Final Report

Evaluation of the Performance and Air Pollutant Emissions of Vehicles Operating on Various Natural Gas Blends – Heavy-Duty Vehicle Testing

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Acronyms and Abbreviations

ARB ....Air Resources Board
bhp ………………………………… brake horse power
bhp-hr ……………………………… brake horse power - hour
CAI..California Analytical Instruments
CARB..California Air Resources Board
CE-CERT..College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CEC...California Energy Commission
CBD ....Central Business District
CFR...Code of Federal Regulations
CH_4…………………………………Methane
CNG ....compressed natural gas
CO ....carbon monoxide
COV ....coefficient of variation
CO_2...carbon dioxide
CPC ....condensation particle counter
CVS...constant volume sampling
DMA………………………………..Differential Mobility Analyzer
DNPH………………………………2,4-Dinitrophenylhydrazine
Dp..particle diameter
DPF ....diesel particle filter
ECM…………………………………engine control module
EEPS………………………………...Engine Exhaust Particle Sizer
EGR…………………………………exhaust gas recirculation
EIA…………………………………Energy Information Administration
FID ....flame ionization detector
GGE…………………………………gasoline gallon equivalent
g/mi ....grams per mile
HDV...heavy-duty vehicle
HHV..higher heating value (BTU/ft^3)
HPLC………………………………..High Performance Liquid Chromatography
km ....kilometer
km/hr...kilometers per hour
lbs...pounds
L-CNG ....CNG blend produced from an LNG fuel tank
LNG…………………………………Liquefied natural gas
MEL ....CE-CERT's Mobile Emissions Laboratory
MN ....methane number
mpg ....miles per gallon
m/s^2 ....meters per second squared
NDIR……………………………….non-dispersive infrared detector
NG...natural gas
NGL…………………………………natural gas liquid
NGV..natural gas vehicle

NH_3 ....ammonia
nm………………………………….. nanometer
NMHC..non-methane hydrocarbons
NO_x ....oxides of nitrogen
OC…………………………………..Oxidation Catalyst
OEM..original equipment manufacturer
PAHs..polycyclic aromatic hydrocarbons
PDP-CVS...positive displacement pump-constant volume sampling
PM...particulate matter
PN ....particle number
tcf……………………………………trillion cubic feet
TDL...tunable diode laser
THC...total hydrocarbons
TWC…………………………………Three-Way Catalyst
SCAQMD ....South Coast Air Quality Management District
SMPS ....Scanning Mobility Particle Sizer
UCR…………………………………University of California, Riverside
whp………………………………….wheel horse power
whp-hr………………………………wheel horse power - hour
WN...Wobbe Number - higher heating value divided by the square root of the specific gravity with respect to air
WVU..West Virginia University

Abstract

The composition of natural gas (NG) can have an important impact on the emissions and performance of natural gas vehicles (NGVs). With the expansion of NG production via horizontal drilling and hydraulic fracturing as well as the potential of liquefied natural gas (LNG) from the Costa Azul LNG terminal in Baja California, Mexico, there is the potential for a wider range of NG compositions being used throughout California. The objective of the present study was to evaluate the impact of NG composition on the performance and emissions of heavy-duty vehicles. Three NG buses were tested over the Central Business District cycle and a NG waste hauler was tested over the Refuse Truck Cycle on a heavy-duty chassis dynamometer on a range of five to seven different test gases. The vehicles included two older technology buses and one older technology waste hauler with lean burn spark ignition engines and oxidation catalysts. The model years for these vehicles ranged from 2002 to 2004. Also tested was a bus with a 2009 stoichiometric combustion spark ignition engine, a three-way catalyst (TWC), and cooled exhaust gas recirculation. The older technology buses and the waste hauler showed general trends of higher emissions of nitrogen oxides (NO_x) and non-methane hydrocarbons (NMHC), and lower emissions of total hydrocarbons (THC), methane (CH_4), and formaldehyde, and improved fuel economy for the gases with lower methane contents. The other pollutants generally did not show strong trends over the older buses and the waste hauler, although lower particulate matter (PM) and carbon monoxide (CO) emissions were found for the waste hauler for the gases with lower methane contents. The waste hauler showed the strongest trends of any of the older vehicles tested. A bus with a newer 2009 stoichiometric combustion engine had lower emissions for most of the pollutants and generally did not show strong fuel effects. The bus with the 2009 stoichiometric combustion engine did, however, show higher CO and ammonia (NH_3) emissions compared to the other buses. This could be attributed to the richer operation for the stoichiometric combustion engine compared to the lean burn engines, as well as the TWC for the NH_3 emissions.

Executive Summary

Natural gas vehicles (NGVs) have been implemented in a variety of applications as part of efforts to improve urban air quality, particularly within California. In California, the use of natural gas has been increasing for a number of years, due predominantly to expanded power and home heating needs. The availability of natural gas (NG) within the State from a wider range of sources is also expanding, with the rapid development of NG production via horizontal drilling and hydraulic fracturing as well as the potential of liquefied natural gas (LNG) from the Costa Azul LNG terminal in Baja California, Mexico. The expansion of these new sources coupled with changes in the extent of NG processing to meet markets for natural gas liquids (NGLs) could contribute to a wider more varied composition of NG being used throughout the State that could impact the emissions and performance of NGVs.

The California Air Resources Board (CARB) is currently revisiting the compressed natural gas (CNG) fuel standards for motor vehicles. Previous studies of interchangeability, or the impacts of changing NG composition, have been conducted on small stationary source engines, such as compressors, heavy-duty engines, and light-duty NGVs. Some of the previous studies have shown that NG composition can have an impact on emissions, including studies that have shown increases in oxides of nitrogen (NO_x) emissions with increasing Wobbe number. Wobbe Number is defined as the higher heating value (HHV) of a gas divided by the square root of the specific gravity of the gas with respect to air. The higher the WN of the gas, the greater the heating value per volume of gas that will flow through a hole of a given size in a given amount of time.

The objective of the present study is to evaluate the impact of NG composition on the performance and emissions of heavy-duty vehicles. For this study, three NG buses were tested over the Central Business District (CBD) cycle and a NG waste hauler was tested over the Refuse Truck Cycle on a heavy-duty chassis dynamometer on a range of five to seven different test gases. The test vehicles included a bus with a 2009 8.9L stoichiometric combustion spark ignited Cummins Westport ISL-G engine with cooled exhaust gas recirculation (EGR) and a three-way catalyst (TWC), a bus with a 2004 8.1L 6081H John Deere lean burn spark ignition engine with an oxidation catalyst (OC), and a bus with a 2003 C-Gas Plus lean burn spark ignition engine with an OC, and a waste hauler with a 2002 Cummins Westport 8.3L C-Gas Plus lean burn engine with an OC. The certification values for these engines are provided in Appendix A.

The test gases included three gases representative of historical baseline fuels for Southern California (labeled H1, H2, and H7) and four gases representing low methane gases (labeled LM3, LM4, LM5, and LM6). The historical test gases were representative of Texas Pipeline Gas (H1) and Rocky Mountain Pipeline Gas (H2), which is also representative of that found in the Kern/Mohave Pipeline between 2000 and 2010. The third historical gas was an L-CNG fuel, which is a natural gas blend produced from liquefied natural gas, identified as H7. This is also a base gas. Since NG-fueled waste haulers come equipped for dedicated fueling on either LNG or CNG, an L-CNG fuel was included to capture the LNG fueled base line. Note that LNG refers to North American supplies that have been processed to take out most components heavier than methane. The four low methane gases included a Peruvian LNG with nitrogen added to achieve a Wobbe Number of 1385 (LM3), a Middle East LNG (WN above 1400 labeled LM4) and two gases with high WN and low MN, one with a high ethane content and the other with a high propane content, identified as LM5 and LM6. The WN and MN are the same for both LM5 and LM6. The gases

were designed to determine whether there are differences due to composition. The main properties of the test fuels are provided in Table ES-1.

The results of this study are summarized below and in Table ES-2. Comparisons between test gases were made for regulated exhaust emissions, fuel economy, PM mass, particle number (PN) and particle size distributions, ammonia emissions, carbonyl compounds emissions, and power maps. Table ES-2 provides the percentage differences between the different fuels compared to the baseline H1 gas. More detailed emissions results and corresponding p-values for the statistical analyses are provided in Appendix B. In the discussions below, results are generally statistically significant, except as noted.

Table ES-1. Test Fuel Specifications

Gas #	Description	methane	ethane	propane	I-butane	N_2	CO_2	MN	Wobbe #	HHV	H/C ratio
H1	**Baseline, Texas Pipeline**	96	1.8	0.4	0.15	0.7	0.95	99	1338	1021	3.94
H2	**Baseline, Rocky Mountain Pipeline**	94.5	3.5	0.6	0.3	0.35	0.75	95	1361	1046	3.89
LM3	**Peruvian LNG**	88.3	10.5	0	0	1.2	0	84	1385	1083	3.81
LM4	**Middle East LNG-Untreated**	89.3	6.8	2.6	1.3	0	0	80	1428	1136	3.73
LM5	**High Ethane**	83.65	10.75	2.7	0.2	2.7	0	75.3	1385	1115	3.71
LM6	**High Propane**	87.2	4.5	4.4	1.2	2.7	0	75.1	1385	1116	3.70
H7	**L-CNG fuel**	98.4	1.2	0.2	0.1	0	0	103.1	1370	1029	3.96

MN = Methane Number determined via CARB calculations; Wobbe # = HHV/square root of the specific gravity of the blend with respect to air; HHV = Higher Heating Value (BTU/ft^3); H/C = ratio of hydrogen to carbon atoms in the hydrocarbon portion of the blend

*Properties evaluated at 60 °F (15.6 °C) and 14.73 psi (101.6 kPa)

2002 Cummins Westport 8.3L C-Gas Plus Waste Hauler

Waste hauler truck emissions were evaluated over a refuse truck cycle that included, transport, compaction, and curbside segments. Overall, the waste hauler showed the strongest fuel effects for most of the pollutants compared to the buses. Almost all the pollutants showed some fuel effects for at least one of the cycle segments. The low methane gases showed higher NO_x emissions for all three segments of the cycle. Low methane gases showed lower THC, CH_4, formaldehyde and acetaldehyde emissions. For the compaction and curbside phases, higher NMHC emissions were seen for the low methane gases, but for the transport phase the opposite trend was observed. Cumulative PM emissions and CO emissions for the compaction cycle showed a trend of lower emissions for the low methane gases. Fuel economy/consumption on a volumetric basis showed increases for the low methane gases with higher energy contents for the transport and curbside phases of the cycle and decreases for the compaction cycle. On an energy equivalent basis, fuel economy/consumption showed no fuel differences for the curbside and mixed results for the compaction cycles, but higher energy equivalent fuel economy was seen for the low methane gases with higher energy contents for the transport phase. Particle number showed similar fuel trends over the three cycle segments, but the gases showing lower particle numbers included some with higher levels of methane (i.e., H2) and some with lower levels of methane (i.e., LM3 and LM4). CO_2 emissions did not show strong trends for the curbside phase, but the transport phase showed lower CO_2 emissions for the low methane gases with lower H/C ratios, compared to H1 and H2 gases, but not compared to H7. For the compaction segment, CO_2 emissions for LM5 were higher at a statistically significant level than those for H1, H2, and H7 on a whp-hr basis for the compaction segment. On a bhp-hr basis for the compaction segment, CO_2 emissions for all of the low methane fuel gas blends exhibited statistically significant increases in CO_2 emissions of between 5.2 to 19.4% compared to H1, H2, and H7. This can be attributed to the bhp energy readings being lower for the higher energy gases, because the ECM bhp reading does not take into account the differences between fuels. NH_3 emissions showed some fuel differences, but no consistent fuel trends over the three segments of the cycle. The particle size distributions showed a peak in the 10 nm range.

