

Emissions and Fuel Economy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends

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ABSTRACT

Gaseous and particulate matter (PM) emissions were assessed from two current technology heavy-duty vehicles operated on CARB ultra-low sulfur diesel (ULSD), hydrotreated vegetable oil (HVO) blends, and a biodiesel blend. Testing was performed on a 2014 model year Cummins ISX15 vehicle and on a 2010 model year Cummins ISB6.7 vehicle. Both vehicles were equipped with diesel oxidation catalysts (DOC), diesel particulate filter (DPF), and selective catalytic reduction (SCR) systems. Testing was conducted over the Heavy-Duty Urban Dynamometer Driving Schedule (UDDS) and Heavy Heavy-Duty Diesel Truck (HHDDT) Transient Cycle. The results showed lower total hydrocarbons (THC), non-methane hydrocarbons (NMHC), and methane (CH_4) emissions for the HVO fuels and the biodiesel blend compared to CARB ULSD. Overall, nitrogen oxide (NO_x) emissions showed discordant results, with both increases and decreases for the HVO fuels. NO_x emissions with the biodiesel blend for both vehicles were higher compared to the HVO fuels and CARB ULSD. Carbon dioxide (CO_2) emissions were generally lower for the HVO fuels relative to CARB ULSD, but not for the biodiesel blend. Fuel economy showed some significant reductions for the HVO fuels and the biodiesel blend over both test cycles for one of the vehicles, but not for the other. PM mass emissions were higher for the biofuels, while particle number emissions were lower. Results of the particle size distribution for the ISX-15 vehicle revealed bimodal size distribution profiles for most cases, with a nucleation mode centered from 9 to 11 nm size range and an accumulation mode peaking at around 125 nm.

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INTRODUCTION

Energy is considered to be one of the main backbones of any economy. Concerns about the limited availability of fossil fuels and the global climate change have led to mandates worldwide to increase use of sustainable fuels. Currently, fatty acid methyl esters (FAMES), commonly known as biodiesel, derived from vegetable oils, waste cooking oils, and animal fats appear to be the biofuel of choice in both the United States (US) and Europe for petroleum diesel fuel displacement. Biodiesel is produced via the transesterification reaction, which is the process that takes one mole of a triglyceride molecule (an ester) and reacts it with three moles of an alcohol (usually methanol) to form three moles of monoesters (biodiesel) and one mole of glycerol [1]. This reversible reaction, which is either acid- or alkaline-catalyzed, involves stepwise conversions of triglycerides to diglycerides to monoglycerides to glycerol producing

three moles of ester in the process [2]. Biodiesel is free of sulfur and aromatic compounds and offers better lubrication properties than petroleum diesel [3]. However, unsaturated biodiesel fuels are known to adversely affect oxidation stability and storage stability [4].

More recently, hydrotreated vegetable oils (HVO) produced from vegetable oils, waste cooking oils or animal fats have also been gaining increased attention [5-6]. Although HVO is produced from the same feedstocks as FAME, the feedstock source has little or no effect to the quality or properties of HVO fuels. In the HVO production process, hydrogen is used to remove the oxygen from the triglyceride in the presence of a catalyst under standard temperature conditions of 350-400 °C. The reaction produced involves hydrogenolysis of C-C bonds of triglycerides, which leads to a mixture of lower molecular weight alkanes by three different routes: decarbonylation,

decarboxylation, and hydrodesoxygenation. HVOs are mixture of paraffinic hydrocarbons and are essentially free of sulfur and polycyclic aromatic hydrocarbons. The increased amounts of paraffinic hydrocarbons in HVO fuel lead to a significantly higher cetane number than conventional diesel fuel [6, 7, 8].

In the US, renewable fuels have been promoted by several legislative measures, including the Energy Independence and Security Act (EISA 2007) and the Renewable Fuel Standard (RFS), which was initiated in 2005 and expanded in 2007 [9-10]. With the recently released proposed rule by the US EPA for the 2014 to 2017 RFS volume requirements, there is a significant growth for both biodiesel and renewable diesel (i.e., HVO) volumes ranging from 1.63 to 1.90 billion gallons per year [11].

