

**CRC Report No. E-117**

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

**July 2022**



**COORDINATING RESEARCH COUNCIL, INC.  
5755 NORTH POINT PARKWAY SUITE 265 ALPHARETTA, GA 30022**

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Revised July 2022 -- Calculation errors corrected in data given in Appendix A. Figures and discussion are updated for corrected data.

**FINAL REVISED REPORT**

**CRC Project No. E-117:  
Combustion and Engine-Out Emissions Characteristics of a Light Duty  
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**Prepared for:**

**Christopher Tennant, Ph.D.  
Coordinating Research Council Inc.  
5755 North Point Parkway, Suite 265  
Alpharetta, GA 30022  
678-795-0506**

**Originally Submitted July 2019 by:**

Georgios Karavalakis, Ph.D.  
Kent Johnson, Ph.D.  
Thomas D. Durbin, Ph.D.  
Cavan McCaffery

**Revised and Edited by CRC Emissions Committee July 2022**

College of Engineering-Center for Environmental Research and Technology  
University of California  
CE-CERT  
Riverside, CA 92521  
951-781-5799  
951-781-5790 (fax)

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## Executive Summary

The purpose of this project 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 findings and implications in terms of the broader literature.

Two fuels were used in this study, including an Ultra Low Sulfur Diesel (ULSD) and a neat-hydrogenated vegetable oil (HVO) to evaluate one light-duty diesel truck equipped with a common rail direct injection fuel system, a diesel particle filter (DPF) and a selective catalytic reduction (SCR) aftertreatment system. The HVO fuel contained 98.5 vol % of HVO and 1.5 vol % petroleum; and is hereinafter, the fuel denoted as HVO. All exhaust sampling focused on engine-out emissions occurring before the catalyst system. 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 four different loads, 25%, 50%, 75% and 100%. 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 ( $\text{NO}_x$ ), carbon monoxide (CO), carbon dioxide ( $\text{CO}_2$ ), 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. A number of technical issues with the combustion parameter measurements made during this study led to a decision to omit the discussion and analysis of these data from this report.

The engine-out emissions measurements over the LA92 test cycle yielded the following conclusions:

- HVO resulted in statistically significant lower particulate matter and particulate number emissions compared to ULSD
- HVO resulted in statistically significant lower CO emissions compared to ULSD
- HVO trends lower in THC, NO<sub>x</sub> and soot emissions compared to ULSD
- There was no difference in CO<sub>2</sub> emissions with HVO compared to ULSD
- There was no difference in fuel economy with HVO compared to ULSD

The reductions in engine-out gaseous and particulate emissions with HVO compared to ULSD may be attributed to the lower volatility and absence of sulfur and aromatic compounds. More specifically, the reductions in particulate emissions for HVO relative to ULSD may 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.

The engine-out emissions measurements under steady state conditions at 30 mph and 50 mph at four different loads yielded the following conclusions:

- HVO resulted in lower THC emissions at 30 mph and 50 mph for all loads

- HVO at 30 mph and 25% and 50% loads resulted in lower CO emissions.
- HVO at 30 mph and 75% and 100% loads increased CO emissions compared to ULSD
- HVO at 50 mph and 25%, 50% and 100% loads resulted in lower CO emissions, however, greater CO at 75% load compared to ULSD
- HVO at 30 mph and 50 mph and 25%, 50% and 75% loads resulted in the same NOx emissions, however, at 100% load had greater NOx emissions
- HVO at 30 mph and 50 mph had the same CO2 emissions at 25% and 50% load, but greater CO2 emissions at 75% and 100% loads
- HVO at 30 mph lowered soot mass at 25% through 75% loads, but substantially increased at 100% load
- HVO at 50 mph resulted in substantially greater soot mass at 75% load, but lower at all other loads

Overall, the emissions results from this project suggest that HVO could be adopted in modern technology direct injection diesel engines.

## **List of Acronyms**

CAD Crank Angle Degrees

CARB California Air Resources Board

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

CI Confidence Interval

CLD Chemiluminescence Detector

CO Carbon Monoxide

CO<sub>2</sub> 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

NO<sub>x</sub> 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 a 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 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).

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 (NO<sub>x</sub>) 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 NO<sub>x</sub> 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 NO<sub>x</sub> 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 deployment of low carbon-intensity fuels such as HVO 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 findings 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 by CRC members and were deemed sufficient to provide a qualitative (as opposed to a detailed quantitative) assessment of combustion control parameters. CE-CERT had originally proposed the option of using AVL's high-precision *piezoelectric* in-cylinder pressure sensors. However, the occurrence of considerable schedule delays in conjunction with additional delays by AVL to deliver the sensors, led to a decision to use the sensors provided by CRC members and work with FEV Inc. to set up the combustion acquisition system and instrument the vehicle with the sensors. The results for the combustion parameters measured in this program revealed that the in-cylinder pressure signals lacked high resolution and exhibited relatively high amounts of noise. These effects ultimately influenced the calculation of the heat release rates. Consequently, the analysis and discussion for the combustion noise parameters was omitted from this report, despite that results were consistent with the published literature on HVO combustion. The main reason for omitting the combustion noise data was that it was derived from the in-cylinder pressure rise, which likely led to incorrect combustion noise calculations.

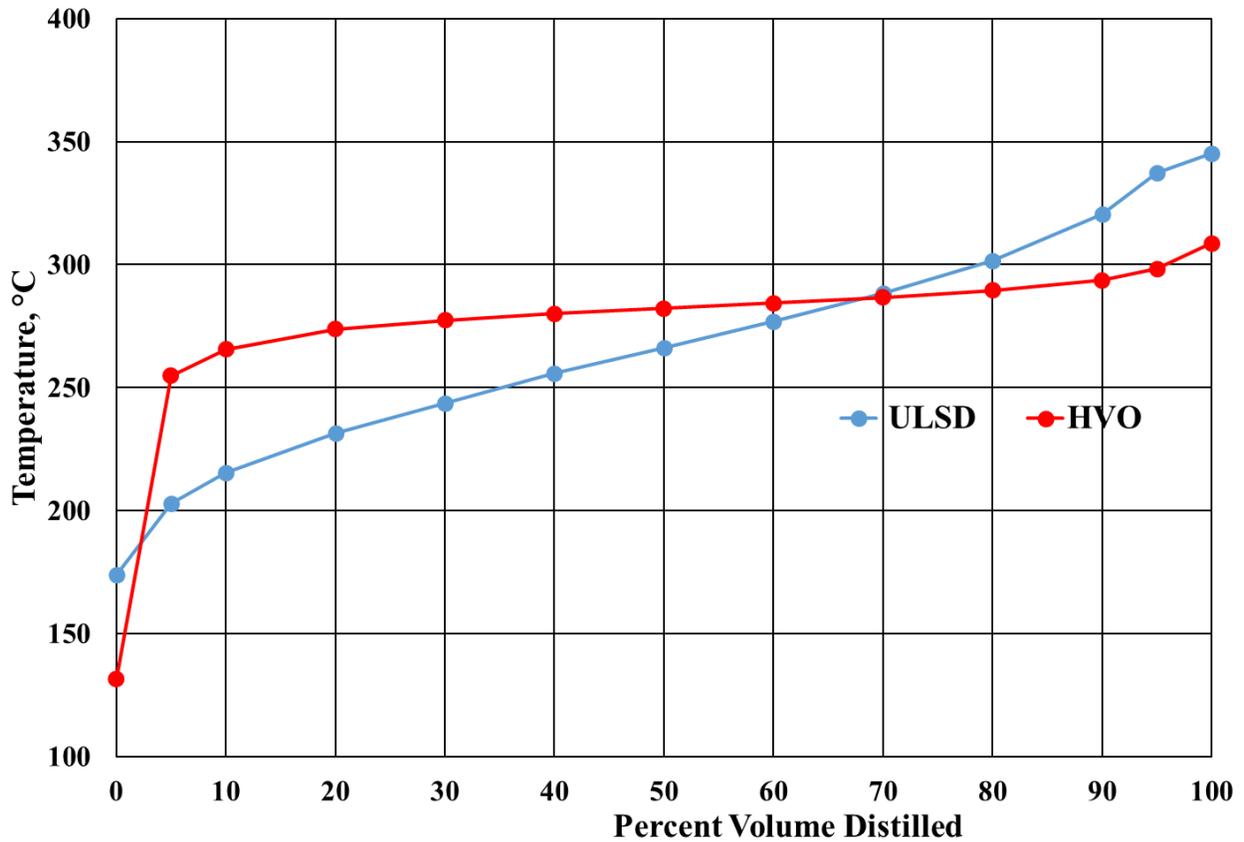
## **2. Experimental Procedures**

### **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/cm <sup>3</sup> )	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 @ 104°F/ 40°C (mm <sup>2</sup> /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.

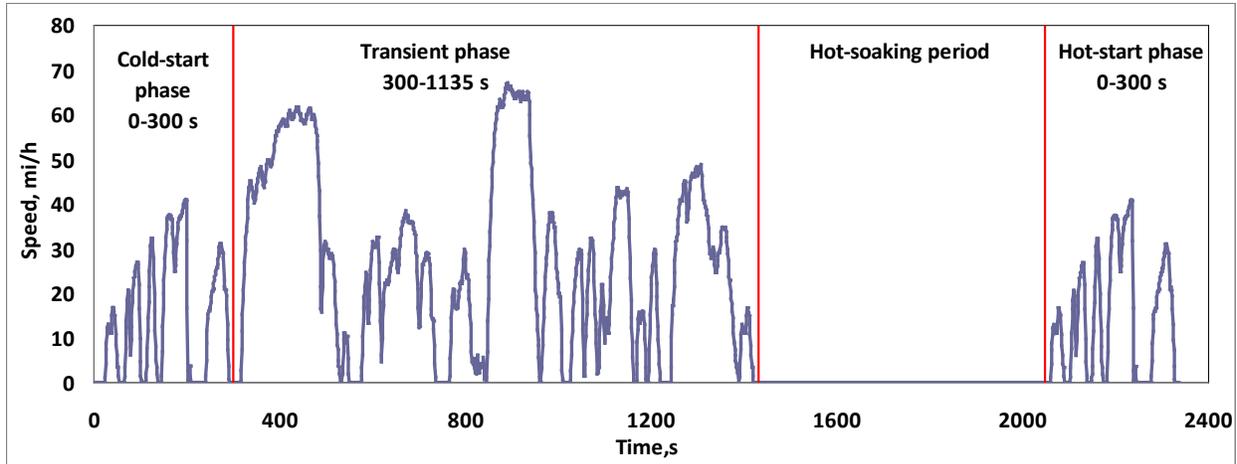
For the purpose of this project, the vehicle was tested using the original OEM engine calibration. The vehicle was not re-calibrated for testing with HVO.