2004 John Deere 8.1L 6081H transit bus

The John Deere bus was tested on two separate occasions due to a mechanical failure during the initial testing. The post-repair John Deere bus tests showed a number of fuel effects. These tests were conducted for only three of the main test gases. Fuels with higher methane contents showed higher THC, CH_4, and formaldehyde emissions, but lower NMHC emissions. The low methane gases showed higher NO_x emissions, although these increases were not statistically significant for all fuel combinations. Low methane gases with higher energy contents showed higher fuel economy on a volumetric basis. One of the low methane gases also showed higher fuel economy on an energy equivalent basis. PM mass, acetaldehyde, CO, CO_2, and NH_3 emissions did not show any significant fuel trends. PM mass, CO and NH_3 emissions were very low for the post-repair bus. The particle size distributions showed a broad peak stretching from sub 10 nm into the 70 nm range.

Some fuel effects were also seen for the initial testing of the John Deere bus. These tests were conducted for only four of the main test gases. Trends for THC, CH_4, formaldehyde, and NO_x were consistent with the post-repair results. Higher methane content gases resulted in higher THC, CH_4, and formaldehyde emissions and particle number counts, but lower NMHC emissions. NO_x emissions showed increases for the highest WN gas compared to the baseline gas. The low methane gases with higher energy contents showed higher fuel economy on a volumetric basis, but slight trends of decreasing fuel economy on an energy equivalent basis. CO_2 showed some statistically significant differences between fuels, but no real trends. CO and NH_3 emissions did not show any specific trends. PM mass emissions were very low and did not show consistent trends with fuel properties, although some differences between different fuel combinations were seen. Acetaldehyde emissions showed a statistically significant reduction for LM3 and LM4 compared to H1, and a marginally statistically significant reduction of H2 compared to H1. The particle size distributions also showed a peak in the sub 10 nm range, but this peak was sharper compared to the post-repair testing.

2003 Cummins Westport 8.3L C-Gas Plus engine transit bus

For the 2003 Cummins Westport 8.3L C-Gas Plus bus, NO_x and NMHC emissions and volumetric fuel economy were higher, and THC, CH_4, and formaldehyde emissions were lower for the low methane gases. CO emissions showed some statistically significant increases with some of the low methane gases. Energy equivalent fuel economy, CO_2, PM, and NH_3, and acetaldehyde emissions did not show any strong fuel effects, and particle number showed inconsistent fuel trends. The particle size distributions showed a peak around 10 nm.

2009 Cummins Westport ISL-G 8.9 L transit bus

The bus with a 2009 Cummins Westport ISL-G stoichiometric combustion engine with cooled EGR and a TWC was the newest technology tested during this program. In general, for this bus, most of the pollutants did not show any specific fuel effects. THC, NMHC, CH_4, NO_x, and formaldehyde emissions for the Westport ISL-G bus were considerably lower than for the other buses. The Cummins Westport ISL-G bus did, however, show higher CO and NH_3 emissions compared to the other buses. This could be attributed to the richer operation for the stoichiometric combustion engine compared to the lean burn engines, as well as the TWC for the NH_3 emissions. Some fuel effects were seen for fuel economy, but not for the other pollutants. The low methane gases with higher energy contents showed higher fuel economy on a volumetric basis but not on an energy equivalent basis. Some differences between fuels were seen for THC and CH_4 emissions, but these differences were on the order of the background levels. The size distributions of the particles emitted from this bus were mainly in the sub 10 nm nucleation particle range.

General

Although trends were found between gases with higher vs. lower methane contents, other trends between gases were not as strong. For example, although H7 has a WN that is much higher than H1 and H2, these gases show similar emissions. Similarly LM4, which has a high WN but an intermediate MN, has emissions similar to LM5 and LM6. Additionally, gases LM5 and LM6, which have varying contents of ethane and propane and butane have similar emissions.

Table ES-2: Percentage Differences of the Emissions From All the Fuel Combinations Compared to H1 for All the Buses and the Waste Hauler

		Waste Hauler				2004 John Deere		2003 Cummins Westport C-Gas Plus	2009 Cummins Westport ISL-G
	Fuel	**Transport**	**Curbside**	**Compaction bhp-hr**	**Compaction whp-hr**	**Initial**	**Post-repair**		
Bold : Statistically significant (p-value ≤ 0.05) Underline: Marginally statistically significant (0.05<p-value≤0.1)									
Fuel Economy/Consumption (Volumetric basis)	H2	3.2%	1.5%	**2.9%**	**-3.1%**	-1.0%		**4.1%**	2.5%
	LM3	**13.2%**	**7.7%**	**3.9%**	**-7.0%**	**4.8%**		**7.4%**	**9.7%**
	LM4	**19.1%**	**7.9%**	**1.6%**	**-12.1%**	**8.0%**			**15.1%**
	LM5	15.3%	17.1%	1.0%	-7.6%		**15.1%**	**11.6%**	**14.9%**
	LM6	**17.7%**	<u>6.4%</u>	**2.4%**	**-9.8%**		**8.7%**	**10.8%**	**13.1%**
	H7	2.4%	-3.4%	**-1.7%**	0.1%				
CO_2	H2	-0.4%	1.3%	**6.1%**	0.0%	**4.0%**		-1.3%	0.3%
	LM3	**-5.0%**	-0.5%	**11.6%**	-0.1%	**2.2%**		-0.1%	-2.7%
	LM4	**-4.0%**	<u>5.3%</u>	**15.9%**	0.2%	**5.2%**			-1.7%
	LM5	-2.3%	1.7%	**16.8%**	**2.8%**		-2.7%	0.8%	<u>-3.0%</u>
	LM6	**-4.3%**	5.2%	**15.0%**	1.3%		<u>3.1%</u>	1.3%	-1.3%
	H7	<u>-2.6%</u>	2.7%	**-2.2%**	-0.4%				
NO_x	H2	**17.3%**	**13.4%**	**49.0%**	**40%**	<u>6.7%</u>		-1.7%	14.8%
	LM3	**84.1%**	**52%**	**191%**	**160%**	10.8%		**38%**	0.8%
	LM4	**121.2%**	**72%**	**278%**	**228%**	**18.8%**			-6.5%
	LM5	**129.6%**	**71%**	**286%**	**240%**		23.9%	**53.4%**	-3.8%
	LM6	**104.8%**	**68%**	**248%**	**207%**		**49.9%**	**32.4%**	-14.4%
	H7	**-8.7%**	-6.6%	**-17.0%**	**-16%**				
CO	H2	21.1%	11.0%	-2.7%	-7.9%	-3.3%		58.9%	3.3%
	LM3	39.7%	-10.1%	**-33.3%**	**-40.0%**	8.6%		**78%**	11.3%
	LM4	**68.5%**	86.2%	**-48.1%**	**-55.0%**	13.9%			9.5%
	LM5	**51.0%**	87.7%	**-43.4%**	**-49.8%**		-23.2%	**185.0%**	3.3%
	LM6	<u>37.4%</u>	70.7%	**-38.3%**	**-45.5%**		-10.9%	**102.9%**	3.9%

		Waste Hauler				**2004 John Deere**		**2003 Cummins Westport C-Gas Plus**	**2009 Cummins Westport ISL-G**
	Fuel	**Transport**	**Curbside**	**Compaction bhp-hr**	**Compaction whp-hr**	**Initial**	**Post-repair**		
Bold : Statistically significant (p-value ≤ 0.05) Underline: Marginally statistically significant (0.05<p-value≤0.1)									
	H7	-13.8%	-12.2%	-9.3%	-7.4%				
THC	H2	-2.8%	-7.5%	**-16.5%**	**-21%**	-1.9%		-1.8%	9.6%
	LM3	**-36%**	**-19.6%**	**-40%**	**-46%**	**-11.8%**		**-15.3%**	43.4%
	LM4	**-48%**	**-17.7%**	**-45%**	**-53%**	**-8.8%**			**107.4%**
	LM5	-54%	-28.1%	-48%	-52%		**-17.0%**	**-23.9%**	11.7%
	LM6	**-45%**	**-15.3%**	**-43%**	**-50%**		**-13.0%**	**-20.7%**	21.6%
	H7	-7.3%	**11.5%**	**11%**	**13%**				
NMHC	H2	-2.6%	**-20.3%**	79.2%	75%	**28.4%**		**22.1%**	-49.7%
	LM3	-20.7%	9.2%	**511.5%**	**451%**	**78.0%**		**62%**	**-126.5%**
	LM4	**-34.4%**	**15.1%**	**508.6%**	**430%**	**101.8%**			51.2%
	LM5	-36.8%	18.9%	666.1%	605%		**87.7%**	**62.3%**	**-124.0%**
	LM6	-33.9	**19.2%**	**611.9%**	**529%**		**71.6%**	**39.2%**	-80.5%
	H7	-35.0	-16.1%	**-91.4%**	**-91%**				
CH_4	H2	-5.3%	**-9.7%**	**-18.3%**	**-23%**	-5.4%		**-4.3%**	20.1%
	LM3	**-38.5%**	**-28.1%**	**-45%**	**-51%**	**-22.4%**		**-23.2%**	**65.0%**
	LM4	**-49.2%**	**-26.3%**	**-51%**	**-57%**	**-21.8%**			**68.7%**
	LM5	**-52.0%**	**-34.4%**	**-54%**	**-60%**		**-31.6%**	**-33%**	**41.5%**
	LM6	**-47.4%**	**-25.1%**	**-49%**	**-55%**		**-24.8%**	**-26.8%**	**37.9%**
	H7	-3.5%	**13%**	**12.0%**	**14.0%**				
NH_3	H2	-22.0%	-8.4%	**-30.9%**	**-35%**	-22.4%		40.4%	-10.9%
	LM3	-13.8%	-18.5%	25.4%	13%	-57.4%		39.0%	-0.7%
	LM4	-26.9%	-27.1%	-15.1%	-27%	19.3%			7.1%
	LM5	2.8%	-7.6%	-35.8%	-44%		101.3%	4.2%	**14.5%**
	LM6	-26.2%	-19.8%	**-51.9%**	**-58%**		-1.9%	10.9%	**19.6%**
	H7	-10.8%	4.2%	-18.6%	-17%				

		Waste Hauler				**2004 John Deere**		**2003 Cummins Westport C-Gas Plus**	**2009 Cummins Westport ISL-G**
	Fuel	**Transport**	**Curbside**	**Compaction bhp-hr**	**Compaction whp-hr**	**Initial**	**Post-repair**		
Bold : Statistically significant (p-value ≤ 0.05) Underline: Marginally statistically significant (0.05<p-value≤0.1)									
PN	H2	**-39.0%**	**-34.7%**	**-39.6%**	**-43.1%**	**-13%**		47%	38%
	LM3	**-61.5%**	**-53.1%**	**-59.7%**	**-64.1%**	**-26%**		28%	-20%
	LM4	**-63.1%**	**-46.7%**	**-71.4%**	**-75.4%**	**-26%**			**-52%**
	LM5	5.1%	-0.2%	-2.1%	-14.1%			0.4%	-18%
	LM6	0.3%	4.7%	-4.9%	-15.1%			6%	-10%
	H7	14.4%	15.3%	-4.1%	-2.9%				
		For the whole cycle							
PM	H2	12.3%				-15.9%		-1.7%	-16.1%
	LM3	-36%				**-68.3%**		-25.0%	-1.0%
	LM4	**-54%**				-45.8%			-16.3%
	LM5	**-60%**					57.1%	-32.4%	-17.1%
	LM6	**-51%**					-16.1%	-55.5%	-9.7%
	H7	-26%							
		For the whole cycle							
Formaldehyde	H2	-7.6%				**-16.9%**		-4.6%	43.4%
	LM3	**-54.6%**				**-41.4%**		-23.7%	55.3%
	LM4	**-46.9%**				**-45.2%**			32.0%
	LM5	**-47.6%**					**-27%**	**-14.0%**	-3.2%
	LM6	**-51.4%**					**-41%**	**-24.3%**	7.3%
	H7	12.7%							
		For the whole cycle							
Acetaldehyde	H2	3.1%				-60.9%		64.1%	-47.1%
	LM3	**-60.7%**				**-100.0%**		-17.7%	-41.7%
	LM4	**-62.9%**				**-100.0%**			-67.6%
	LM5	**-52.6%**					-60%	59.0%	-0.2%