There are a myriad of studies available in the open literature reporting the effects of pure and blended biodiesel fuels on the gaseous and particulate emissions from light-duty and heavy-duty engines/vehicles [12, 13, 14]. While there is some lack of information about the impact of biodiesel on the emissions from vehicles equipped with selective catalytic reduction (SCR) and diesel particulate filters (DPFs) and meeting the 2010 and 2007 US Environmental Protection Agency (USEPA) standards for nitrogen oxides (NO_x) and particulate matter (PM) emissions, respectively, most studies have found reductions in total hydrocarbons (THC), carbon monoxide (CO), and PM emissions with biodiesel application, while a NO_x increase is usually acknowledged [15, 16, 17]. For example, Hajbabaie et al. [18] reported systematic increases in NO_x emissions when tested soy-based and waste cooking oil-based biodiesel blends at 20 volume % and 5 volume % with CARB ultra-low sulfur diesel (ULSD) in a heavy-duty diesel engine. They also reported NO_x reductions with the more saturated animal fat-based biodiesel blends compared to CARB ULSD. In a different study, Hajbabaie and coworkers [19] confirmed the association of biodiesel source material and NO_x emissions, showing that unsaturated soy-based blends produced higher NO_x than the more saturated animal fat-based biodiesel blends. Kawano et al. [20] showed higher NO_x and lower THC, CO, and PM emissions with biodiesel blends when tested in heavy-duty vehicles equipped with DPF and SCR controls, consistent with the results seen for the engines without aftertreatment.

HVO has been largely studied in the past years as an automotive fuel, mostly in light-duty and heavy-duty engines/vehicles [21, 22, 23]. There is limited information available about the emission impacts of either pure or blended HVO on current technology heavy-duty vehicles equipped with more robust aftertreatment systems. For example, Hajbabaie et al. [19] tested HVO blends and pure HVO on a 2006 model year Cummins ISM engine fitted with a DPF and found significant reductions on NO_x emissions compared to diesel fuel. Several studies have shown that HVO generally reduces THC, CO, and PM emissions, with also small NO_x benefits compared to petroleum diesel fuel [24-25]. Pellegrini et al. [26] tested a single

cylinder Euro 5-compliant diesel engine and found lower THC and CO emissions and a negligible effect on NO_x emissions for the HVO fuels. On the other hand, other studies have found that high HVO blends, up to 50 volume %, showed higher NO_x emissions than diesel fuel [27]. Similar results were also found by Kousoulidou et al. [28] when they tested neat HVO on a Euro 5 common-rail diesel engine over the New European Driving Cycle (NEDC). Higher NO_x emissions were also seen for HVO blends and pure HVO relative to CARB diesel over the heavy heavy-duty diesel truck (HHDDT) Cruise cycle, but not over the Urban Dynamometer Driving Schedule (UDDS) when tested on a 2000 Caterpillar truck with no exhaust aftertreatment [29]. Gotz et al. [30] and Westphal et al. [31] tested neat HVO in heavy-duty engines and showed reductions in PM, CO, THC, and NO_x emissions compared to diesel fuels. Lehto et al. [32] also observed a reduction in NO_x and PM emissions with HVO compared to diesel fuel when used in a single cylinder engine equipped with exhaust gas recirculation (EGR). Large reductions in CO, THC, PM, and NO_x emissions were also seen in a study conducted by Kuronen et al. [33] on two heavy-duty engines and two city buses with HVO.

The aim of this study is to assess the potential emissions and fuel economy impacts of the use of high concentration HVO blends and neat HVO in current technology heavy-duty vehicles. Recently, the commercialization of HVO fuels is gaining increased attention in the US and especially in California for partially replacing petroleum diesel and for providing emissions benefits. For this study, emissions and fuel economy measurements with HVO blends are compared to a typical on-road CARB ULSD fuel and a biodiesel blend of 20 % by volume. Testing was conducted on two heavy-duty vehicles over the Heavy-Duty Urban Dynamometer Driving Schedule (UDDS) and Heavy Heavy-Duty Diesel Truck (HHDDT) Transient Cycle.