**Table 2-2:** Technical specifications of the test vehicle

<b>Engine</b>	<b>6.6L Turbo-diesel V8</b>
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**

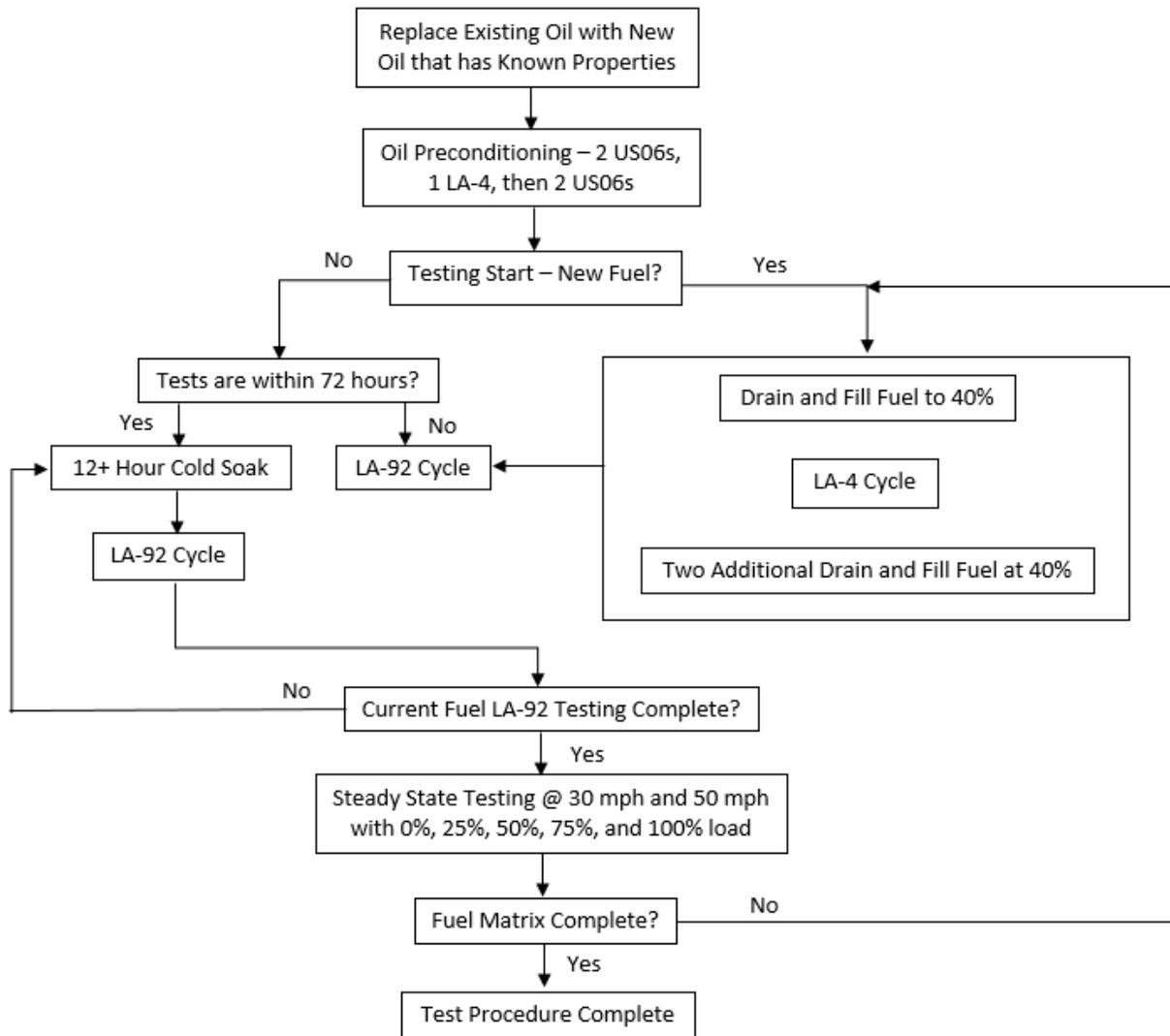
After completing the initial duplicate LA-92 tests on each fuel, the data were evaluated to determine whether additional testing was required. A third test was performed if differences in LA-92 regulated emissions exceeded a predefined limit. This limit was defined using the same criteria as used in 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<sub>x</sub> 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.

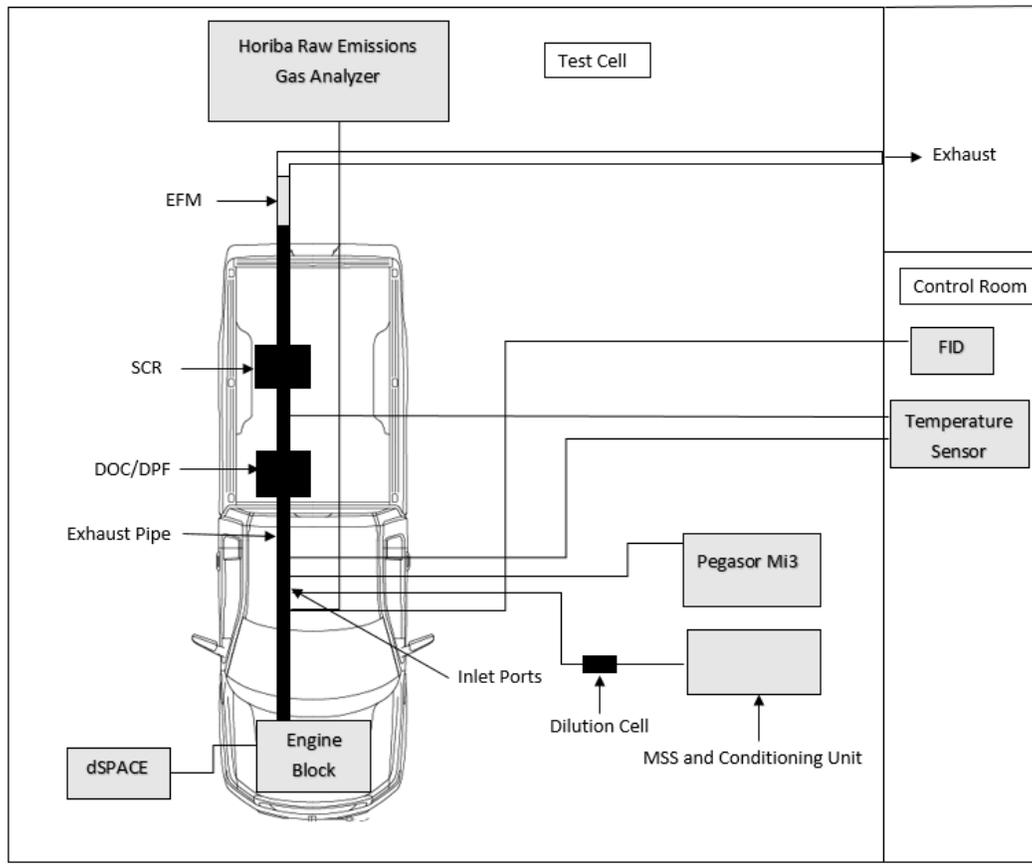
After completing the LA-92 tests on each vehicle/fuel combination, each fuel was evaluated at steady-state conditions at 30 miles per hour (mph) and 50 mph, at loads of 0, 25%, 50%, 75%, and 100%. For each test condition/fuel combination, combustion characteristics were monitored and recorded over the LA-92 and steady-state testing. 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  $\frac{1}{4}$  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  $5 \mu\text{g}/\text{m}^3$ , 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  $\frac{1}{4}$  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<sub>2</sub> and NO<sub>x</sub>, a Horiba series 200 analyzer raw emissions unit was used. CO and CO<sub>2</sub> were measured using a non-dispersive infrared (NDIR) analyzer while a chemiluminescence (CLD) detector was used to measure NO<sub>x</sub>. A separate California Analytical Instruments Model 300-HFID HC analyzer was used to measure THC. A  $\frac{1}{4}$  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. The two phases were separated by an 8 day period during which no testing was conducted. The test vehicle remained on the chassis dynamometer room in a temperature controlled environment. Prior to the initiation of 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.<sup>2</sup> The results for each test fuel represent the average of all four of the test runs. Each test run comprised of two tests on a given fuel, followed by a fuel change, (HVO to ULSD). This procedure was repeated a second time, resulting in four runs per 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. The error bars represent the minimum and maximum emissions values from the four test runs and not the standard deviation for each test point. For the steady-state tests, values presented in figures represent the average for two tests on a given fuel for each load point and speed condition. An additional statistical analysis was performed using the difference of means approach whereby the error bars represent the probable differences between two datasets. For these cases, a 95% confidence interval was used. More specifically, if a 95% CI band does not cross zero for a given comparison, the difference in means is considered significant.

This section also presents the emission results for the steady-state conditions at 30 mph and 50 mph.

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**

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<sup>2</sup> See Chapter 4 for a discussion of additional statistical analysis of the LA-92 test cycle results.

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. On an average basis, Engine-out THC emissions were found in lower concentrations for the HVO compared to the ULSD. Similarly, HVO resulted in a weighted engine-out CO emissions reduction of 26.0% 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.