		Waste Hauler				2004 John Deere		2003 Cummins Westport C-Gas Plus	2009 Cummins Westport ISL-G
	Fuel	Transport	Curbside	Compaction bhp-hr	Compaction whp-hr	Initial	Post-repair		
Bold : Statistically significant (p-value ≤ 0.05) Underline: Marginally statistically significant (0.05<p-value≤0.1)									
	LM6	**-62.0%**					49%	44.1%	-100.0%
	H7	<u>-24.2%</u>							

Bold : Statistically significant (p-value ≤ 0.05) Underline: Marginally statistically significant (0.05<p-value≤0.1); whp-hr = wheel horsepower-hour basis; bhp-hr = brake horsepower-hour basis from engine control module (ECM)

1 Introduction

Natural gas (NG) is a potential alternative to conventional liquid fuels for use in internal combustion engines in motor vehicles. Natural gas vehicles (NGVs) have been implemented in a variety of applications as part of efforts to improve urban air quality, particularly within California. These vehicles are predominantly implemented in fleet applications, because travel is relatively centralized and a large refueling infrastructure is not needed. NGVs were generally believed to produce lower emissions of non-methane hydrocarbons (NMHC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM) compared to diesel vehicles without aftertreatment [1–3], although this is becoming less of an issue with the introduction of diesel particle filters (DPFs) and selective catalytic reduction (SCR) systems on diesel vehicles [4–11].

For NGVs, one issue that has been shown to be important with respect to emissions is the effect of changing the composition of the NG fuel. This is part of a broader range of issues which are classified under the term interchangeability, which is the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions. Studies of the effects of NG composition have been conducted for small stationary source engines, such as compressors, and in heavy-duty engines [12–22]. These studies have shown that NG composition can have an impact on emissions. NO_x emissions, for example, were found to increase with increasing Wobbe number (WN) and/or decreasing methane number (MN) in several of these studies [12–22]. MN and WN are terms used to describe natural gas quality characteristics. MN is a measure of the knock resistance of a gas, with the knock resistance of a gas increasing with increasing MN. WN is defined as the higher heating value (HHV) of a gas divided by the square root of the specific gravity of the gas with respect to air. The higher the WN of the gas, the greater the heating value per volume of gas that will flow through a hole of a given size in a given amount of time.

The importance of changing NG composition is underscored by the dramatic changes in the market for NG in recent years due to the rapid development of horizontal drilling and hydraulic fracturing, advanced techniques that have made it possible to unlock vast reserves of oil and gas trapped underneath sedimentary rocks, or shales. The U.S. Energy Information Administration (EIA) anticipates domestic NG production to continue to expand into the future, growing from levels of 23.5 quadrillion Btu in 2011 to a projected 33.9 quadrillion Btu in 2040, representing a sizable 44% increase [23]. Shale gas production, which already accounted for 23% of total U.S. natural gas production in 2010, is expected to be the primary driver of this expansion, with shale gas production going from 6.8 trillion cubic feet (tcf) in 2011 to 13.6 tcf in 2035 [24]. In California, the use of natural gas has also been increasing for a number of years, due predominantly to expanded power and home heating needs. Currently, California supplies 85-90% of its needs with NG imported domestically from the Rockies, from southwest states, such as Texas, and from Canada [12-15]. As new producing fields are developed in the US, however, the makeup of imported domestic NG supplies could change. Additionally, with the introduction of the Costa Azul LNG terminal in Baja California, Mexico, there is the potential for more NG from imported sources, such as the Pacific Rim, to become available, especially for regions in the southern part of the state. LNG will also likely differ in composition from what is currently being used in the state.

Natural gas quality depends on both its source as well as the degree to which it is processed. Natural gas can be produced from oil fields (termed associated gas) or from gas fields (termed non-associated gas). Associated gas is typically higher in heavier hydrocarbons, which gives the gas a higher WN and a lower MN. Associated gas is often processed using techniques such as refrigeration, lean oil absorption, and cryogenic extraction to recover valuable natural gas liquids (NGLs) for other uses, such as ethane, propane, butanes, pentanes and hexanes plus [25,26]. Traditional North American gas from Texas, for example, is often processed to recover feedstock for chemical plants. This results in a natural gas stream with a lower WN and higher MN. As the economics for these secondary products change, there could be a reduced emphasis on recovering NGLs from NG. This could lead to NG with higher WNs and lower MNs being fed into the pipeline, which would likewise result in a pipeline gas with a higher WN and lower MN.

The objective of the present study is to evaluate the impact of NG composition on the performance and exhaust emissions of heavy-duty vehicles. The California Air Resources Board (CARB) is currently revisiting the compressed natural gas (CNG) fuel standards for motor vehicles [27]. Information on the impact of changing NG composition on performance and emissions can be used for regulatory development, to ensure new NG compositions do not have an adverse impact on air quality, and to evaluate the viability of using a broader mixture of NG blends in transportation applications. For this study, four NG heavy-duty vehicles (HDVs) were tested on a range of between five to seven different test gases. This included three NG buses and one NG waste hauler tested over the central business district cycle (CBD) and the refuse truck cycle, respectively. The test gases included gases representative of Texas Pipeline Gas and Rocky Mountain Pipeline Gas; a gas representing Peruvian LNG modified to 1385 WN; a gas representing Middle East LNG-Untreated (WN above 1400); two gases with 1385 WNs and 75 MNs, one with a high ethane content and the other with a high propane content; and one L-CNG fuel, which is a CNG blend produced from an LNG fuel tank. In addition to the regulated emissions and fuel economy/consumption, measurements were also made of ammonia (NH_3), of carbonyls, and of particle number (PN) and particle size distributions. This report discusses these test results. This study is part of the larger program that included the testing of light-duty NGVs on a chassis dynamometer, which is discussed in a previous report [28].

2 Experimental Procedures

2.1 Test Fuels

The six NG blends used for testing are characterized as follows:

- Gases H1 and H2 are representative of Texas and Rocky Mountain Pipeline Gases and serve as the baseline fuels. These gases are based on actual pipeline data.
- Gas LM3 is representative of Peruvian LNG that has been modified to meet a WN of 1385 and a MN of 75.
- Gas LM4 is representative of Middle East LNG-Untreated with a high WN (above 1400)
- Gas LM5 is a high ethane gas with a WN of 1385 and a MN of 75.
- Gas LM6 is a high propane, high butane gas with a WN of 1385 and a MN of 75.

Test gases H1 and H2 represent historical baseline fuels for Southern California. Test gas H1, "Baseline, Texas Pipeline," refers to gas entering the Southern California Gas territory through the El Paso Pipeline at Blythe and Topock and through the Transwestern Pipeline at North Needles and Topock. Test gas H2, "Baseline, Rocky Mountain Pipeline," refers to gas entering the Southern California Gas territory through the Kern/Mohave Pipeline at Wheeler Ridge and Kramer Station. The actual test gas compositions for H1 and H2 were derived by Air Resources Board staff from gas quality data submitted by the Southern California Gas Company for the period from January 2000 to October 2010.

Gases LM5 and LM6 are hypothetical gases designed to see whether two fuels with the same WN and MN, but different compositions, would produce different performance and exhaust emissions. Gases with higher propane and butane are found locally in South Central Coast region oil and gas fields, while gases with high ethane are found in San Joaquin Valley oil and gas fields. Gases LM5 and LM6 are both at the extremes for WN and MN, so the typical local gas in the pipeline in these areas will have lower WNs and higher MNs. For this program, the wide range of scenarios were examined to evaluate the viability of permitting the use of a broader mixture of NG blends in transportation applications. Gases LM3 to LM6 with lower methane contents, and corresponding higher WNs and HHVs, and lower MNs are denoted as low methane gases throughout this report. The test fuels are presented in Table 2-1.

In addition, the CNG fueled waste hauler was run on an L-CNG, identified as H7. Test gas H7 is a historical gas representing an L-CNG fuel sold in the South Coast Air Basin in 2011. Test gas H7 was included to capture the base line for waste haulers that fuel on LNG. Because a CNG waste hauler was tested, a L-CNG fuel, rather than an LNG fuel, was used. L-CNG is LNG which has been vaporized to a gas at the fueling station. Although L-CNG was included as a test gas to represent a waste hauler operating on LNG, it should be noted that a LNG waste hauler would never see LM3, LM5, LM6 because these fuels have inert gases. LNG, on the other hand, has almost no inert components because inerts are removed during the liquefaction process. LNG purchased at commercial fueling stations in the South Coast Air Basin is manufactured from pipeline quality natural gas, which has been purified to remove most of the hydrocarbon components heavier than methane as well as inert gases. The fuel is then refrigerated to minus 260 degrees for conversion to LNG. LNG at the fueling station is generally 98+ percent purity methane. This fuel was sampled to determine its composition at the time of testing.

Table 2-1. Test Fuel Specifications

Gas #	Description	methane	ethane	propane	I-butane	N_2	CO_2	MN	Wobbe #	HHV	H/C ratio
H1	**Baseline, Texas Pipeline**	96	1.8	0.4	0.15	0.7	0.95	99	1338	1021	3.94
H2	**Baseline, Rocky Mountain Pipeline**	94.5	3.5	0.6	0.3	0.35	0.75	95	1361	1046	3.89
LM3	**Peruvian LNG**	88.3	10.5	0	0	1.2	0	84	1385	1083	3.81
LM4	**Middle East LNG-Untreated**	89.3	6.8	2.6	1.3	0	0	80	1428	1136	3.73
LM5	**High Ethane**	83.65	10.75	2.7	0.2	2.7	0	75.3	1385	1115	3.71
LM6	**High Propane**	87.2	4.5	4.4	1.2	2.7	0	75.1	1385	1116	3.70
H7	**L-CNG fuel**	98.4	1.2	0.2	0.1	0	0	103.1	1370	1029	3.96

MN = Methane Number determined via CARB calculations; Wobbe # = HHV/square root of the specific gravity of the blend with respect to air; HHV = Higher Heating Value (BTU/ft^3); H/C = ratio of hydrogen to carbon atoms in the hydrocarbon portion of the blend

* Properties evaluated at 60 °F (15.6 °C) and 14.73 psi (101.6 kPa)

2.2 Test Vehicles

Four vehicles were utilized for the testing in this program. The vehicles were selected to represent different vehicle types, including transit buses and waste haulers, and different types of engines. The inclusion of the two vehicle types provides some information on the differences between transit and refuse service vehicles. One vehicle was a bus equipped with a 2009 stoichiometric combustion spark ignited Cummins Westport ISL-G 8.9 L engine, with a three-way catalyst (TWC) and a cooled exhaust gas recirculation (EGR) system. The second vehicle was a bus equipped with a 2004 John Deere 8.1L 6081H engine. The third vehicle was a bus equipped with a 2003 8.3L C-Gas Plus engine. The fourth vehicle was a waste hauler with a 2002 Cummins Westport 8.3L C-Gas Plus engine. The latter three vehicles are all lean burn spark ignition engines that are equipped with oxidation catalysts (OC). The specifications of the engines are provided in Table 2 2. The certification Executive Orders for each of the engines tested are provided in Appendix A. The buses were provided on loan from Omnitrans, which is the public transit agency serving the San Bernardino Valley area of southern California. The waste hauler was provided by Waste Management.