EXPERIMENTAL

Test Fuels

A total of five fuels were used in this study, including a CARB ULSD and four biofuel blends. The CARB ULSD was used as the reference fuel. The HVO was used to prepare blends of 20 vol% (HVO20) and 50 vol% (HVO50) with CARB ULSD. The HVO was also tested neat (HVO100) for this study. In addition, FAME produced from waste cooking oil was used to prepare a blend of 20 vol% (WCO20) with CARB ULSD. The main physicochemical properties of the test fuels are shown in Table A1 (Appendix A). The CARB ULSD, neat HVO, and HVO blends were tested for ASTM D975 properties, while the CARB ULSD blend with waste cooking oil based biodiesel was tested for fuel properties under the ASTM D7467.

Test Vehicles

Two vehicles were utilized for the testing in this program. The vehicles were selected to represent different vehicle types. The first vehicle was equipped with a 2014 model year Cummins ISX15 400ST diesel

engine, with diesel oxidation catalyst (DOC), DPF, and SCR aftertreatment controls. The second vehicle was equipped with a 2010 model year Cummins ISB6.7 220 diesel engine, with DOC, DPF, and SCR emission controls. A description of the engines in the test vehicles is provided in Table 1.

Table 1. Technical specifications of the test vehicles.

	Cummins ISX15 400ST	Cummins ISB6.7 220
Model year	2014	2010
Displacement (L)	14.9	6.7
Rated horsepower (hp)	400	220
Peak Torque (lb-ft)	1450/1650 at 1000 rpm	520 at 1600 rpm
Cylinders	6	6
Engine family	ECEXH0912XAT	ACEXH0408BAH
Mileage	65544	99194
Test weight	65,000 lbs.	20,800 lbs.
Aftertreatment	DOC, DPF, SCR-u, EGR	DOC, DPF, SCR-u, EGR
Chassis Make	Navistar Prostar+	Freightliner

Driving Cycles and Test Matrix

Each vehicle/fuel combination was exercised in triplicate using the EPA Urban Dynamometer Driving Schedule (UDDS) and the California Air Resources Board Heavy Heavy-Duty Diesel Truck (HHDDT) Transient Cycles. The Federal heavy-duty vehicle UDDS is a cycle commonly used to collect emissions data on engines already in heavy heavy-duty diesel trucks. The cycle has a duration of 1060 seconds and covers a distance of 5.55 miles with an average speed of 18.8 miles/hour and a maximum speed of 58 miles/hour. The HHDDT schedule consists of four speed-time modes, including idle, creep, transient, and (high speed) cruise. For this study, only the HHDDT Transient cycle was used. The HHDDT Transient cycle has duration of 668 seconds and covers a distance of 2.75 miles with an average speed of 15 miles/hour and a maximum speed of 47.50 miles/hour. The speed-time profiles for the UDDS and HHDDT Transient cycles are shown in Figure 1 and Figure 2, respectively.