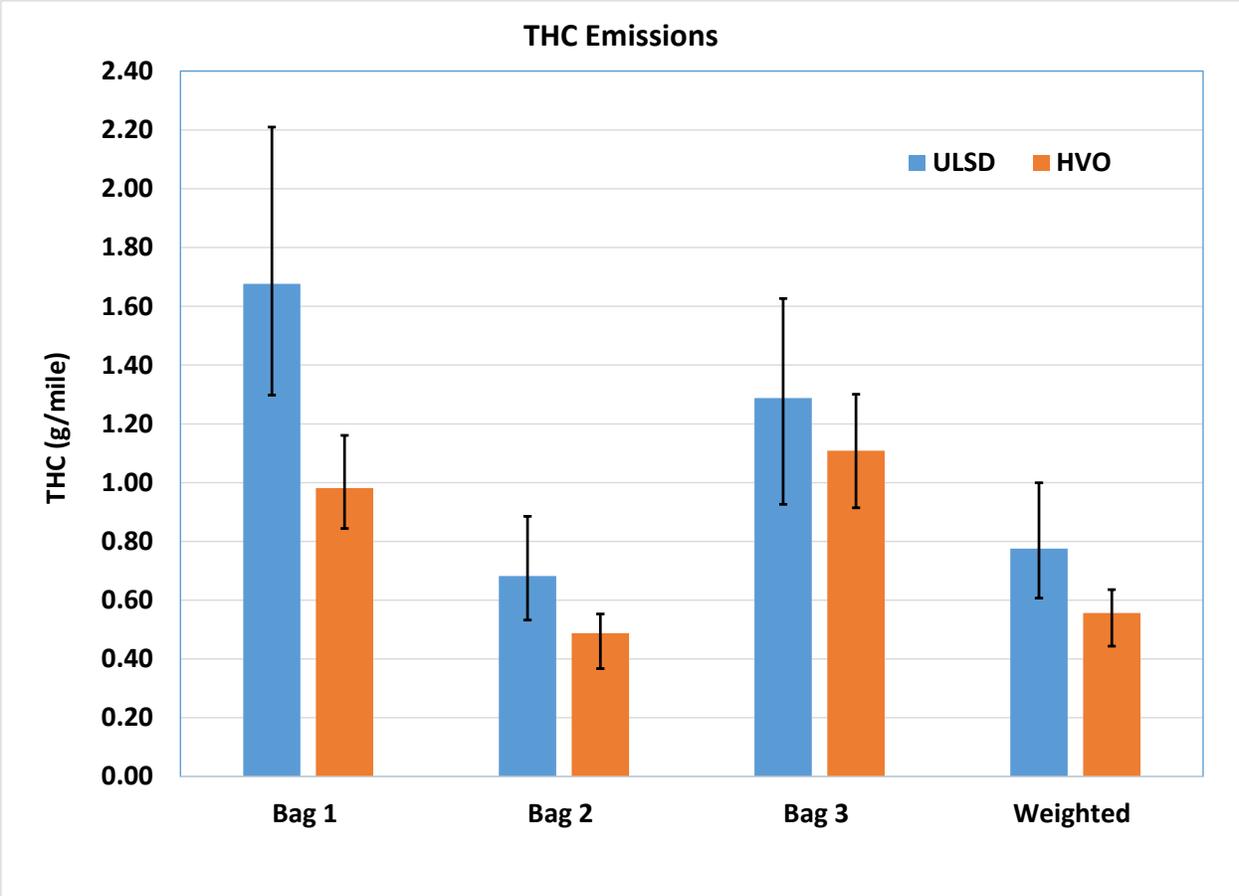


Figure 3-1: THC emissions over the LA-92

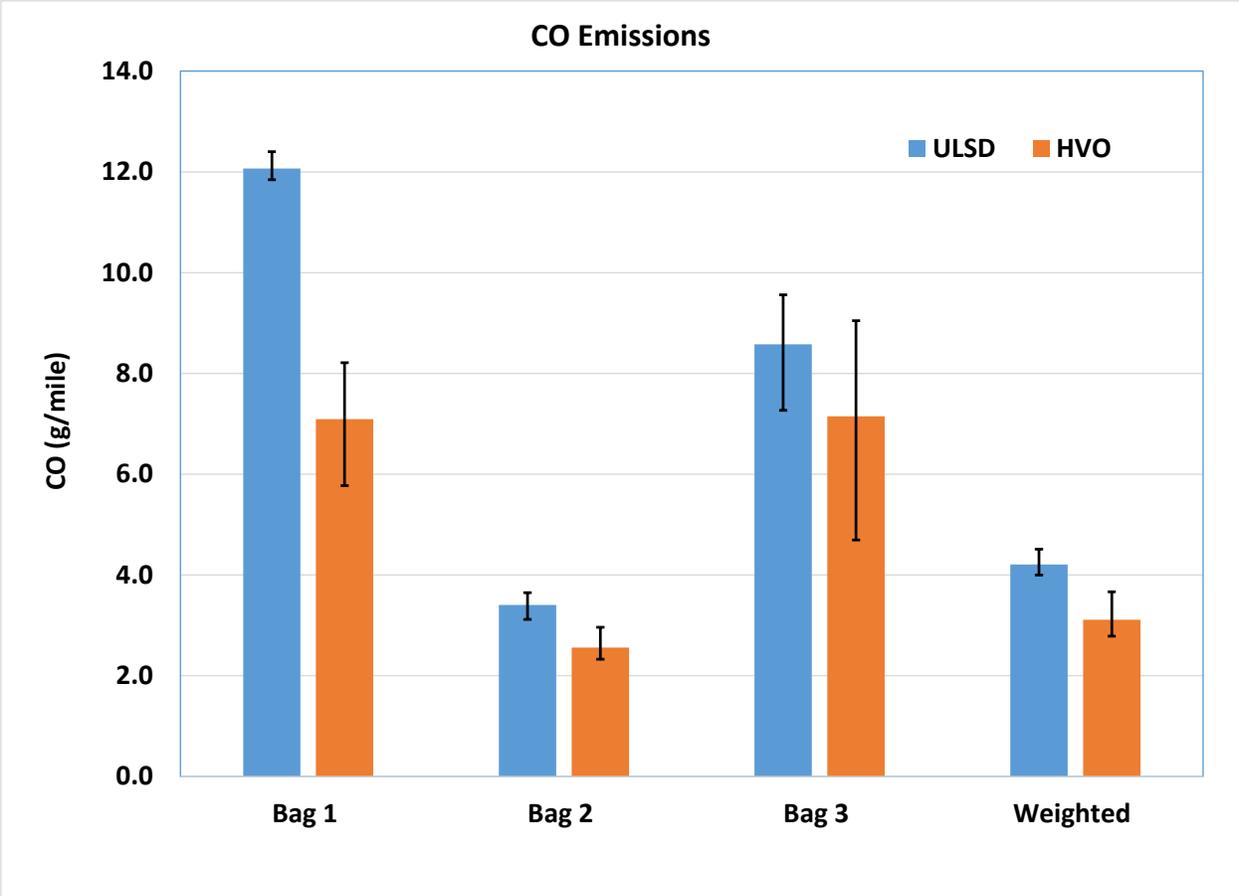


Figure 3-2: CO emissions over the LA-92

### 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<sub>2</sub>), 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, and generally trended lower with HVO 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).

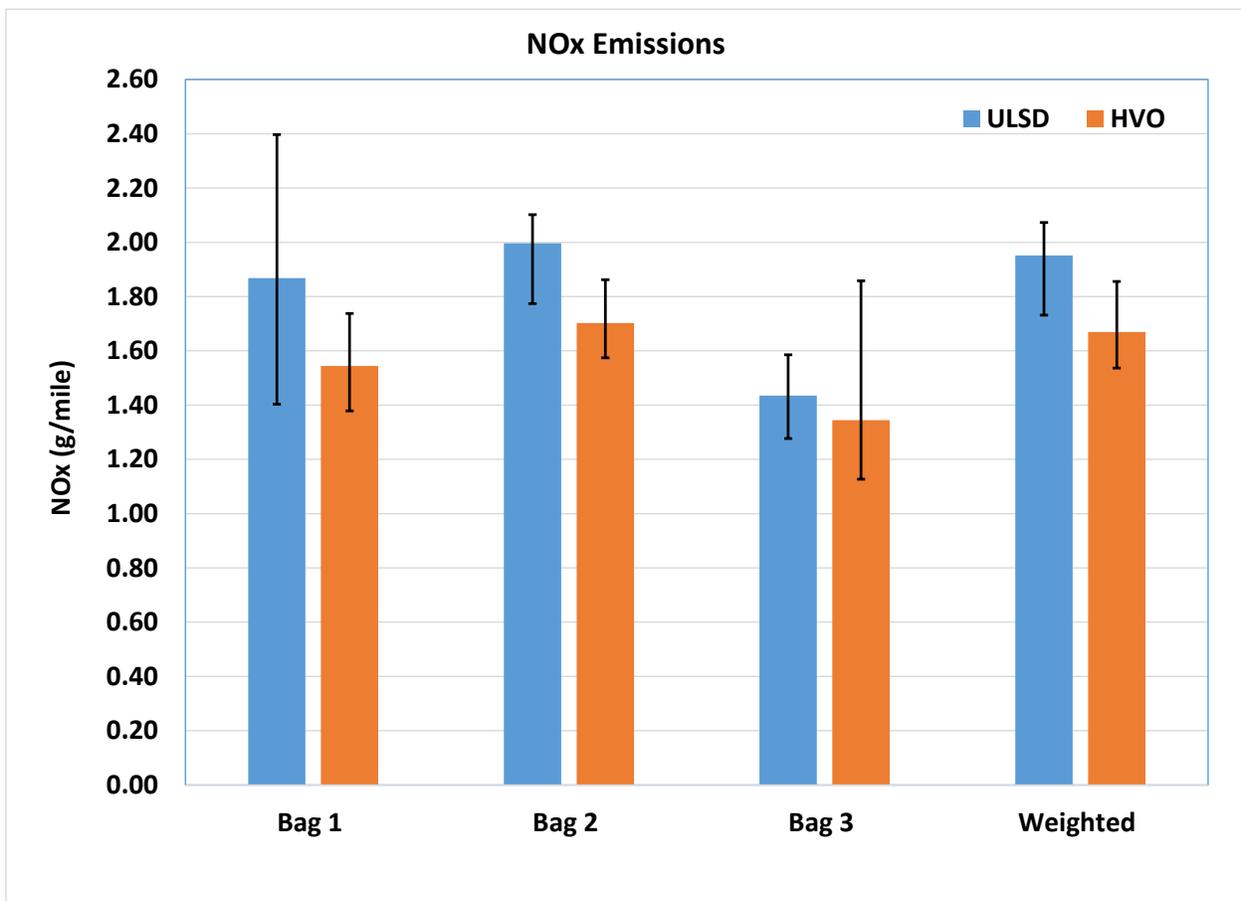
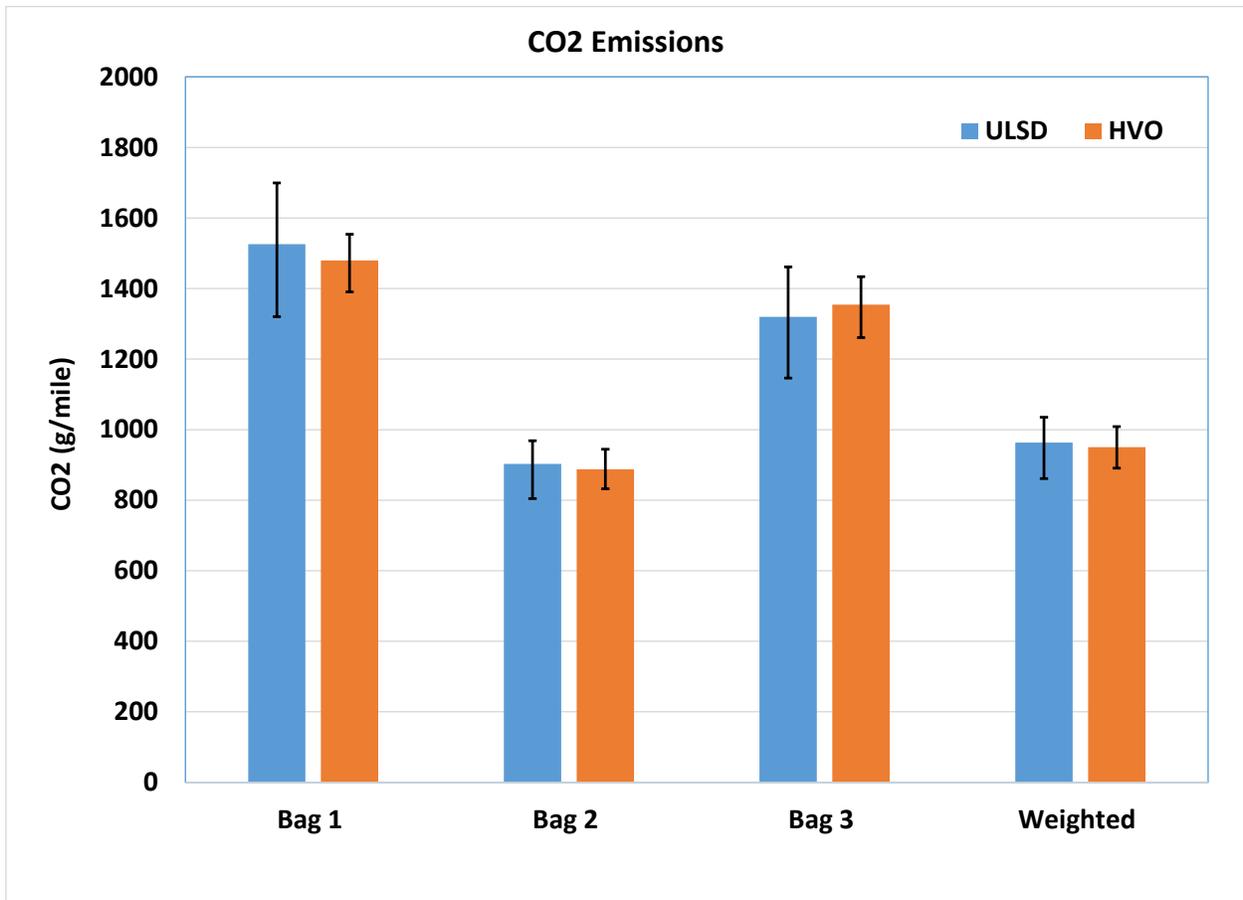


Figure 3-3: NOx emissions over the LA-92

### 3.3 CO<sub>2</sub> Emissions and Fuel Economy

Engine-out Carbon dioxide emissions are shown in Figure 3.4 and appear to be relatively similar for both fuels across each individual phase of the LA-92 test cycle. Previous studies have shown that CO<sub>2</sub> 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<sub>2</sub> 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.

$$\text{Fuel Economy via Carbon Balance} = \frac{CWF \times sp.gr \times 3781.8}{(CWF \times THC \left(\frac{g}{mile}\right)) + (0.429 \times CO \left(\frac{g}{mile}\right)) + (0.273 \times CO_2 \left(\frac{g}{mile}\right))}$$

Where:

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

THC: THC emission rate (g/mile)