It should be noted that the John Deere bus was tested on two separate occasions, once before and again after a mechanical issue was discovered. Specifically, the bus lost compression in one of its combustion cylinders. This issue was discovered while the bus initially underwent testing on LM5. The retesting on the repaired vehicle was done approximately one year after the initial testing.

Table 2-2. Engine Specification

Manufacturer	Cummins Westport	John Deere	Cummins Westport	Cummins Westport
Engine Model	ISL-G	6081HF	C-Gas Plus	C-Gas Plus
Model Year	2009	2004	2003	2002
Vehicle Type	Bus	Bus	Bus	Waste Hauler
Engine Family	9CEXH054 LBD	4JDXH08.1066	3CEXH0505CBK	2CEXH0505CBH
Engine Type	Stoichiometric Spark-ignited Turbocharged, EGR	Lean burn Spark-ignited Turbocharged	Lean burn Spark-ignited Turbocharged	Lean burn Spark-ignited Turbocharged
Horsepower	280 HP	280 HP	280 HP	275-280 HP
Number of Cylinders	6	6	6	6
Bore and Stroke	114 mm x 145 mm	116 mmx 129 mm	114 mm x 135 mm	114 mm x 135 mm
Displacement	8.9 L	8.1 L	8.3 L	8.3 L
Compression Ratio	12:1	16.5:1	10:1	10:1
Peak Torque	900 ft-lbs. @ 1300 rpm	900 ft-lbs. @ 1500 rpm	850 ft-lbs. @ 1400 rpm	750-850 ft-lbs. @ 1400 rpm
Aftertreatment	TWC	OC	OC	OC
Certification Level (g/bhp-hr)	NMHC: 0.13 NO_x:0.10 CO:1.2 PM:0.009	NMHC+NO_x:1.5 CO:0.1 PM:0.01	NMHC+NO_x:1.7 CO:2.0 PM:0.01	NMHC: 0.2 NO_x:1.5 CO:1.3 PM:0.01

2.3 Test Cycles

For the buses, testing was performed over the CBD test cycle. For the waste hauler, the testing was performed on the William H. Martin (WHM) refuse truck cycle. The test matrix was randomized to allow some measure of the experimental reproducibility. Six tests were run on each vehicle/fuel combination for all vehicles, except as noted otherwise. The test matrix for the heavy-duty chassis dynamometer testing is provided below in Table 2-3. For the buses, only 6 test gases were used, so the matrix was only for 6 days ending with testing of gas 1. This test sequence differed for the John Deere bus, which was tested on two separate occasions. Also, LM4 was not tested on the C-Gas Plus bus.

Table 2-3. Chassis Dynamometer Test Matrix For each Test Vehicle

Test Day	Morning Schedule (assumes 3 replicates)	Afternoon Schedule (assumes 3 replicates)
CBD or WHM Refuse Cycle		
Day 1	111	222
Day 2	222	333
Day 3	333	444
Day 4	444	555
Day 5	555	666
Day 6*	666	777
Day 7	777	111

CBD = Central Business District; WHM = William H. Martin;
1 = Gas #1, 2 = Gas #2, 3 = Gas #3, 4 = Gas #4, 5 = Gas #5, 6 = Gas#6
* Gas 7 will be used in the Waste Hauler

A specially developed cycle was used for the CBD testing. This cycle consisted of a single CBD cycle as a warm-up, followed by two iterations (i.e., a double) CBD cycle. The CBD cycle was repeated twice to provide a more sufficient particle sample for analysis. The CBD cycle is characterized by an average speed of 20.23 km/h, a maximum speed of 32.18 km/h (20 mph), an average acceleration of 0.89 m/s^2, a maximum acceleration of 1.79 m/s^2. The driving distance for a single CBD cycle is 3.22 km, or 9.66 km for the full cycle, including the warm-up. Emissions analyses for gaseous emissions were collected as an integrated sample over the double CBD cycle. West Virginia University (WVU) has used a similar cycle in some of its earlier testing on CNG buses [11]. A speed-time trace for the extended CBD is provided in Figure 2-1

The waste hauler was tested over the William H. Martin Refuse Truck Cycle. This cycle was developed by WVU to simulate waste hauler operation. The cycle consists of a transport segment, a curbside pickup segment, and a compaction segment. The initial 277 second segment of the cycle is a warm-up period where no emissions were collected. The transport portion of the cycle represents the 1st 300 seconds of the actual cycle for the trip out to the service area and the 300 seconds after the curbside segment for the return trip from the service area. Note that the first and second part of the transport cycle represent different types of driving conditions that a waste hauler might do. The curbside pickup portion of the cycle is 520 seconds. It is the middle portion of the cycle with a series of low speed accelerations. The compaction portion of the cycle is the final phase. Before the start of the actual compaction cycle where emissions data are collected, there is an interval for an acceleration up to and stabilization at the appropriate test speed. Data collection for the compaction phase begins once the vehicle has stabilized at the test speed for the compaction, and data for the compaction phase is collected for a period of 155 seconds. The compaction load is simulated by applying a predetermined torque to the drive axle while maintaining a fixed speed of 45 mph. The compaction load used in this study was 80 horsepower (hp), the same as used previously by WVU [11]. The Refuse Truck Cycle is shown in Figure 2-2.

Figure 2-1. Double CBD Cycle with Warm-up

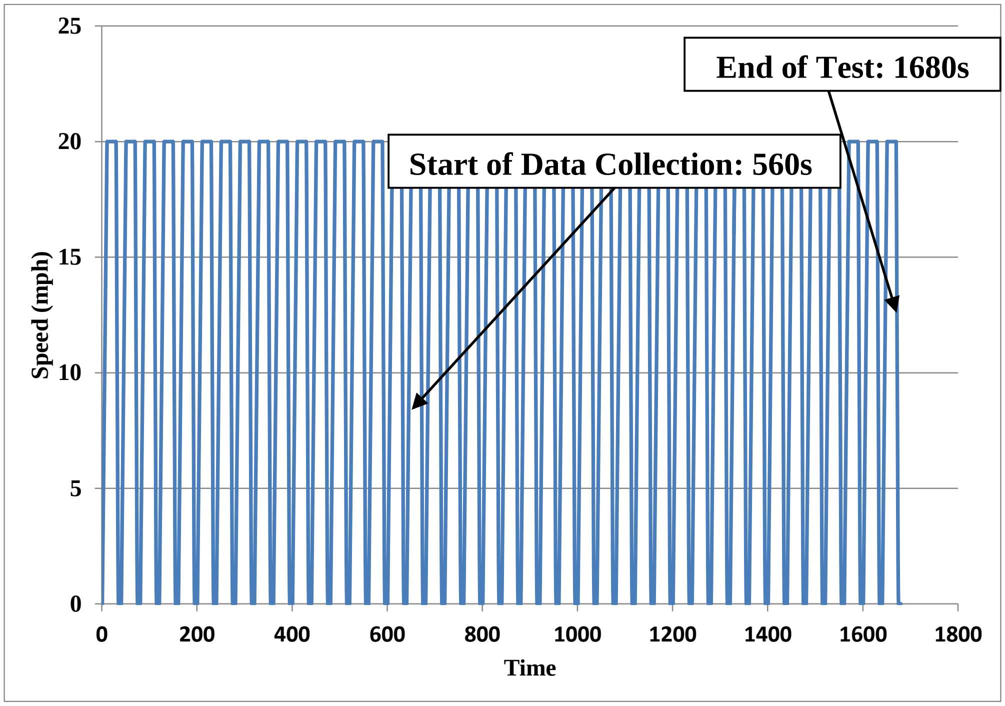
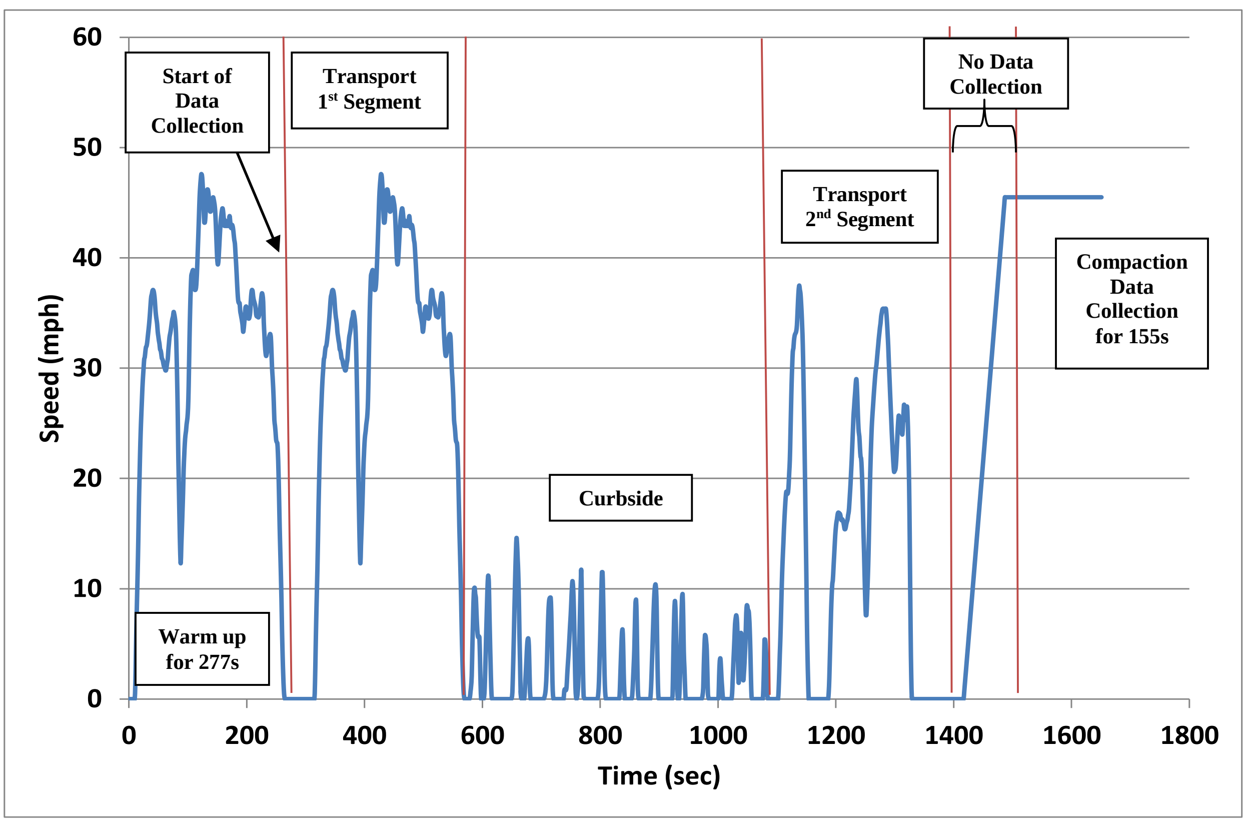


Figure 2-2. Refuse Truck Cycle [23]



The vehicles were preconditioned at the start of each test day by performing a power map. Between tests, there was a “hot soak”, where the engine is turned off for about 10-15 minutes. As discussed above, all tests were conducted as “hot running” tests, with a single CBD used as the warm-up for the buses and a 277 second warm-up being used by the waste haulers.