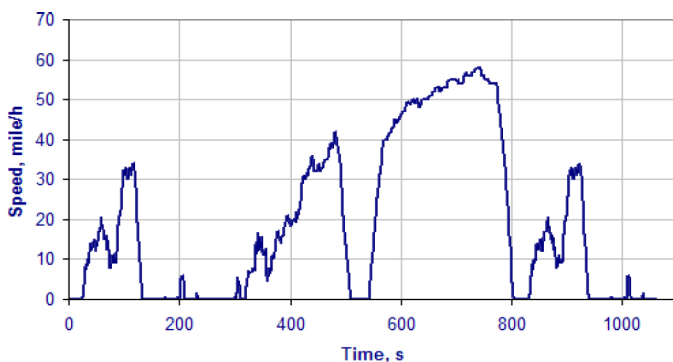


Figure 1. Speed-time profile of the EPA UDDS

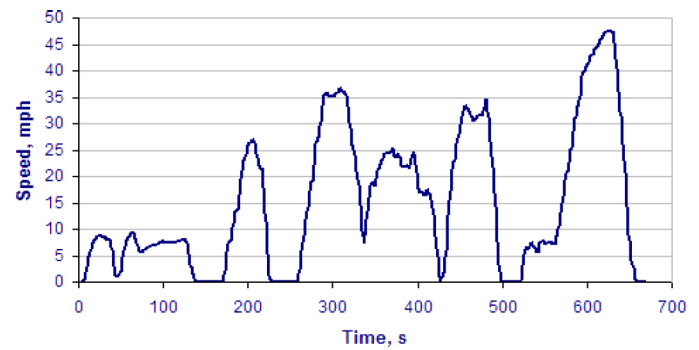


Figure 2. Speed-time profile of the HHDDT Transient cycle

The preconditioning for the UDDS test cycle included one iteration of the UDDS cycle and the preconditioning for the HHDDT transient cycle included 5 minutes of driving at 50 miles/hour. In addition to the preconditioning before each test, the vehicle was also warmed up approximately 30 minutes at the beginning of each test day to ensure that the vehicle would not be in cold-start mode prior to any of the test sequences. The preconditioning cycles would warm up both the vehicle and dynamometer to the testing conditions, thus reducing emissions variability between tests. It should be noted that a special preconditioning was not done for the aftertreatment systems.

Emissions Measurements

All tests were conducted at University of California, Riverside (UCR's) Heavy-Duty Chassis Dynamometer facility. Emissions measurements were obtained using the CE-CERT Mobile Emissions Laboratory (MEL). The facility and sampling setup have been described in detail previously and are only discussed briefly here [34]. For all tests, standard emissions measurements of THC, non-methane hydrocarbons (NMHC), methane (CH_4), CO , NO_x , carbon dioxide (CO_2), and PM, were measured. CO and CO_2 emissions were measured with a 602P nondispersive infrared (NDIR) analyzer from California Analytical Instruments (CAI). THC, NMHC, and CH_4 emissions were measured with a 600HFID flame ionization detector (FID) from CAI. NO_x emissions were measured with a 600HPLC chemiluminescence analyzer from CAI. Measurements of ammonia (NH_3) were also obtained on a real-time basis using a Unisearch Associates Inc. LasIR S Series tunable diode laser (TDL) near infrared absorption spectrometer.

The mass concentrations of PM were obtained by analysis of particulates collected on 47 mm diameter 2 μm pore Teflo filters (Whatman brand). The filters were measured for net gains using a UM2 ultra precision microbalance with buoyancy correction following the weighing procedure guidelines of the Code of Federal Regulations (CFR). Total particle number was measured using a TSI 3776 ultrafine-Condensation Particle Counter (CPC) with a 2.5 nm cut point. The instrument operated at a flowrate of 1.5 L/min. Solid particle number counts were measured with the use of a catalytic stripper. The catalytic stripper both vaporizes volatile species and

oxidizes them, and hence more efficiently removes volatiles from the sample than thermal treatment alone. For this study, the catalytic stripper used was 40 mm long with a diameter of 17 mm and was based on a cordierite monolith with a 400 cpsi cell density and a 6 mil substrate thickness. It had both oxidation and sulfur storage capability, but its exact chemical composition was unknown. This particular unit was characterized according to the protocol outlined by Amanatidis et al. [35] and was deemed appropriate for the measurements of this study. Particles were counted downstream of the catalytic stripper with a TSI 3776 ultrafine CPC at a flow rate of 1.5 L/min. Real-time particle size distributions were also obtained using an Engine Exhaust Particle Sizer (EEPS) spectrometer. The EEPS (TSI 3090, firmware version 8.0.0) was used to obtain real-time second-by-second size distributions between 5.6 to 560 nm. Particles were sampled at a flow rate of 10 L/min by the EEPS, which is considered to be high enough to minimize diffusional losses. They were then charged with a corona charger and sized based on their electrical mobility in an electrical field. Concentrations were determined through the use of multiple electrometers.