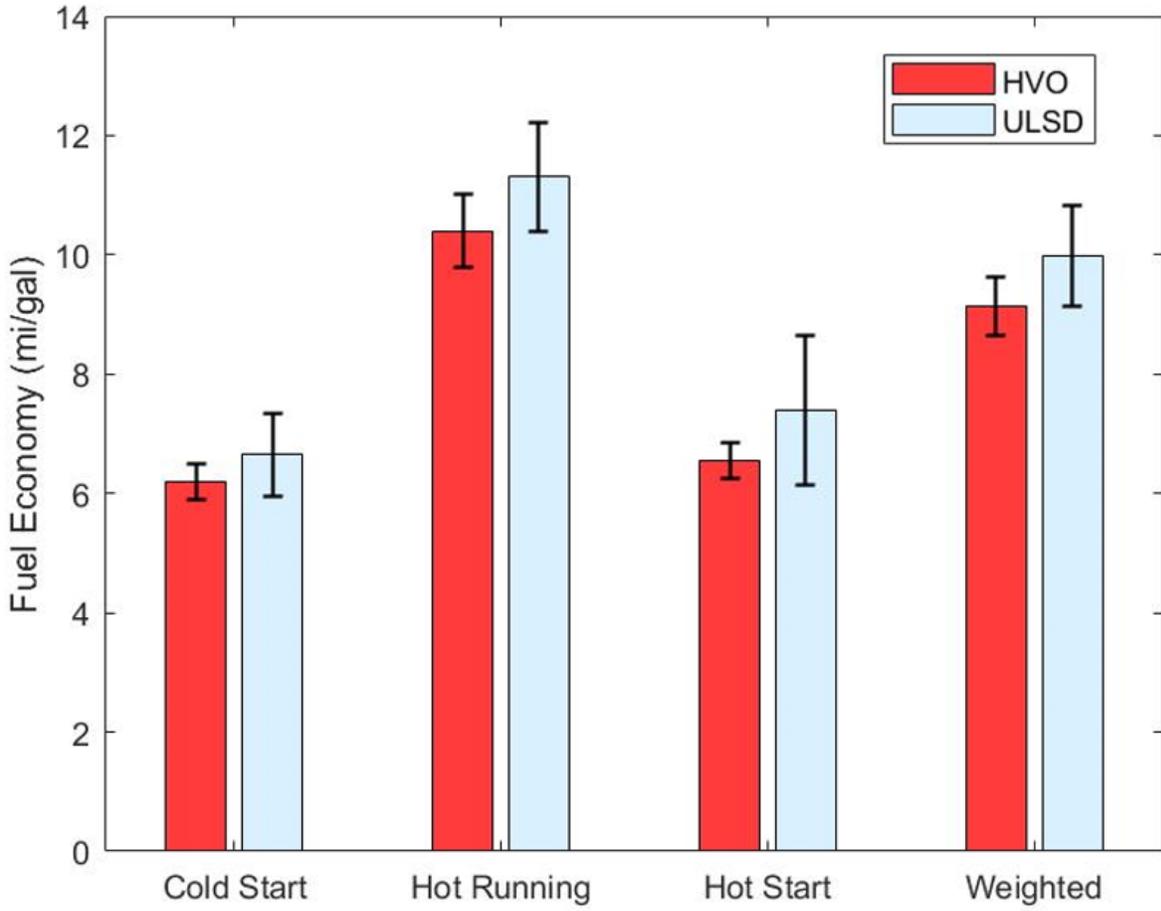
CO: CO emission rate (g/mile)

CO<sub>2</sub>: CO<sub>2</sub> emission rate (g/mile)

CWF: Carbon weight fraction of the test fuel

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

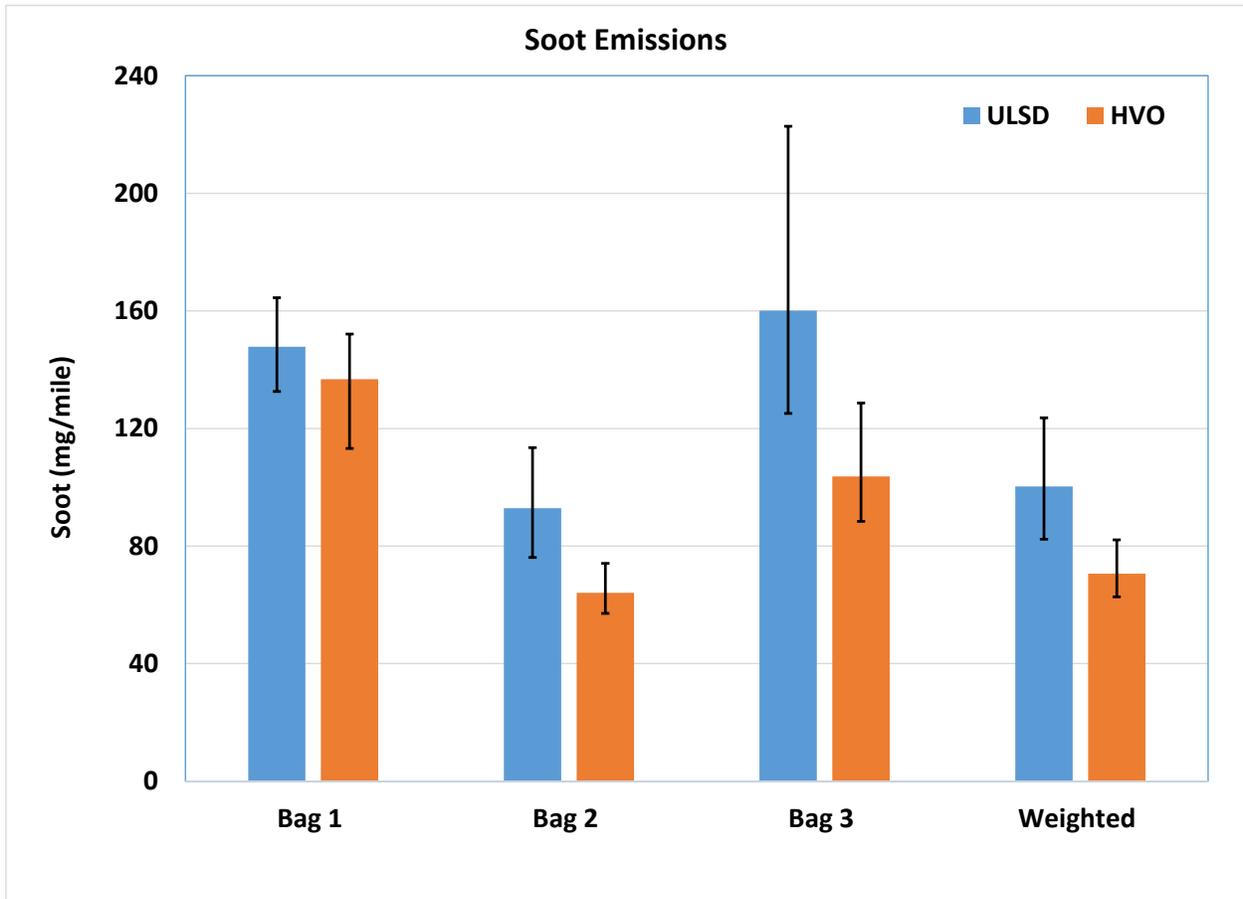
Fuel economy trended lower for the HVO fuel compared to ULSD for the weighted LA-92 cycle and each individual phase. Previous studies have reported lower volumetric fuel economy with HVO due to its lower density compared to petroleum diesel (Kuronen et al., 2007; Napolitano et al., 2018; Kousoulidou et al., 2014). The little observed 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

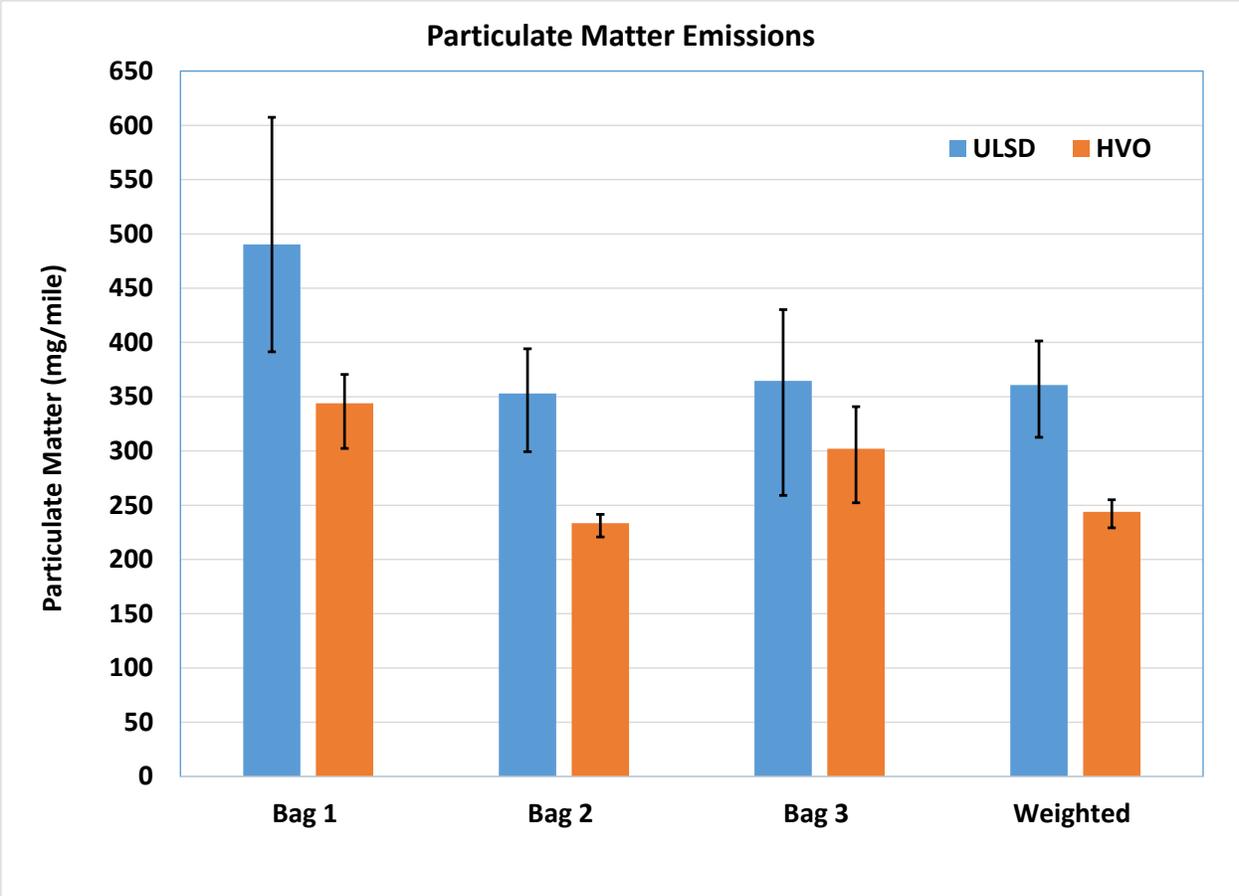
### 3.4 Particulate Emissions

Soot mass or black carbon emissions are shown in Figure 3-6. The ULSD resulted in similar engine-out soot mass emissions compared to HVO. The trends, however, indicate a reduction in engine-out soot mass emissions for HVO.