The road load coefficients for the first bus and waste hauler were determined by coasting down the vehicle from approximately 60 mph to approximately 10 mph. The test weight used for each of the three buses was 32,220 lbs and for the waste hauler was 33,520 lbs. The test weights were based on the weight of the waste hauler and on the weight of the first bus when these vehicles arrived for testing. The second and third buses were not weighed or coasted down, since all three buses have the same vehicle shape and were assumed to have approximately the same test weights, and consequently the same road load coefficients. Using the same weight and road load coefficients for all three buses has the benefit of eliminating weight and road load coefficients as a variable.

2.4 Emissions Testing and Measurements

The chassis dynamometer testing was conducted in University of California, Riverside (UCR) Center for Environmental Research and Technology’s (CE-CERT’s) heavy-duty chassis dynamometer facility. A picture of a typical vehicle set up on the chassis dynamometer is provided in Figure 2-3. For the power map, the vehicle was driven at a constant starting speed. The load was then slowly increased while the accelerator pedal was held down fully trying to maintain the same speed, until the vehicle down shifted. The starting speeds for the power maps for the Cummins Westport ISL G bus, the waste hauler, and the initial testing on the John Deere bus were between 60 and 70 mph, while the starting speeds for the post-repair John Deere bus test and the C Gas Plus bus test were approximately 40 mph. The vehicles were driven at different speeds in part because the dynamometer was upgraded towards the later portion of the project to allow for higher power settings at lower vehicle speeds. The vehicles were also monitored throughout the course of testing to evaluate the operability of the engines on the different blends, including characteristics such as knock. No engine knock was observed during the course of normal testing.

The emissions measurements were obtained using CE-CERT’s Mobile Emissions Laboratory (MEL). For all tests, standard emissions measurements of total hydrocarbons (THC), 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 600HFID flame ionization detector (FID) from CAI. NO_x emissions were measured with 600HPLC chemiluminescence analyzer from CAI. Measurements were also made of NH_3 using a tunable diode laser (TDL) from Unisearch Associates Inc. LasIR S Series and of carbonyls, including formaldehyde and acetaldehyde, using 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges with subsequent analysis with a Agilent 1100 series high performance liquid chromatograph (HPLC) equipped with a diode array detector. A schematic of the experimental setup is provided in Figure 2-4. The sampling of carbonyls was done for 3-4 tests per test fuel/vehicle combination. Sampling for the PM, formaldehyde, and acetaldehyde was done cumulatively over the entire duration of the cycles for the buses and the waste hauler due to the low mass levels expected for these pollutants. As such, results for the individual segments of the Refuse Truck Cycle are not available for these pollutants.

Figure 2-3. Typical Setup of Test Vehicles on the Chassis Dynamometer

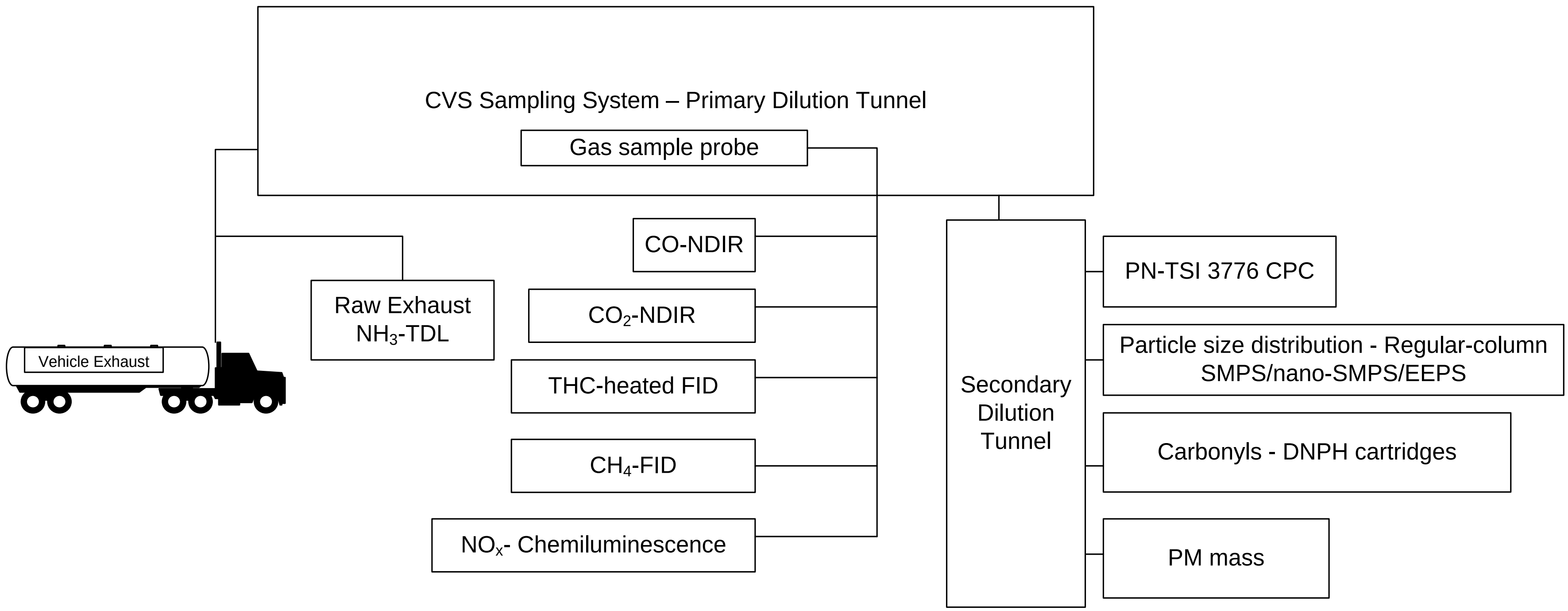
Particle number counts were measured with a TSI 3776 Condensation Particle Counter (CPC) with a 2.5 nm cut point for all cases except for the post-repair John Deere and the C-Gas Plus bus testing. Particle number counts were not measured for the post repair vehicle because of issues with the data acquisition system for the CPC. For the C-Gas Plus testing, the TSI 3776 CPC did not appear to be functioning correctly. Particle size distributions were measured using several different instruments throughout the program. This was due to the availability of different instruments at different times over the course of testing. A nano scanning mobility particle sizer (nano-SMPS) was used for the 2009 Cummins Westport ISL-G8.9 bus, the waste hauler truck, and the John Deere bus tests to characterize particle size distributions. The size range of the nano-SMPS was 4 to 70 nm in electrical mobility diameter with a scan time of 118 seconds. A regular, long column SMPS was used at the very beginning of the test campaign for part of the testing on the 2009 Cummins Westport ISL-G8.9 bus. The long column SMPS was used for some of the initial testing, but was subsequently replaced by the nano-SMPS to provide measurements of the smaller diameter particles. The long column SMPS had an operating range of 20 to 400 nm in electrical mobility diameter with a scan time of 135 seconds. For the C-Gas Plus bus testing, an Engine Exhaust Particle Sizer (EEPS) was available and used for measuring particle size distributions and particle number. The EEPS has a faster scan time of one second and provides a wider size range from 6 to 423 nm in electrical mobility than either of the other SMPS instruments. The faster scan time allows the EEPS to more accurately capture the size distributions under transient operating conditions. Table 2-4 summarizes the instruments used in this program for measuring particle number and size distributions.

Table 2-4. Summary of the Particle Number and Size Distribution Instruments Used in Each Vehicle Testing

	PM measurement	Cummins Westport C-Gas Plus Waste Hauler	Initial John Deere Bus	Post-repair John Deere Bus	Cummins Westport C-Gas Plus Bus	Cummins Westport ISL-G Bus
Nano-SMPS –with 3085 TSI DMA Column (4-70 nm, 118s scan time)	Particle size	√	√	√		√
TSI 3081 Regular long-column SMPS (20-400 nm, 135s scan time)	Particle size					√*
TSI 3090 EEPS (6-423 nm, 1s scan time)	Particle size and number				√	
TSI 3776 CPC (2.5 nm cut-off size)	Particle number	√	√		√	√

*regular long–column SMPS was only used at the beginning of testing on this bus.

Figure 2-4. Schematic of the Sampling Systems and Instruments



3 Heavy-Duty Vehicle Chassis Dynamometer Testing Results

The emissions results are presented in the following section. The figures for each pollutant show 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 each test combination. The average emissions test results with percentage differences between fuels and p-values for statistical analyses are provided in Appendix B. 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 $0.05 < p \leq 0.1$ in this analysis. The John Deere results are shown separately for the initial and post-repair testing. A subset of 3 tests on LM4 was eliminated from the data set of the initial testing of John Deere since they showed some irregularities, i.e., unrealistically low NO_x emissions. Also, only three replicates were obtained for H1 for the John Deere before the mechanical failure occurred. The second phase of testing on John Deere bus included the remaining three replicates on H1 and six replicates on LM5 and LM6.

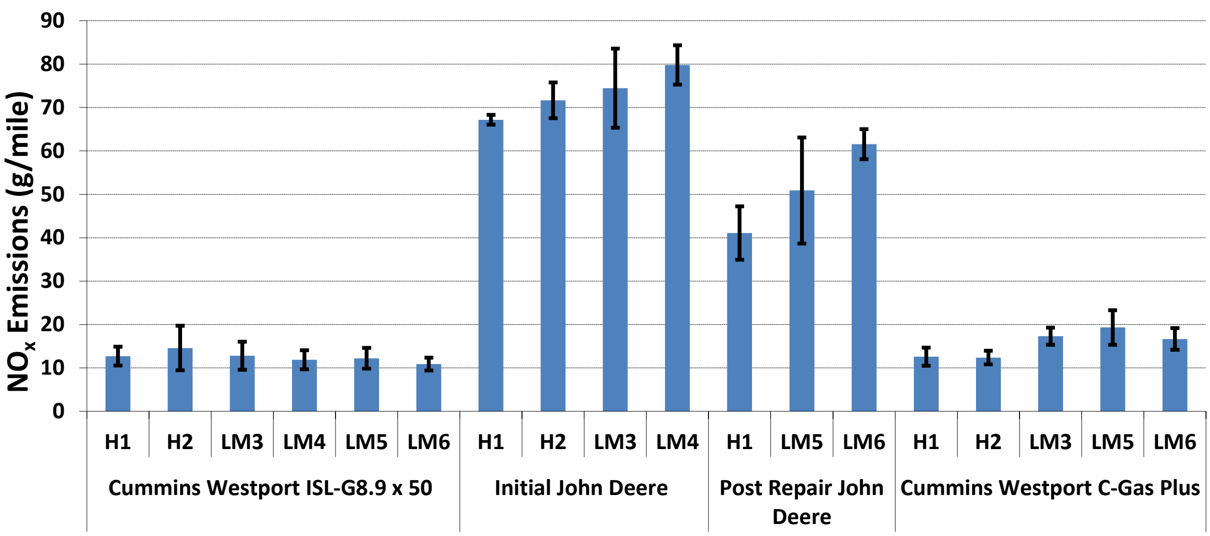
3.1 NO_x Emissions

Emissions of NO_x are shown in Figure 3-1 for the NG buses. NO_x emission levels for the Cummins Westport ISL-G8.9 bus were significantly lower than those of the C-Gas Plus and John Deere buses, noting that the emissions for the Cummins Westport ISL-G8.9 bus are multiplied by 50 in the figure. For the John Deere and C-Gas Plus buses, the NO_x emissions generally showed trends of higher NO_x emissions for the low methane gases. The C-Gas Plus bus showed statistically significant increases of 38%, 53%, and 32%, respectively, for LM3, LM5, and LM6 compared to H1. For the post-repair John Deere results, these increases were statistically significant for LM6 compared to H1 (+50%), while for the initial John Deere testing a statistically significant increase was found for LM4 fuel compared to H1 (+18.8%). The Cummins Westport ISL-G8.9 did not show significant differences between fuels for NO_x emissions. Initial testing of the John Deere bus showed a marginally statistically significant difference in NO_x emissions between H1 and H2.