RESULTS AND DISCUSSION

The following section present the results for each vehicle/fuel/cycle combination based on the average of tests conducted on that particular test combination. The error bars on the figures are the standard deviation over all tests for test combination. The statistical analyses were conducted using a 2-tailed, 2 sample equal variance *t*-test. For the statistical analyses, results are considered to be statistically significant for $p \leq 0.05$, or marginally statistically significant for $0.05 < p \leq 0.1$.

THC, NMHC, and CH₄ Emissions

THC emissions are shown in Table 1 for both vehicles over the UDSS and HHDDT transient cycles. For the Cummins ISX-15 vehicle, the results showed a statistically significant reduction in THC emissions of 49% for HVO50 compared to CARB ULSD over the UDSS cycle, while the HVO20 and HVO100 did not show any trends in THC emissions. The WCO20 blend, on the other hand, showed a statistically significant increase in THC emissions of 40.5% compared to CARB ULSD over the UDSS cycle. For the HHDDT cycle, THC emissions were lower at a statistically significant level by 74.3% and 62%, respectively, for HVO50 and HVO100 compared to CARB ULSD. The results for THC emissions for the Cummins ISB6.7 vehicle over the UDSS and HHDDT cycles appeared to be below the detection limits of the instrument for all test fuels, suggesting that the DOC system was effective in oxidizing the unburned hydrocarbon components. Overall, the lower THC emissions from HVO were expected due to the higher cetane number of HVO and the absence of aromatic compounds [4]. Previous studies have shown that HVO fuels generally reduce THC emissions due to their improved ignition related properties and better evaporation behavior [23, 24, 25, 36].

For the Cummins ISX-15 vehicle, for the UDSS cycle, NMHC emissions showed a statistically significant decrease of 84.9% for HVO50 and a statistically significant increase of 83.8% for WCO20 compared to CARB ULSD, as shown in Table 1. For the

HHDDT cycle, both HVO50 and HVO100 showed statistically significant decreases in NMHC emissions of 85% and 87.6%, respectively, compared to CARB ULSD. For the Cummins ISB6.7 vehicle, NMHC emissions for all tests were negligible over both test cycles.

For the Cummins ISX-15 vehicle, CH₄ emissions did not show significant fuel effects, with the exception of WCO20 blend over the UDSS cycle (Table 1). For the WCO20 blend, CH₄ emissions showed a marginally statistically significant increase of 9.3% compared to CARB ULSD. For the HHDDT cycle, the HVO50 and HVO100 showed statistically significant decreases in CH₄ emissions of 62.5% and 33.8%, respectively, compared to CARB ULSD. For the Cummins ISB6.7 vehicle, emissions of CH₄ were generally found at very low levels for both test cycles. Although there were some statistically significant differences between fuels for CH₄, these differences did not show consistent fuel trends between cycles or different blend levels. For the UDSS cycle, CH₄ emissions showed a statistically significant increase of 104% for HVO20 compared to CARB ULSD, while for the HHDDT cycle CH₄ emissions showed statistically significant reductions of 40% and 20%, respectively for HVO100 and WCO20 compared to CARB ULSD.

Table 1. THC, NMHC, and CH₄ emissions, expressed in g/mile, for the Cummins ISX-15 and Cummins ISB6.7 vehicles over the UDSS and HHDDT transient cycles.