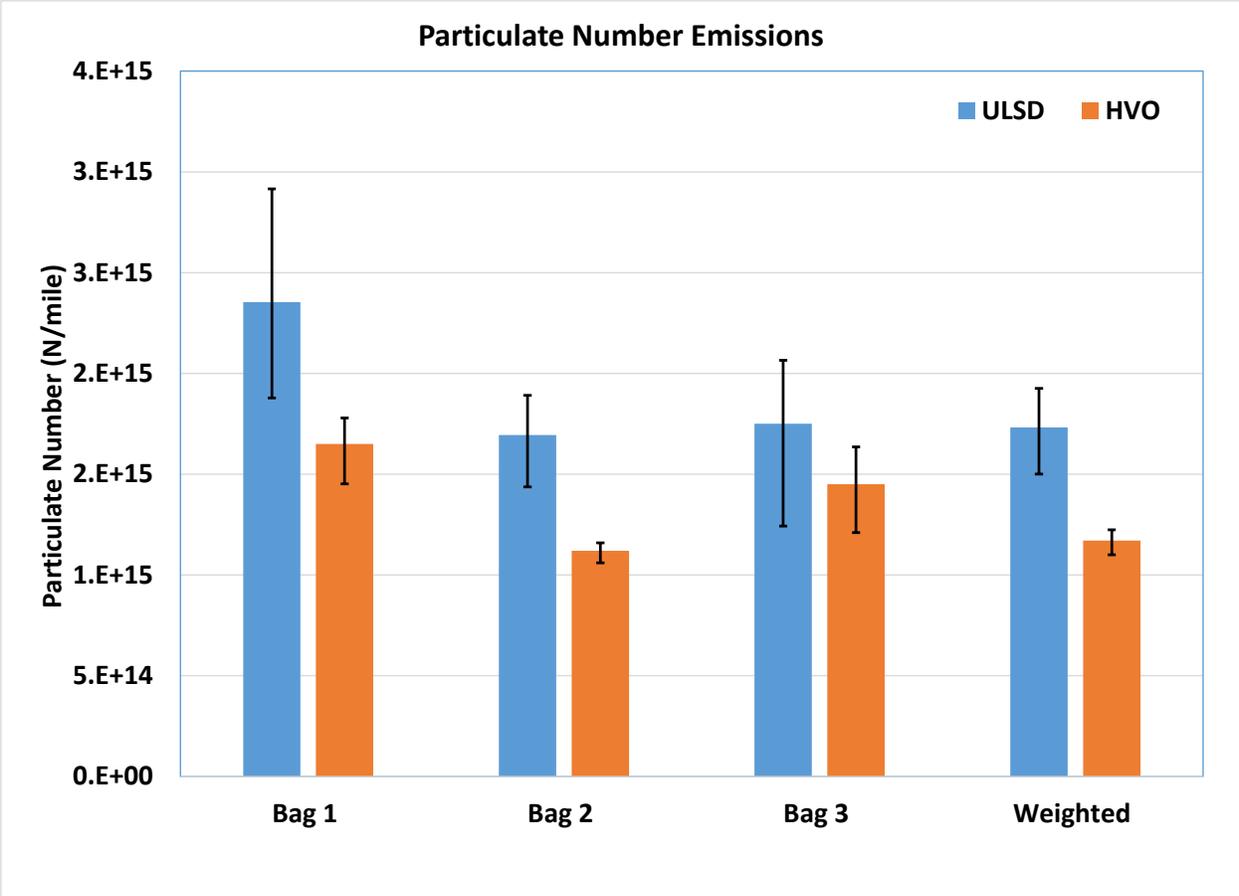
**Figure 3-6:** Soot mass emissions over the LA-92

In contrast, Figure 3-7 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 phase. For example use of HVO on the LA-92 decreased weighted PM mass emissions by 32.4%.



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

Engine-out solid particle number emissions followed the same pattern as PM mass emissions in terms of showing large reductions for the HVO compared to ULSD (reduction of 32.4%).



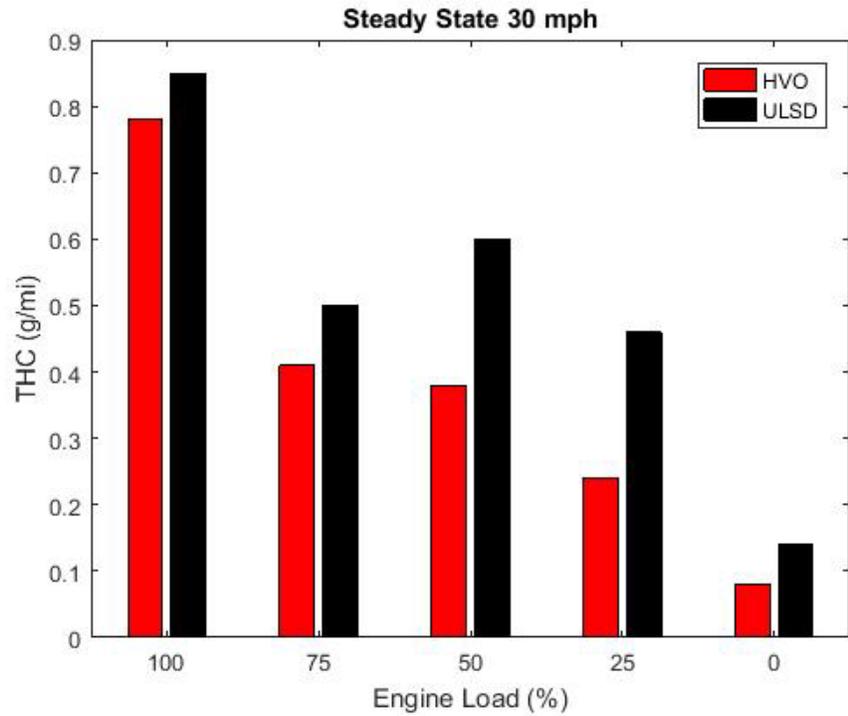
**Figure 3-8:** Particle number emissions over the LA-92

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).

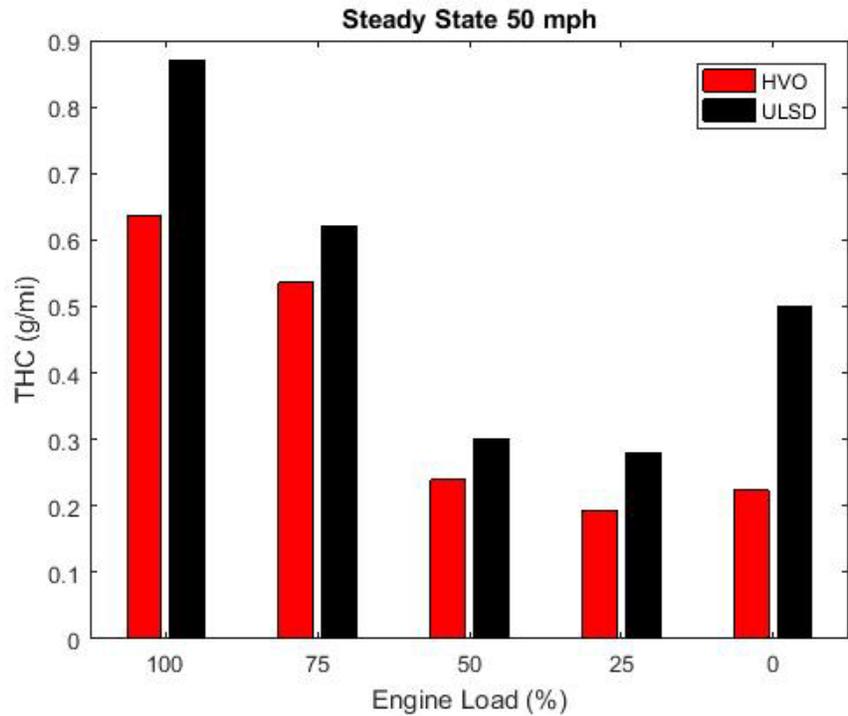
### **3.5 Steady-State Emissions Testing**

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.