Figure 3-2 (a-b) shows the emissions of NO_x for the waste hauler for the transport and curbside segment of the Refuse Truck Cycle. Figure 3-3 (a-b) shows the emissions of NO_x for the waste hauler for the compaction segment of the Refuse Truck Cycle. For the compaction segment, the emissions are presented on both a brake horsepower-hour (bhp-hr) basis based on readings from the engine's control module (ECM) and on a wheel horsepower-hour (whp-hr) basis based on the dynamometer load to the wheels of the vehicle. These are both important emission measurement metrics. Heavy-duty natural gas engines are certified on a bhp-hr basis. The whp-hr, on the other hand, is a direct measure of the load being applied to the vehicle itself. For this study, the bhp-hr values showed some trends between different fuels, with the ECM readings for bhp being lower for the low methane gases compared to H1, H2, and H7. This is shown in Figure 3-4. This is due to the fact that the bhp from the ECM is a calculated value from the engine revolutions per minute (rpm) and the amount of fuel used, but it is based on a fuel with a standard set of properties. As such, the ECM bhp reading does not take into account the differences between fuels. The whp-hr, or the load applied by the dynamometer, is essentially the same from test to test and between the different fuels. Thus, whp-hr provides a more consistent basis for fuel comparisons. The differences between the emissions on bhp-hr and whp-hr basis are discussed below for the different pollutants.

For the waste hauler truck, in general, NO_x emissions increased for the low methane gases during all three segments of the Refuse Truck Cycle. LM3, LM4, LM5, and LM6 exhibited statistically significant increases compared to the baseline H1, H2, and H7 for most of the test combinations on all three segments. For the transport segment, the increases for LM3, LM4, LM5, and LM6 ranged from 84-130% compared to H1, 57-96% compared to H2, and 102-152% compared to H7. For the curbside segment, these increases were 52-72% compared to H1, 34-51% compared to H2, and 63-84% compared to H7. The compaction segment showed the strongest increases. For the compaction segment, these increases were 160-240% compared to H1, 86-143% compared to H2, and 209-303% compared to H7 on a whp-hr basis and these increases were 191-286% compared to H1, 95-159% compared to H2, and 250-365% compared to H7 on a bhp-hr basis. The percentage difference increases during the compaction cycle are larger on a bhp-hr basis compared to the whp-hr basis because of the lower ECM readings for bhp for the higher energy gases, which creates larger differences between the low methane gases and the lower energy/high methane content gases. In comparing the driving segments, NO_x emissions for the curbside segment were much higher than those of the transport segment on a per mile basis. This can be attributed to the fact that the curbside segment is composed of short, low speed accelerations between periods of idle that covers a very short distance (0.36 miles). Such stop and go type of driving tends to create high emissions when evaluated on a per mile basis. For all three segments on both a whp-hr and bhp-hr basis, the differences observed in NO_x emissions between H1 and H2 were statistically significant.

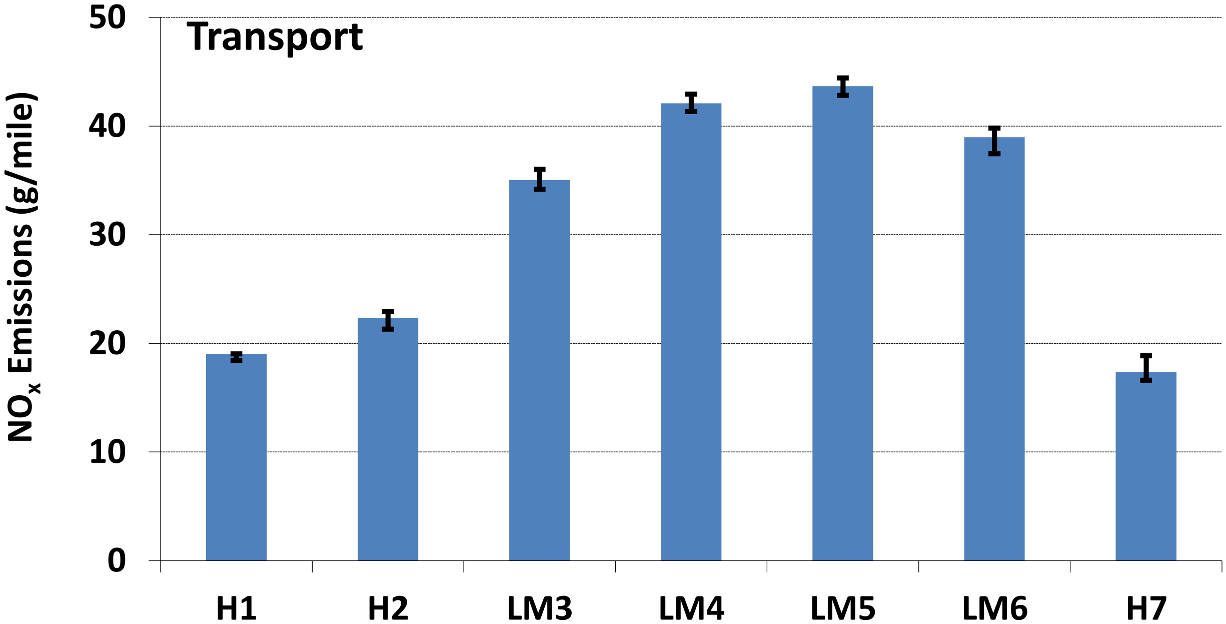
Figure 3-1. Average NO_x Emissions for the NG Buses.



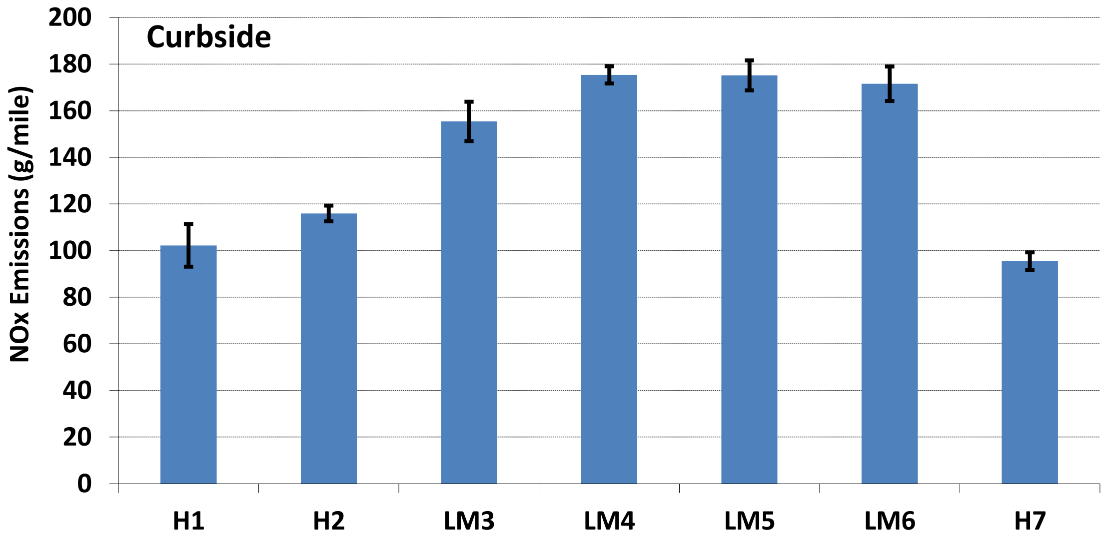
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

The increases in NO_x emissions with LM3, LM4, LM5, and LM6 gases could be attributed to the presence of high molecular-weight hydrocarbons in these gases. The addition of higher hydrocarbons (ethane and propane) can increase the adiabatic flame speed. As flame speed increases at constant ignition timing, peak pressure occurs earlier, at smaller cylinder volumes, and thus higher temperatures. Peak combustion temperatures are therefore higher due to the advanced location of peak pressure and higher adiabatic flame temperature [29], which would result in higher NO_x emissions, as NO_x is generated predominantly through the strongly temperature-dependent thermal NO mechanism [21,22]. Previous studies have also shown that lean-burn engines run richer as MN is decreased [14]. This can lead to the oxidation of more fuel, higher combustion temperatures, and increased cylinder pressures. It is also possible that the higher hydrocarbons promote the formation of reactive radicals, which result in increased formation of prompt NO_x.

Figure 3-2 (a-b). Average NO_x Emissions for the Waste Hauler Transport and Curbside Segments



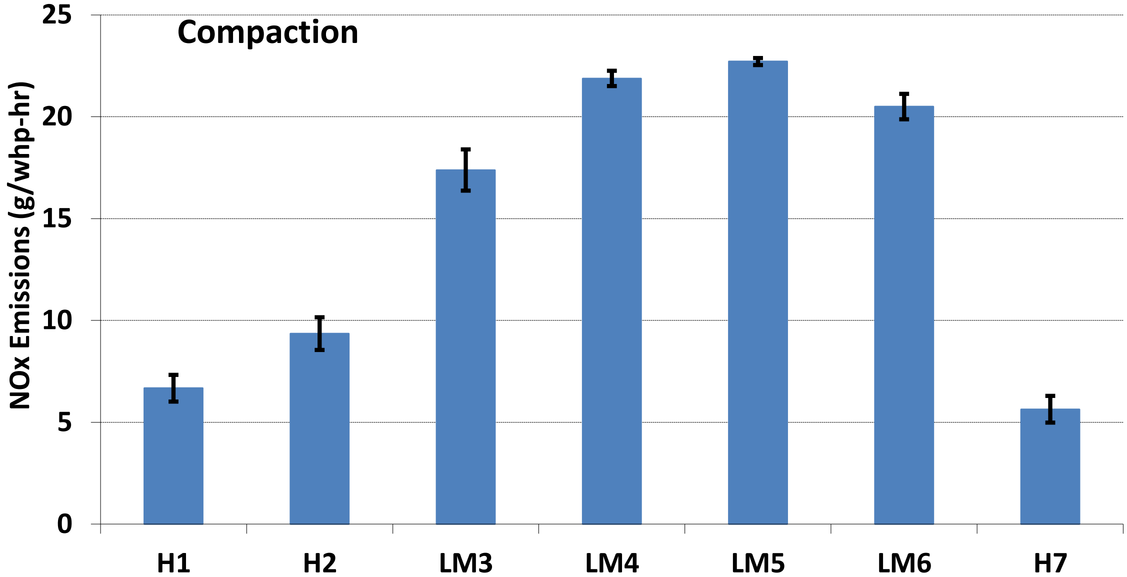
a



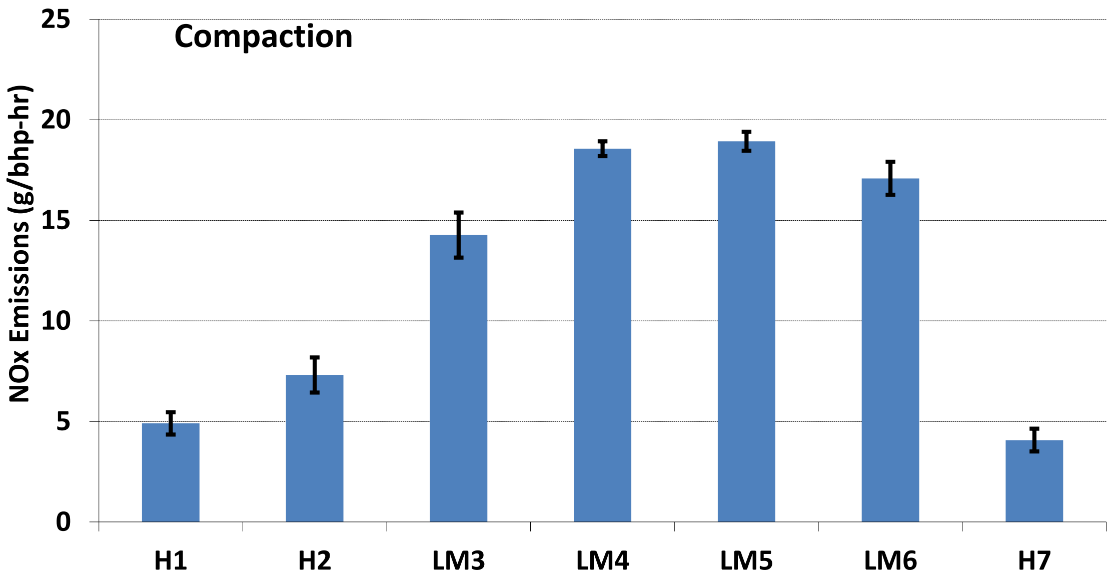
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-3 (a-b). Average NO_x Emissions for the Waste Hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)