		Cummins ISX-15					
Fuel	Cycle	THC (g/mi)		NMHC (g/mi)		CH ₄ (g/mi)	
		Ave	Stdev	Ave	Stdev	Ave	Stdev
CARB	UDSS	0.0235	0.0027	0.0099	0.0025	0.0159	0.0005
	HHDDT Transient	0.0534	0.0181	0.0283	0.0145	0.0295	0.0046
HVO20	UDSS	0.0250	0.0033	0.0121	0.0018	0.0150	0.0019
	HHDDT Transient	0.0505	0.0096	0.0270	0.0065	0.0276	0.0036
HVO50	UDSS	0.0120	0.0058	0.0015	0.0005	0.0122	0.0065
	HHDDT Transient	0.0137	0.0039	0.0043	0.0015	0.0110	0.0057
HVO100	UDSS	0.0334	0.0121	0.0141	0.0061	0.0225	0.0072
	HHDDT Transient	0.0203	0.0035	0.0035	0.0028	0.0195	0.0008
WCO20	UDSS	0.0329	0.0013	0.0182	0.0022	0.0173	0.0010
	HHDDT Transient	0.0607	0.0045	0.0395	0.0055	0.0250	0.0011
		Cummins ISB6.7					
CARB	UDSS	-0.008	0.001	-0.019	0.002	0.012	0.001
	HHDDT Transient	-0.011	0.003	-0.028	0.002	0.019	0.001
HVO20	UDSS	-0.005	0.002	-0.025	0.001	0.024	0.002
	HHDDT Transient	-0.012	0.005	-0.030	0.006	0.020	0.001
HVO50	UDSS	-0.028	0.003	-0.037	0.002	0.010	0.002
	HHDDT Transient	-0.062	0.005	-0.080	0.004	0.020	0.001
HVO100	UDSS	-0.071	0.001	-0.080	0.001	0.010	0.002
	HHDDT Transient	-0.054	0.006	-0.064	0.004	0.011	0.003
WCO20	UDSS	-0.012	0.005	-0.021	0.003	0.010	0.002
	HHDDT Transient	-0.007	0.004	-0.020	0.004	0.015	0.000

CO Emissions

Emissions of CO are shown in Table 2. For the Cummins ISX-15 vehicle, CO emissions were generally lower for HVO50 and neat HVO, but higher for the lower concentration blends of HVO20 and WCO20 relative to CARB ULSD over the UDSS test cycle. CO emissions showed statistically significant increases for HVO20 and WCO20 of 83.7% and 88.5%, respectively, compared to CARB ULSD, whereas CO emissions for HVO50 showed a statistically significant reduction of 97.6% compared to CARB ULSD. For the HHDDT cycle, for the Cummins ISX-15 vehicle, emissions of CO

were lower for all biofuel blends and the neat HVO fuel compared to the reference CARB ULSD. Compared to CARB ULSD, CO emissions showed statistically significant reductions of 81.8%, 115.5%, 42.2%, and 79.1%, respectively, for HVO20, HVO50, HVO100, and WCO20.

For the Cummins ISB6.7 vehicle, CO emissions were found at very low concentrations, with most fuels being below the detection limits of the instrument during HHDDT operation. While some statistically significant fuel differences in CO emissions were seen, no real fuel effects were observed. For the UDDS cycle, CO emissions showed a statistically significant increase of 163% for HVO20 and a marginally statistically significant decrease of 28% for WCO20 compared to CARB ULSD. For the HHDDT cycle, most fuels showed negative CO values, with the exception of the HVO100 and WCO20 blends.

Similar to the general trend observed in this study, previous studies have also reported reductions in CO emissions with the use of HVO fuels and biodiesel blends [23, 24, 25, 28–29, 36]. The absence of aromatics and the better ignition quality of HVO were possible contributing factors for the reductions in CO emissions. The lower CO emissions with the biodiesel blend can be attributed to both the higher oxygen content in the methyl ester molecule, as well as a lower carbon/hydrogen ratio in biodiesel compared to petroleum diesel [37]. Higher oxygen content will lead to more complete combustion, and therefore lower CO emissions.

Table 2. CO emissions, expressed in g/mile, for the Cummins ISX-15 and Cummins ISB6.7 vehicles over the UDDS and HHDDT transient cycles.