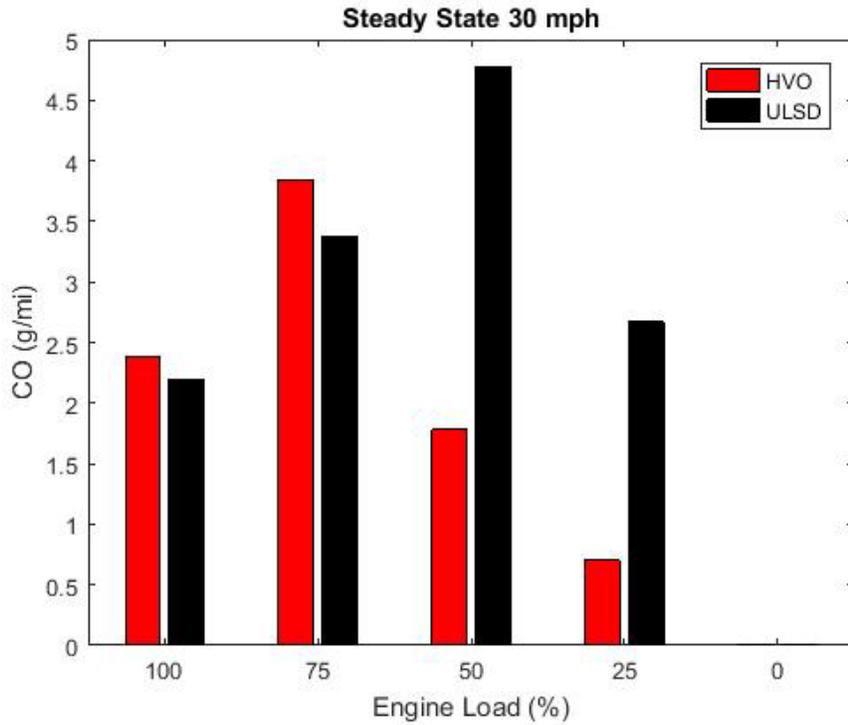


**A**

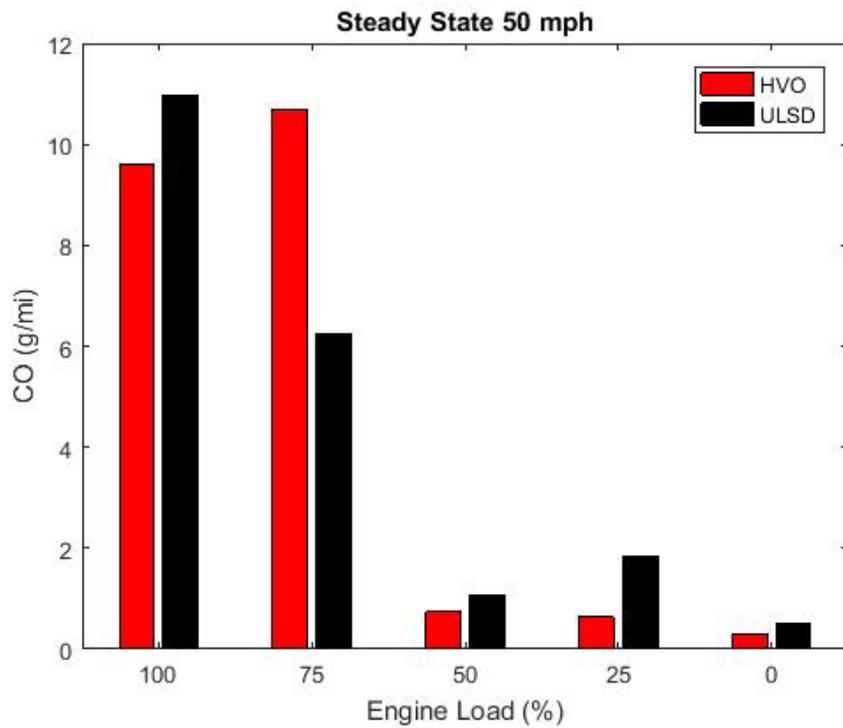


**B**

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



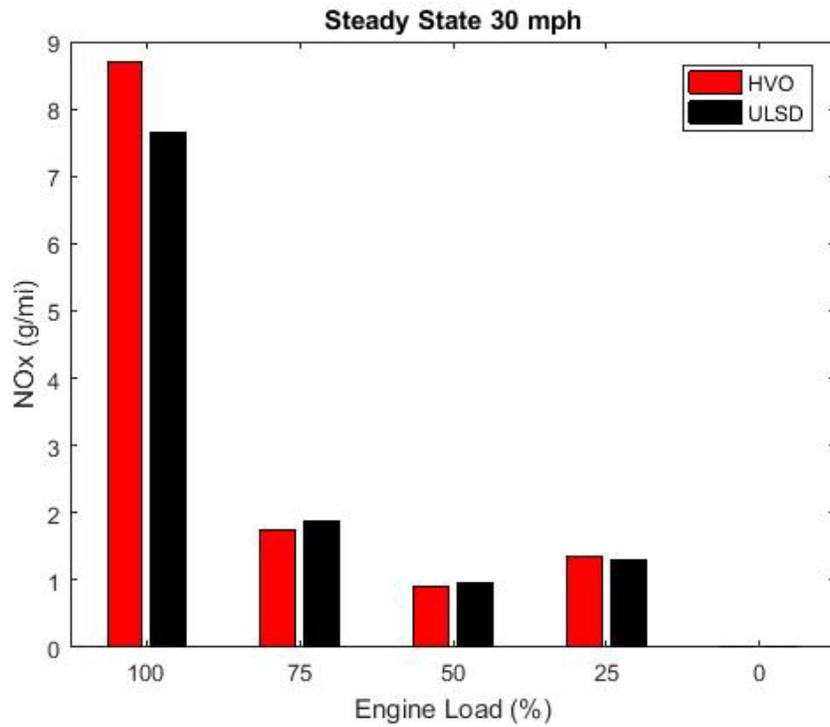
A



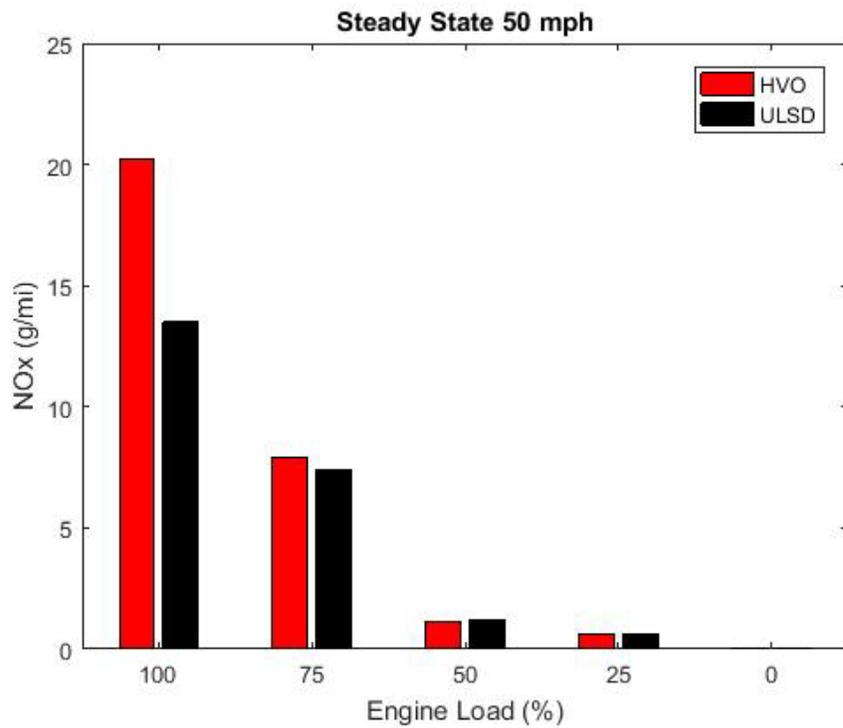
B

**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 NO<sub>x</sub> emissions obtained during the steady-state conditions at 30 mph and 50 mph. Engine-out NO<sub>x</sub> 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 NO<sub>x</sub> 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 NO<sub>x</sub> emissions at higher loads. Previous studies have also shown higher NO<sub>x</sub> emissions for HVO at higher engine loads (Bohl et al., 2018).



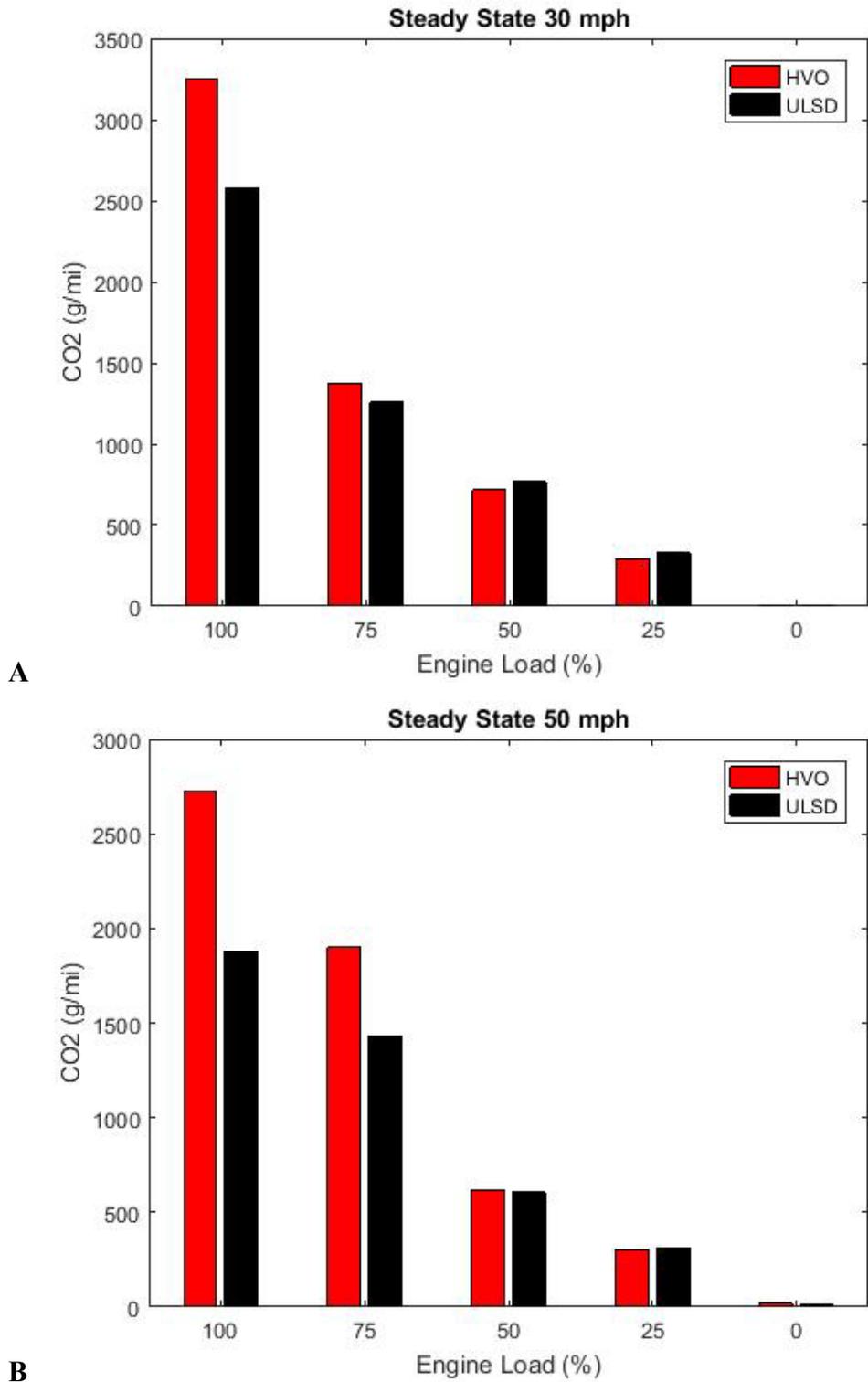
**A**



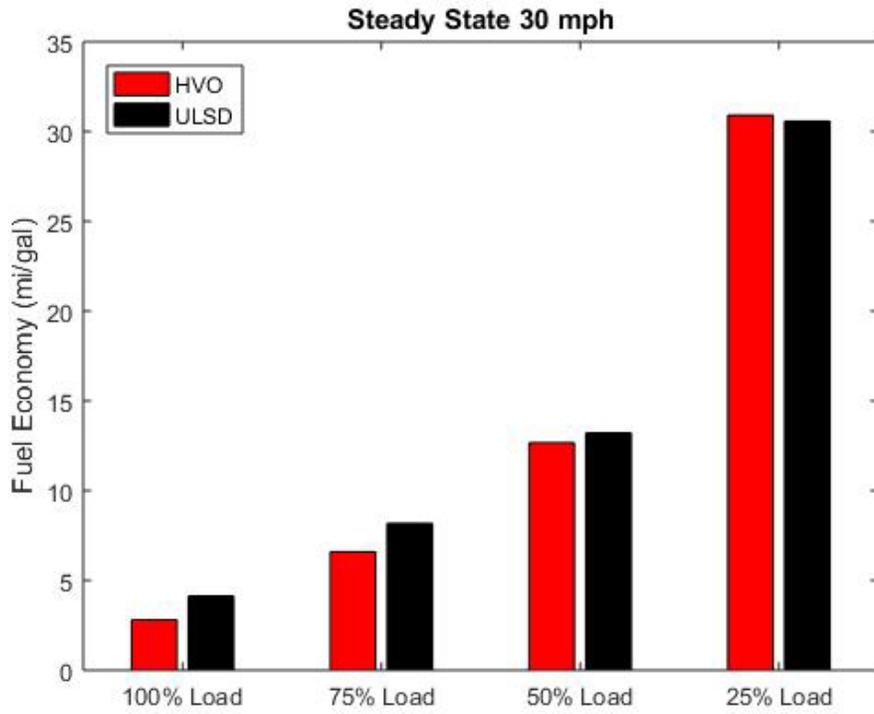
**B**

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

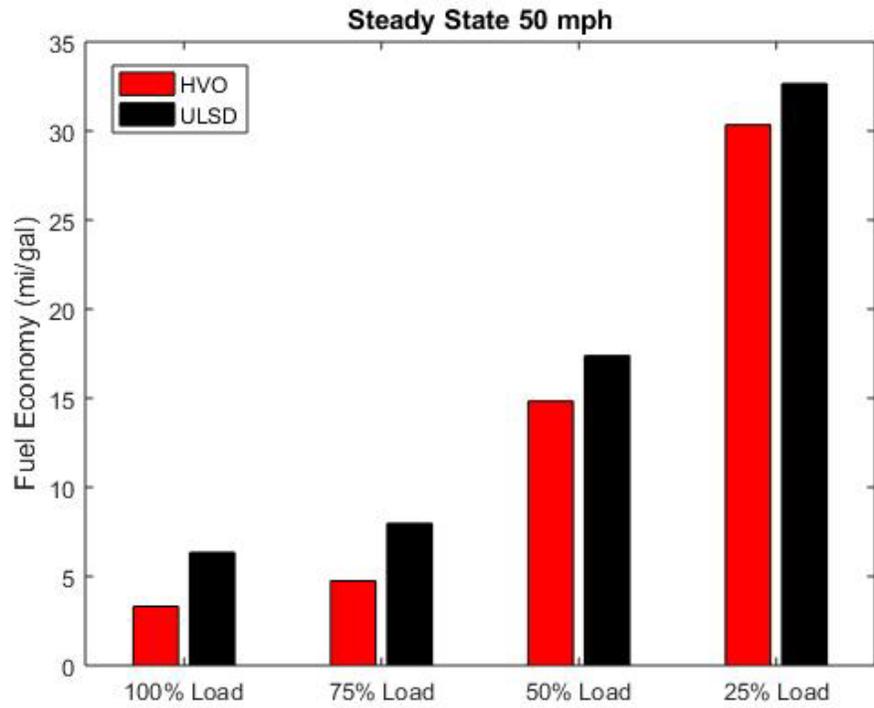
Figure 3-12(a-b) and Figure 3-13(a-b) show the engine-out CO<sub>2</sub> emissions and the carbon balance fuel economy, respectively, for the steady-state speeds of 30 mph and 50 mph over different engine loads. For the CO<sub>2</sub> emissions, at low and partial loads, the test fuels did not show any noticeable differences, however, at higher load test points (75% and 100%), a significant trend in increasing CO<sub>2</sub> 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<sub>2</sub> 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.