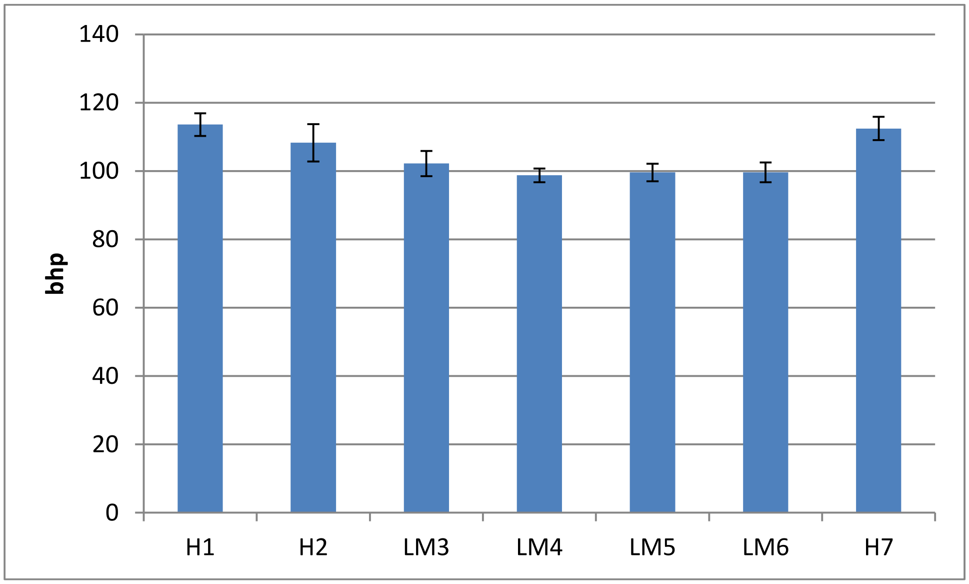
a



b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-4. Average bhp of the Compaction Segment



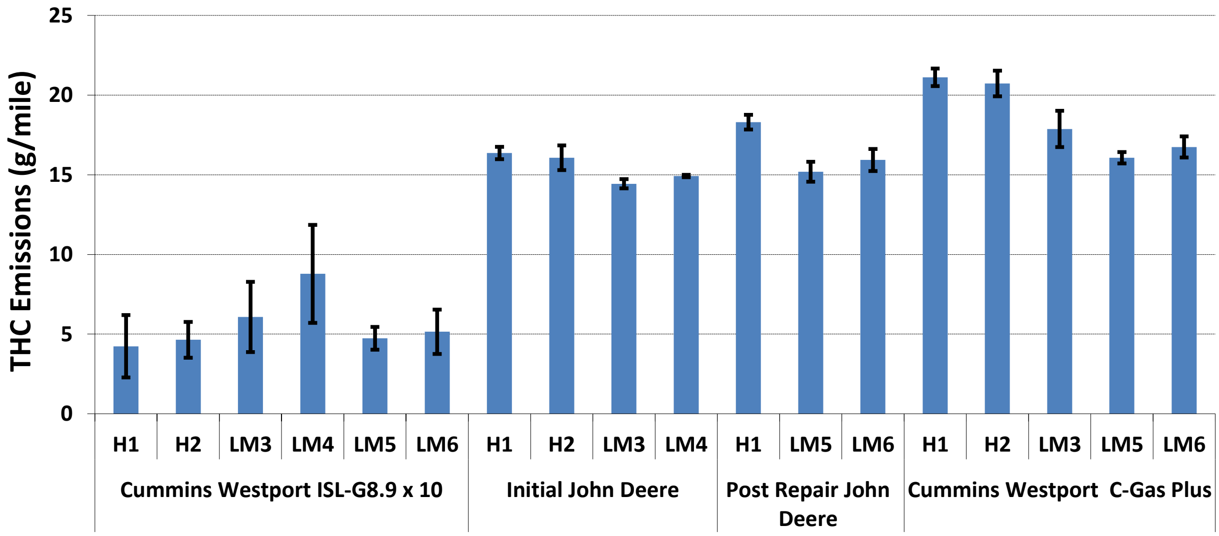
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.2 THC Emissions

Figure 3-5 shows the THC emissions for the three NG buses. Figure 3-6 (a-b) shows the THC emissions for the waste hauler for the transport and curbside segments, while Figure 3-7 (a-b) shows the THC emissions for the compaction segment on a whp-hr and bhp-hr basis. THC emissions were significantly lower for the Cummins Westport ISL-G8.9 bus than the older John Deere and C-Gas Plus buses, noting that the emissions for the Cummins Westport ISL-G8.9 bus are multiplied by 10 in the figure. This can be attributed to the differences in the engine technology, since the older engines are all lean-burn engines with OCs designed to meet an earlier certification standard, and the ISL-G is a stoichiometric combustion engine with a TWC that is designed to meet a recent and more stringent certification standard [30,31]. The John Deere and C-Gas Plus buses showed trends of higher THC emissions for the gases with higher methane contents. This trend is consistent with results previously reported by other authors [10].This is probably due to the fact that the THC emissions were predominately methane. This can be seen from the discussion below, as the CH_4 emissions are roughly comparable to the THC emissions, while the NMHC emissions are very low. The reductions in THC emissions for the low methane gases could also be due to more complete oxidation of the fuel as the combustion temperatures increased, as discussed under the NO_x section. CH_4 is also less reactive from a combustion standpoint than higher hydrocarbons [32], so it is more likely to go through the combustion process unburned and go unreacted across the aftertreatment. For the C-Gas Plus bus, statistically significant reductions in THC emissions of 15%, 24%, and 21%, respectively, for LM3, LM5, and LM6 were found compared to H1. For the post-repair John Deere bus testing, LM5 and LM6 showed statistically significant reductions of 17.0% and 13.0%, respectively, in THC emissions compared to H1. For the initial testing on the John Deere bus, LM3 and LM4 showed statistically significant reductions of 11.8% and 8.8%, respectively, in THC emissions compared to H1. For the Cummins Westport ISL-G bus, THC emissions were very low and did not show strong fuel trends, with only the LM4 showing a statistically significant slight increase (107%) in THC emissions compared to the baseline H1. The differences between fuels for the Cummins Westport ISL-G bus are still on the same order as the background levels of the system, however, and as such could be simply an artifact of measuring at such low levels.

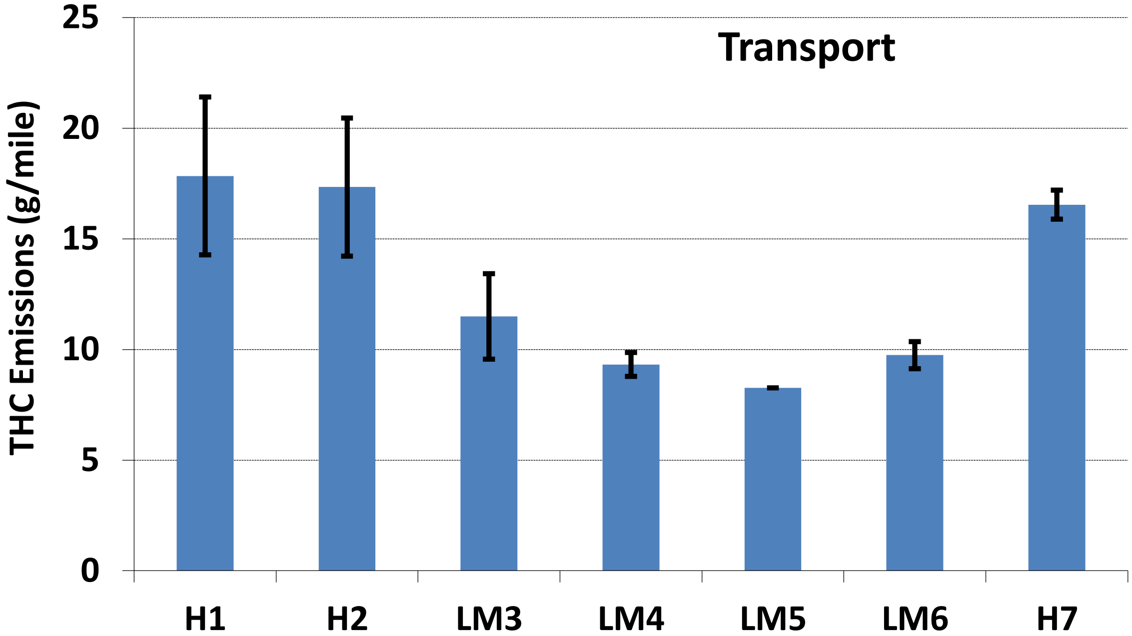
For the waste hauler truck, the high methane gases, such as H1, H2, and H7, also produced higher THC emissions than LM3, LM4, LM5, and LM6. For the transport, curbside, and compaction segments, the reductions in THC emissions with the LM3, LM4, and LM6 gases were all statistically significant when compared to the H1, H2, and H7 gases. Note that for THC emissions, only a single test was available for LM5 for the waste hauler since there was a problem with the flame for the THC flame ionization detector (FID). Thus, no statistical comparisons of the emissions reductions could be made for this fuel, and this fuel is not included in the percentage differences below. For the transport segment, these reductions were 36-48% compared to H1, 34-46% compared to H2, and 31-44% compared to H7. For the curbside segment, the reductions were 15.3-19.6% compared to H1, 8.4-13.0% compared to H2, and 24-28% compared to H7. For the compaction segment, the reductions were 46-53% compared to H1, 32-40% compared to H2, and 52-58% compared to H7 on whp-hr basis, and the reductions were 40-45% compared to H1, 28-34% compared to H2, and 46-50% compared to H7 on a bhp-hr basis. Comparing the transport and curbside modes, THC emissions were found to be lower for the higher speed and higher load transport mode. This result was expected, since THC emissions tend to be higher on a g/mi basis during idling and stop and go driving conditions than in other driving modes. For the compaction segment, the differences in THC emissions between H1 and H2 were statistically significant on both whp-hr and bhp-hr basis.

Figure 3-5. Average THC Emissions for NG Buses.

