359.07
100% load	3246.37	-	2067.2	3090.62
	NOx (g/mi)			
0% load	0	-	0.01	0.02
25% load	1.35	-	1.22	1.38
50% load	0.9	-	1	0.94
75% load	1.75	-	1.7	2.04
100% load	8.7	-	6.01	9.31
	Soot mass (mg/mi)			
0% load	0.18	0.22	0.26	0.15
25% load	11.08	8.84	9.63	17.45
50% load	39.69	30.6	64.95	69.23
75% load	88.27	29.62	124.59	130.33
100% load	652.47	-	196.23	224.61
	PM (mg/mi)			
0% load	-	0	0.07	0
25% load	-	17.82	26.52	29.88
50% load	-	92.32	247.81	179.78
75% load	-	141	653.19	481.85
100% load	-	-	1591.99	1189.75
	PN (#/mi)			
0% load	-	0.00E+00	3.39E+11	0.00E+00
25% load	-	8.55E+13	1.27E+14	1.43E+14
50% load	-	4.43E+14	1.19E+15	8.63E+14
75% load	-	6.77E+14	1.39E+16	2.31E+15
100% load	-	-	7.64E+15	5.71E+15

Table A3: Gaseous and particulate emissions over the 50 mph steady-state conditions

	THC (g/mi)			
Fuel	HVO		ULSD	
Phase	Phase 1	Phase 2	Phase 1	Phase 2
0% load	0.22	-	0.1	0.58
25% load	0.19	-	0.26	0.28
50% load	0.24	-	0.12	0.3
75% load	0.54	-	0.14	0.62
100% load	0.64	-	0.12	0.87
	CO (g/mi)			
0% load	0.29	0.31	0	1.04
25% load	0.66	0.6	2.1	1.6
50% load	0.83	0.65	0.98	1.14
75% load	10.69	-	4.51	7.99
100% load	9.61	-	8.15	13.79
	CO_2 (g/mi)			
0% load	18.08	18.63	2.69	14.83
25% load	311.08	287.44	294.67	327.76
50% load	660.38	570.76	503.02	705.97
75% load	1898.4	-	964.08	1890.91
100% load	2728.5	-	1158.35	2594.56
	NOx (g/mi)			
0% load	0.07	-	0.01	0.04
25% load	0.65	-	0.53	0.76
50% load	1.12	-	0.96	1.49
75% load	7.9	-	4.35	10.47
100% load	20.2	-	7.3	19.69
	Soot mass (mg/mi)			
0% load	0.71	0.52	0.15	0.33
25% load	12.22	7.48	15.7	15.42
50% load	35.46	21.61	39.05	50.33
75% load	574.99	-	99.48	117.01
100% load	732.19	-	82.06	198.89
	PM (mg/mi)			
0% load	0	0.25	0.06	13.85
25% load	0	20.06	51.9	39.37
50% load	0	62.68	183.01	160.1
75% load	0	-	603.54	530.44
100% load	0	-	526.3	546
	PN (#/mi)			
0% load	1.14E+08	1.21E+12	2.66E+11	6.65E+13
25% load	1.13E+08	9.63E+13	2.49E+14	1.89E+14
50% load	3.14E+08	3.01E+14	8.78E+14	7.68E+14
75% load	6.61E+08	-	2.90E+15	2.55E+15
100% load	1.33E+09	-	2.53E+15	2.62E+15

Table A4: Fuel Economy

	Steady State Fuel Economy (miles/gal)			
Fuel	HVO		ULSD	
Speed (mph)	30	50	30	50
0% load	2418.2	475.11	2968.7	1994.0
25% load	30.91	30.34	30.57	32.65
50% load	12.67	14.83	13.21	17.40
75% load	6.6	4.75	8.17	7.97
100% load	2.8	3.32	4.13	6.34

	LA-92 Fuel Economy (miles/gal)	
Fuel	HVO	ULSD
Cold Start	6.19 ± 0.29	6.65 ± 0.70
Hot Running	10.37 ± 0.61	11.31 ± 0.92
Hot Start	6.55 ± 0.31	7.39 ± 1.26
Weighted	9.15 ± 0.49	9.98 ± 0.85