**Figure 3-12 (a-b):** CO<sub>2</sub> emissions over the steady-state 30 mph (A-top panel) and 50 mph (B-bottom panel) conditions



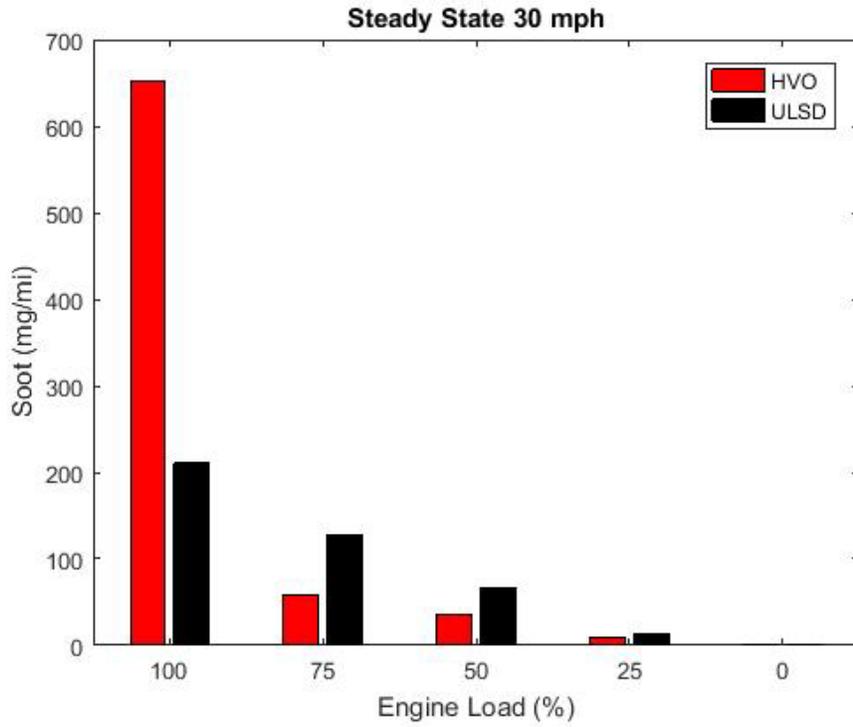
**A**



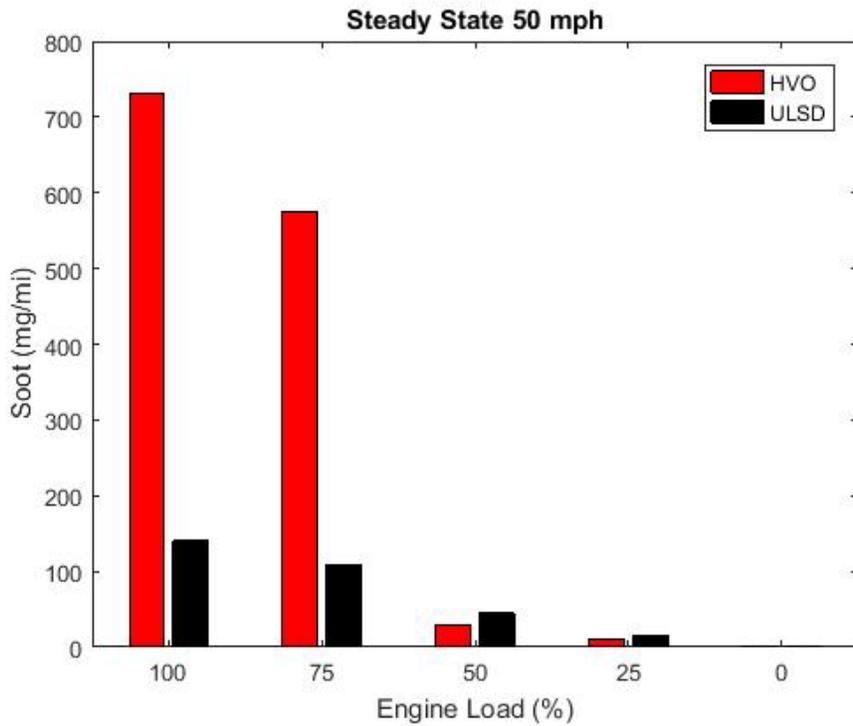
**B**

**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 and higher soot formation, outweighing the benefits of the characteristic of the HVO being aromatic-free compared to diesel fuel.



**A**



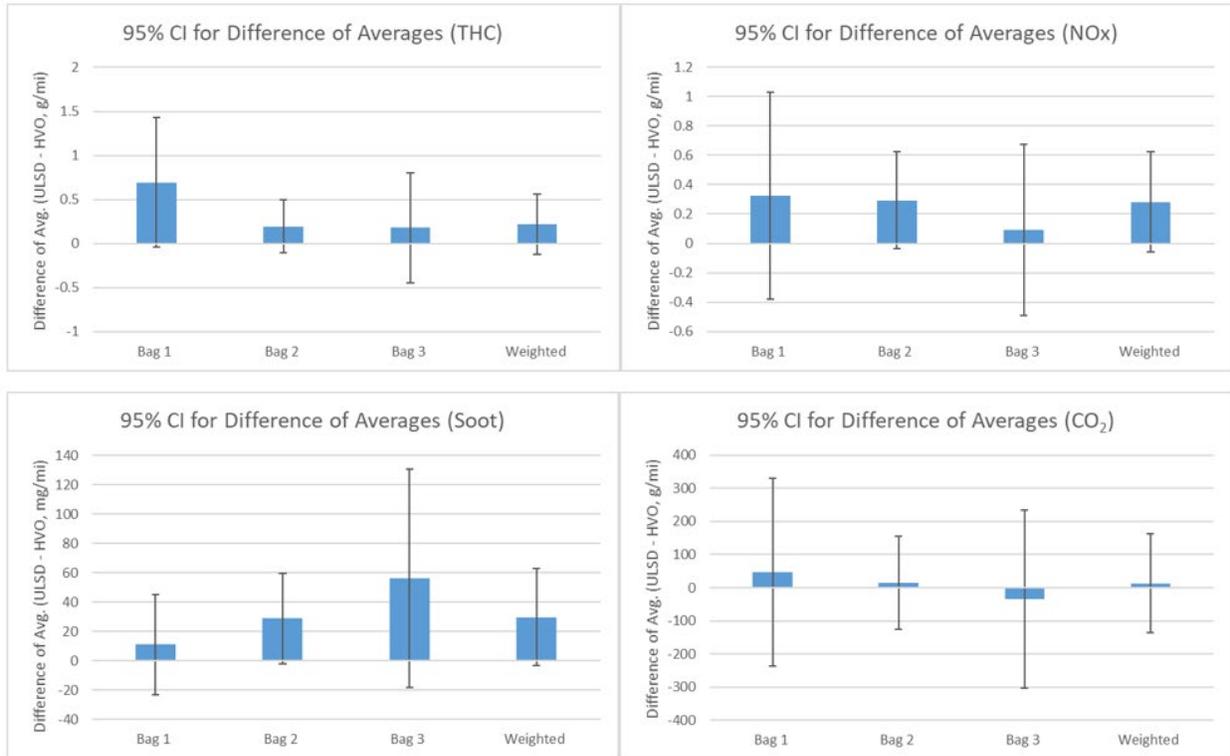
**B**

**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. Statistical Analysis

For this work, a difference of means approach was used to determine statistical significance in comparing ULSD and HVO results for all engine-out emissions values measured over the LA-92 test cycle. This approach allows one to quickly assess whether the difference between the means of two datasets is statistically significant (at the 95% CI level). While in most cases (i.e. emissions type and collection bag), ULSD emissions were higher than HVO, the results of this statistical analysis can be categorized into two parts: 1) differences that are not statistically significant; and 2) differences that are significant at the 95% CI level.

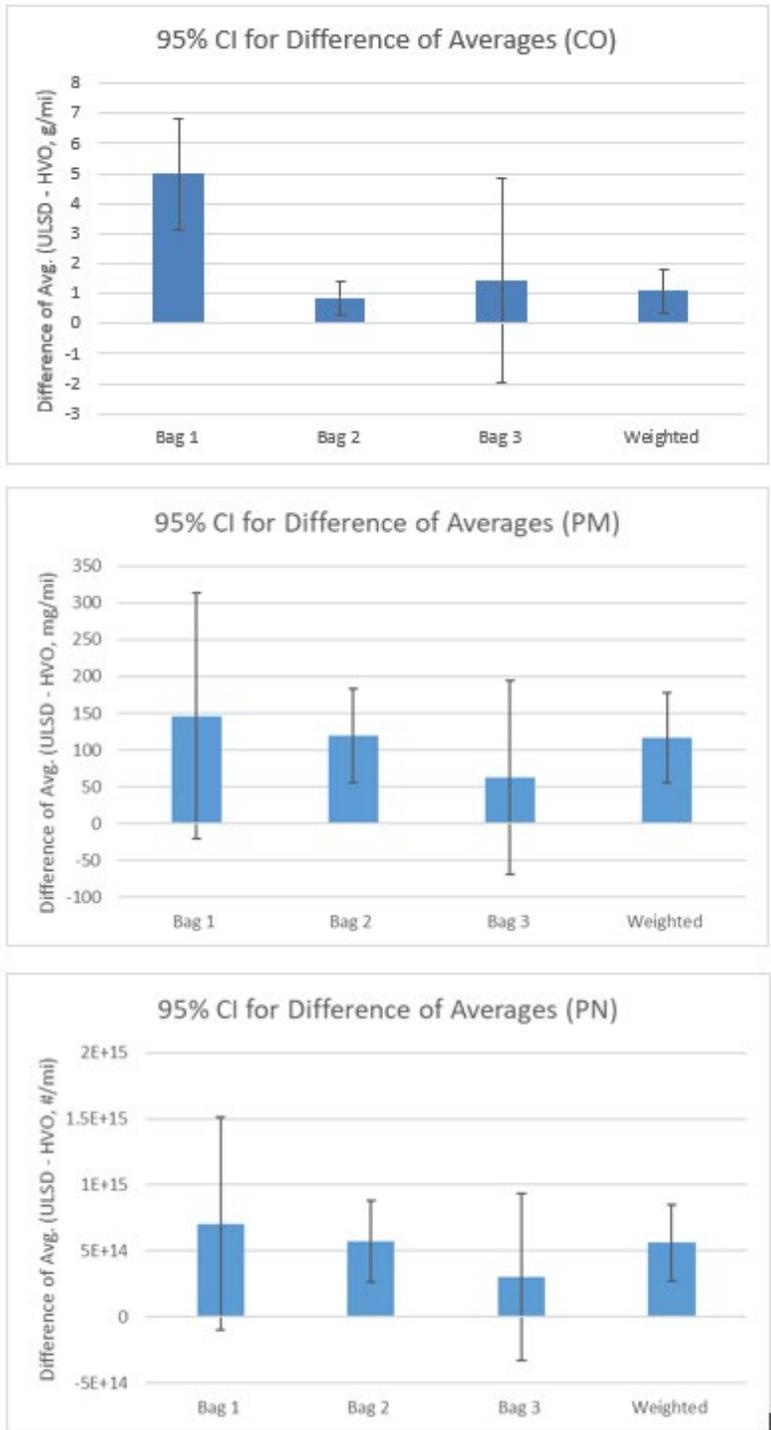
The charts displayed in Figure 4-1 show a couple pieces of key information for the cases where the difference of means are *not* statistically significant at the 95% CI level. First, for THC, NOx and soot average emissions, ULSD levels are higher than HVO across bags one through three (1-3), as well as weighted, or overall emissions. However, the variance across repeated tests was high, and one can observe how this results in upper and lower 95% confidence limits that bound zero. In other words, at the 95% CI level, the average difference between ULSD and HVO is not significant. CO<sub>2</sub> emissions trend slightly different with respect to average differences between ULSD and HVO (ULSD is higher on average than HVO, but lower in bag 3); however, the 95% CI bands again indicate that the differences between the two fuels are not significant.