Cummins ISX-15			
Fuel	Cycle	CO (g/mi)	
		Ave	Stdev
CARB	UDDS	0.1331	0.0399
	HHDDT Tansient	0.4026	0.0402
HVO20	UDDS	0.2444	0.0245
	HHDDT Tansient	0.0732	0.0204
HVO50	UDDS	0.0031	0.0425
	HHDDT Tansient	-0.0625	0.0418
HVO100	UDDS	0.0805	0.0327
	HHDDT Tansient	0.2325	0.0213
WCO20	UDDS	0.2509	0.0311
	HHDDT Tansient	0.0840	0.0114
Cummins ISB6.7			
CARB	UDDS	0.098	0.018
	HHDDT Tansient	-0.127	0.020
HVO20	UDDS	0.259	0.015
	HHDDT Tansient	-0.028	0.049
HVO50	UDDS	-0.005	0.015
	HHDDT Tansient	-0.012	0.064
HVO100	UDDS	0.086	0.026
	HHDDT Tansient	0.164	0.031
WCO20	UDDS	0.071	0.008
	HHDDT Tansient	0.008	0.039

NO_x Emissions

Emissions of NO_x, as a function of fuel type, are presented in Figure 3 for the Cummins ISX-15 vehicle and Figure 4 for the Cummins ISB6.7 vehicle. For the Cummins ISX-15 vehicle, the application of biofuels resulted in higher NO_x emissions compared to CARB ULSD over the UDDS cycle. NO_x emissions showed a statistically significant and a marginally statistically significant increase of 24% and 20.8%, respectively, for HVO50 and HVO100 compared to CARB ULSD. In addition, the biodiesel blend showed a statistically significant increase of 54.6% compared to CARB ULSD. For the HHDDT cycle, NO_x emissions for HVO50 and HVO100 trended lower compared to CARB ULSD, but not at a statistically significant level. As expected, the biodiesel blend showed a statistically significant increase in NO_x emissions of 49.4% compared to CARB ULSD. It should be also noted that for both the UDDS and HHDDT test cycles, the biodiesel blend showed NO_x emissions that were higher at a statistically significant level compared to HVO20, HVO50, and HVO100.

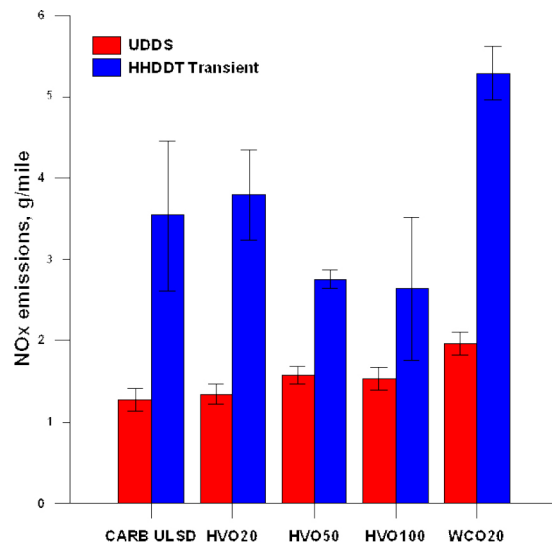


Figure 3. NO_x emissions for the Cummins ISX-15 over the UDDS and HHDDT cycles.

In contrast to the NO_x profile observed for the Cummins ISX-15 vehicle, emissions of NO_x followed a declining trend for the HVO blends relative to CARB ULSD for the Cummins ISB6.7 vehicle over the UDDS cycle. However, consistent with the ISX-15 engine, the WCO20 blend also showed a NO_x increase relative to CARB ULSD. NO_x emissions showed a statistically significant reduction of 13% and a marginally statistically significant reduction of 9% for HVO50 and HVO100, respectively, compared to CARB ULSD. On the contrary, WCO20 showed a statistically significant increase in NO_x emissions of 20% compared to CARB ULSD. For the HHDDT cycle, the variability in the NO_x emission measurements was relatively large and did not show any strong fuel effects. The relatively large measurement variability appears to be associated with changes in the engine operation over the three consecutive HHDDT tests for all of the fuels. In addition,