**Figure 4-1:** No Statistical Significance between HVO and ULSD for Average Weighted Emissions of THC, NOx, Soot and CO<sub>2</sub><sup>3</sup>

Differences between ULSD and HVO that showed significance are shown in Figure 4-2. Similar to results in Figure 4-1, average emissions (CO, PM, and PN) for ULSD trend higher than HVO as indicated by *positive* mean difference values. Whether these mean differences, though, achieve significance at the 95% CI level is dependent on emissions bag and/or weighted value. For CO emissions, significance is observed for bags 1 and 2, as well as weighted values (that is, the 95% CI band does not cross zero). In contrast, significance in PM (and PN) emissions was observed for bag 2 and weighted values.

<sup>3</sup> A statistical significance test featuring difference of means, indicates no statistical significance between fuels (at the 95% CI level) for average weighted emissions of THC, NOx, soot, and CO<sub>2</sub>. This can quickly be observed by error bars that cross over zero indicating ULSD-HVO differences could be either positive or negative.



**Figure 4-2:** Statistical Significance between HVO and ULSD for Average Weighted Emissions of CO, PM and PN.<sup>4</sup>

<sup>4</sup> A difference of means statistical test at the 95% CI level indicates significance across all weighted values. However, significance for individual bags is variable: for CO, significance is observed for bags 1, 2 and weighted; and for PM (and PN), significance is observed in bag 2 and weighted.

## 5. 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.

Statistical analysis and qualitative assessment of the experimental results suggest the following conclusions:

- On the LA-92 test cycle:HVO resulted in statistically significant lower particulate matter and particulate number emissions compared to ULSD
- HVO resulted in statistically significant lower CO emissions compared to ULSD
- HVO trends lower in THC, NO<sub>x</sub> and soot emissions compared to ULSD
- There was no difference in CO<sub>2</sub> emissions with HVO compared to ULSD
- There was no difference in fuel economy with HVO compared to ULSD

Under steady state conditions at 30 mph and 50 mph at four different loads:

- HVO resulted in lower THC emissions at 30 mph and 50 mph for all loads
- HVO at 30 mph and 25% and 50% loads resulted in lower CO emissions.
- HVO at 30 mph and 75% and 100% loads increased CO emissions compared to ULSD

- HVO at 50 mph and 25%, 50% and 100% loads resulted in lower CO emissions, however, greater CO at 75% load compared to ULSD
- HVO at 30 mph and 50 mph and 25%, 50% and 75% loads resulted in the same NOx emissions, however, at 100% load had greater NOx emissions
- HVO at 30 mph and 50 mph had the same CO<sub>2</sub> emissions at 25% and 50% load, but greater CO<sub>2</sub> emissions at 75% and 100% loads
- HVO at 30 mph lowered soot mass at 25% through 75% loads, but substantially increased at 100% load
- HVO at 50 mph resulted in substantially greater soot mass at 75% load, but lower at all other loads

Overall, the emissions results from this project suggest that HVO could be adopted in modern technology direct injection diesel engines.

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## Appendix A

### LA-92 Testing Results

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

Test 1 Run 1 - ULSD							
	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/mi)	PM (mg/mi)	PN(N/mi)
Phase 1	1.87	11.84	1320.31	1.40	164.49	391.33	1.88E+15
Phase 2	0.76	3.38	804.69	1.77	113.52	355.10	1.70E+15
Phase 3	1.63	8.18	1238.60	1.43	222.79	430.20	2.06E+15
Weighted	0.88	4.15	861.27	1.73	123.62	362.11	1.74E+15

Test 1 Run 2 - ULSD							
	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/mi)	PM (mg/mi)	PN(N/mi)
Phase 1	2.21	11.88	1481.23	1.74	145.70	422.57	2.03E+15
Phase 2	0.89	3.48	900.52	2.05	100.99	363.04	1.74E+15
Phase 3	1.55	7.27	1146.30	1.59	153.31	380.21	1.83E+15
Weighted	1.00	4.17	947.38	2.00	106.88	367.30	1.76E+15

Test 2 Run 1 - ULSD							
Cycle 1	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/mi)	PM (mg/mi)	PN(N/mi)
Phase 1	1.33	12.40	1601.73	1.93	148.53	539.83	2.59E+15
Phase 2	0.55	3.65	968.46	2.06	80.92	394.09	1.89E+15
Phase 3	0.93	9.56	1461.17	1.28	139.04	389.42	1.87E+15
Weighted	0.61	4.51	1035.36	2.00	88.45	401.36	1.93E+15

Test 2 Run 2 - ULSD							
Cycle 2	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/mi)	PM (mg/mi)	PN(N/mi)
Phase 1	1.30	12.14	1699.30	2.40	132.59	607.57	2.92E+15
Phase 2	0.53	3.12	937.86	2.10	76.09	299.44	1.44E+15
Phase 3	1.05	9.29	1433.19	1.45	125.15	259.00	1.24E+15
Weighted	0.61	4.00	1010.52	2.07	82.31	312.58	1.50E+15

Test 1 Run 1 - HVO							
Cycle 1	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/r)	PM (mg/m)	PN(N/mi)
Phase 1	1.16	7.87	1460.01	1.38	136.93	370.56	1.78E+15
Phase 2	0.55	2.52	855.49	1.57	57.07	241.59	1.16E+15
Phase 3	1.30	8.00	1389.97	1.17	100.21	340.76	1.64E+15
Weighted	0.64	3.17	923.29	1.54	64.15	255.04	1.22E+15

Test 1 Run 2 - HVO							
Cycle 2	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/r)	PM (mg/m)	PN(N/mi)
Phase 1	0.84	5.77	1390.49	1.46	113.21	302.43	1.45E+15
Phase 2	0.52	2.33	831.97	1.59	57.64	236.47	1.14E+15
Phase 3	0.91	6.85	1261.05	1.13	88.43	297.58	1.43E+15
Weighted	0.56	2.82	891.06	1.55	62.69	244.18	1.17E+15

Test 2 Run 1 - HVO							
Cycle 1	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/r)	PM (mg/m)	PN(N/mi)
Phase 1	0.96	8.21	1514.63	1.60	152.17	362.02	1.74E+15
Phase 2	0.51	2.96	944.36	1.78	74.14	234.75	1.13E+15
Phase 3	1.20	9.05	1433.98	1.22	128.64	317.78	1.53E+15
Weighted	0.58	3.67	1008.80	1.73	82.09	247.31	1.19E+15
Test 2 Run 2 - HVO							
Cycle 2	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/r)	PM (mg/m)	PN(N/mi)
Phase 1	0.96	6.52	1554.07	1.74	144.79	340.53	1.63E+15
Phase 2	0.37	2.42	917.38	1.86	67.36	220.80	1.06E+15
Phase 3	1.02	4.69	1332.54	1.86	97.32	252.23	1.21E+15
Weighted	0.44	2.79	979.02	1.86	73.44	229.17	1.10E+15

ULSD All 4 Tests							
ULSD	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/mi)	PM (mg/mi)	PN(N/mi)
Bag 1	1.68	12.07	1525.64	1.87	147.83	490.32	2.35E+15
Bag 2	0.68	3.41	902.88	2.00	92.88	352.92	1.69E+15
Bag 3	1.29	8.58	1319.81	1.44	160.07	364.71	1.75E+15
Weighted	0.78	4.21	963.64	1.95	100.31	360.84	1.73E+15
Bag 1 min	1.30	11.84	1320.31	1.40	132.59	391.33	1.88E+15
Bag 1 max	2.21	12.40	1699.30	2.40	164.49	607.57	2.92E+15
Bag 1 STD	0.38	0.22	141.49	0.36	11.35	87.45	4.20E+14
Bag 2 min	0.53	3.12	804.69	1.77	76.09	299.44	1.44E+15
Bag 2 max	0.89	3.65	968.46	2.10	113.52	394.09	1.89E+15
Bag 2 STD	0.15	0.19	61.59	0.13	15.14	34.14	1.64E+14
Bag 3 min	0.93	7.27	1146.30	1.28	125.15	259.00	1.24E+15
Bag 3 max	1.63	9.56	1461.17	1.59	222.79	430.20	2.06E+15
Bag 3 STD	0.31	0.92	131.85	0.11	37.55	63.87	3.07E+14
Weighted min	0.61	4.00	861.27	1.73	82.31	312.58	1.50E+15
Weighted max	1.00	4.51	1035.36	2.07	123.62	401.36	1.93E+15
Weighted STD	0.17	0.19	67.24	0.13	16.21	31.68	1.5E+14

HVO All 4 Tests							
HVO	THC(g/mi)	CO(g/mi)	CO2(g/mi)	Nox(g/mi)	Soot (mg/r)	PM (mg/m)	PN(N/mi)
Bag 1	0.98	7.09	1479.80	1.54	136.77	343.89	1.65E+15
Bag 2	0.49	2.56	887.30	1.70	64.05	233.40	1.12E+15
Bag 3	1.11	7.15	1354.38	1.34	103.65	302.09	1.45E+15
Weighted	0.56	3.11	950.54	1.67	70.59	243.92	1.17E+15
Bag 1 min	0.84	5.77	1390.49	1.38	113.21	302.43	1.45E+15
Bag 1 max	1.16	8.21	1554.07	1.74	152.17	370.56	1.78E+15
Bag 1 STD	0.11	0.99	61.43	0.14	14.63	26.32	1.26E+14
Bag 2 min	0.37	2.33	831.97	1.57	57.07	220.80	1.06E+15
Bag 2 max	0.55	2.96	944.36	1.86	74.14	241.59	1.16E+15
Bag 2 STD	0.07	0.24	45.37	0.12	7.12	7.70	3.70E+13
Bag 3 min	0.91	4.69	1261.05	1.13	88.43	252.23	1.21E+15
Bag 3 max	1.30	9.05	1433.98	1.86	128.64	340.76	1.64E+15
Bag 3 STD	0.15	1.62	64.79	0.30	15.07	32.59	1.56E+14
Weighted min	0.44	2.79	891.06	1.54	62.69	229.17	1.10E+15
Weighted max	0.64	3.67	1008.80	1.86	82.09	255.04	1.22E+15
Weighted STD	0.07	0.35	46.06	0.13	7.81	9.39	4.51E+13

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

Fuel	THC (g/mi)			
	HVO		ULSD	
	Test 1	Test 2	Test 1	Test 2
Phase				
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 <sub>2</sub> (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	Test 1	Test 2	Test 1	Test 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 <sub>2</sub> (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	-	0.25	0.06	13.85
25% load	-	20.06	51.9	39.37
50% load	-	62.68	183.01	160.1
75% load	-	-	603.54	530.44
100% load	-	-	526.3	546
	PN (#/mi)			
0% load	-	1.21E+12	2.66E+11	6.65E+13
25% load	-	9.63E+13	2.49E+14	1.89E+14
50% load	-	3.01E+14	8.78E+14	7.68E+14
75% load	-	-	2.90E+15	2.55E+15
100% load	-	-	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 ± 0.25		6.65 ± 0.61	
Hot Running	10.37 ± 0.53		11.31 ± 0.80	
Hot Start	6.55 ± 0.27		7.39 ± 1.09	
Weighted	9.15 ± 0.42		9.98 ± 0.74	