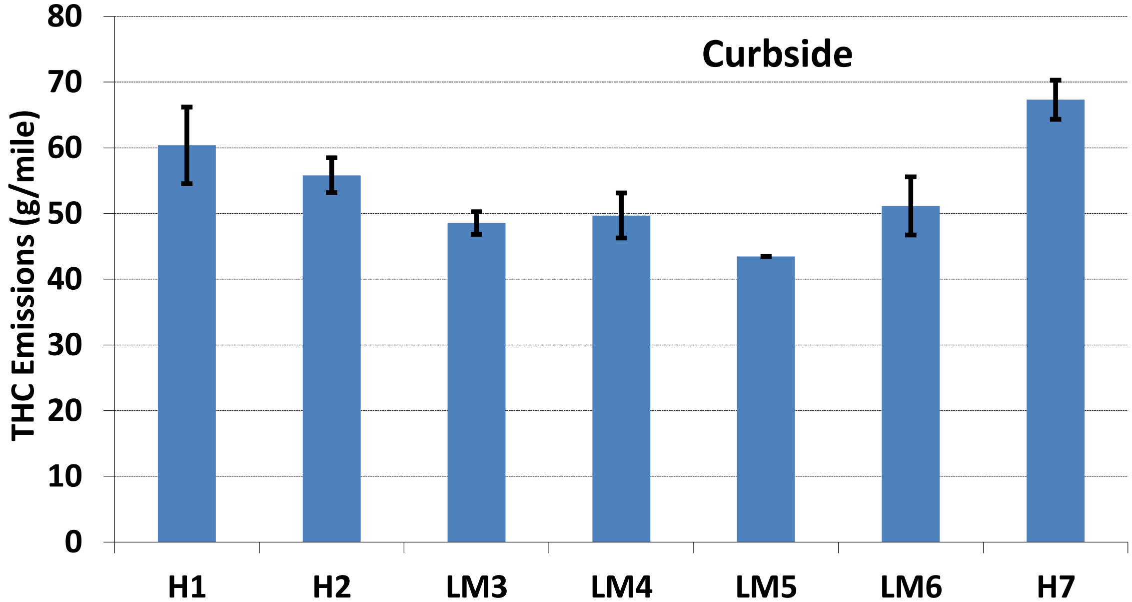


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-6 (a-b). Average THC Emissions for Waste Hauler Transport and Curbside Segments



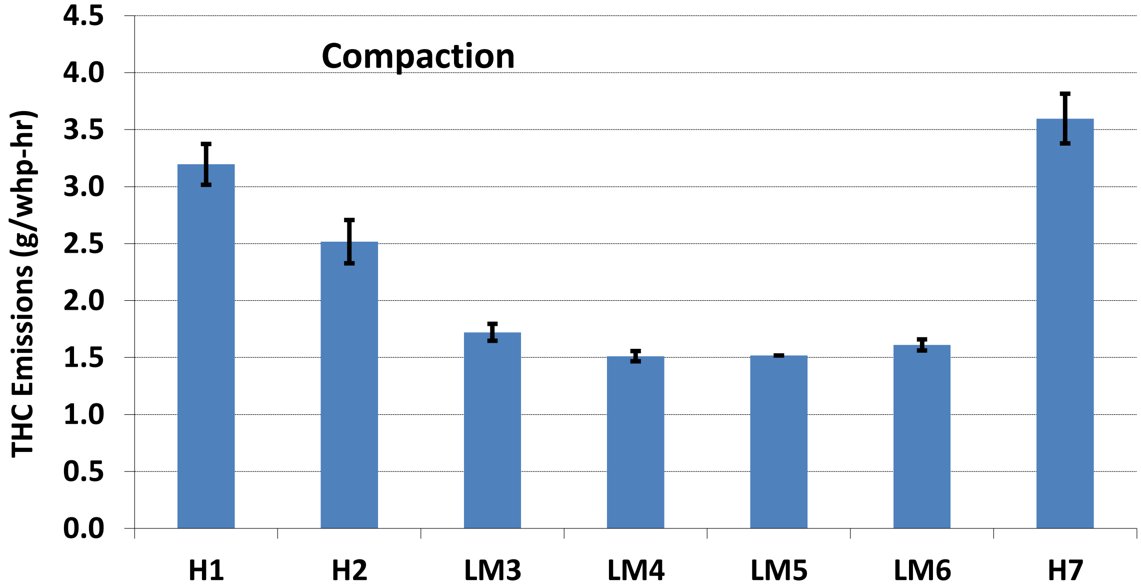
a



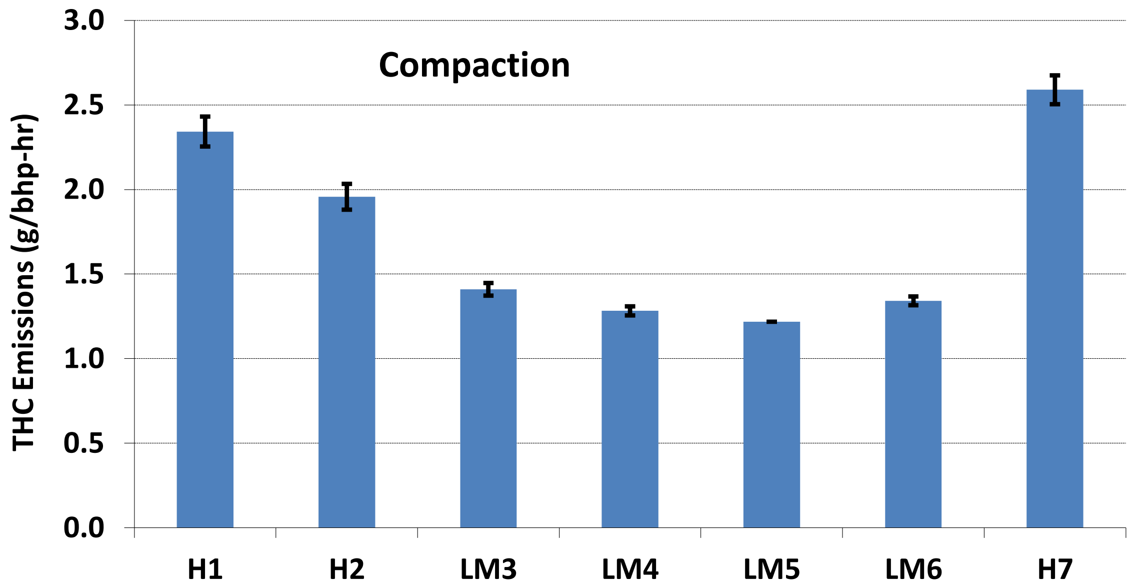
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-7 (a-b). Average THC Emissions for the Waste Hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)



a



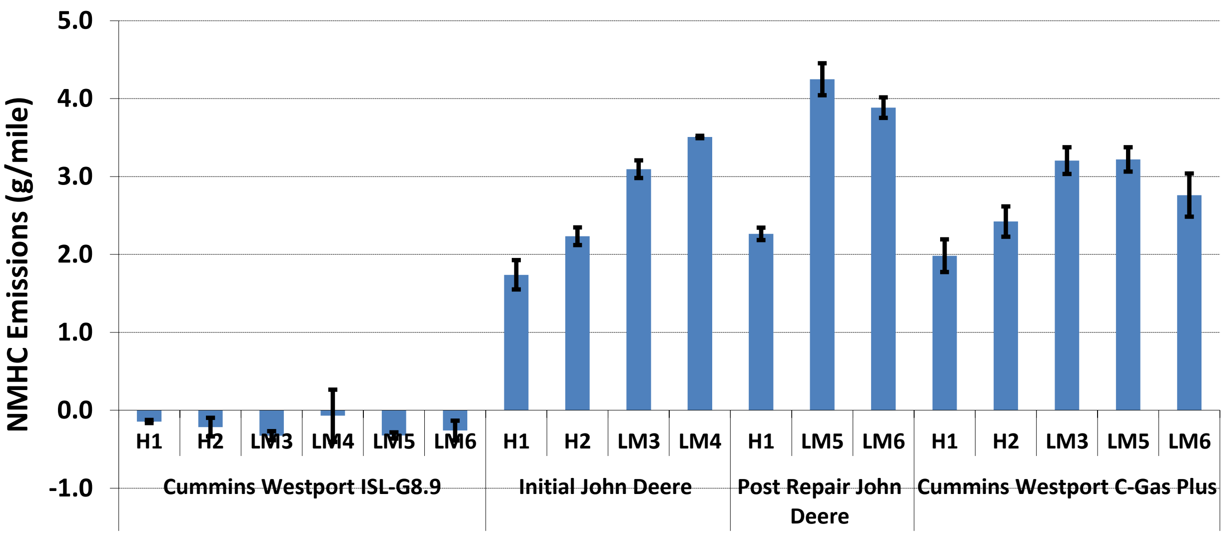
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.3 NMHC Emissions

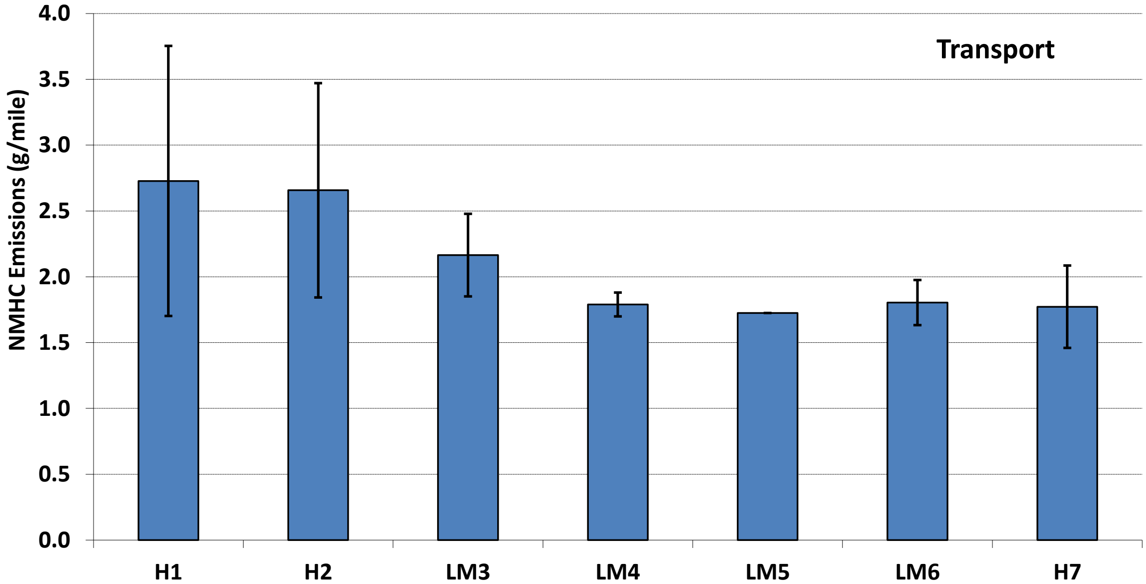
Figure 3-8 shows the NMHC emissions for the NG buses. Figure 3-9 (a-b) shows the NMHC emissions for the waste hauler for the transport and curbside segments, while Figure 3-10 (a-b) shows the NMHC emissions for the compaction segment on a whp-hr and bhp-hr basis. As can be seen, all the NG buses emitted very low levels of NMHC emissions compared to THC emissions, with the NMHC emissions for the newer technology Cummins Westport bus at the background levels. This is consistent with expectations and indicates that the THC emissions from these vehicles are predominantly methane with little NMHC emissions. The older buses all showed trends of higher NMHC emissions for the gases containing higher levels of NMHCs (i.e., ethane, propane, and butane, as shown in Table 2-1). Previous studies have also shown that NMHC emissions increased with decreasing methane number of the fuel gases [29,33]. THC emissions from natural gas engines are predominately unburned fuel, therefore, the non-methane hydrocarbon fraction of THC exhaust emission typically trends with the percentage of non-methane hydrocarbons in the test fuel. The C-Gas Plus bus showed statistically significant increases in NMHC emissions for H2, LM3, LM5, and LM6 of 22%, 62%, 62%, and 39%, respectively, compared to H1. For the post-repair John Deere testing, LM5 and LM6 had statistically significant increases in NMHC emissions of 88% and 72%, respectively, compared to the H1. For the initial John Deere bus testing, the LM3 and LM4 gases showed statistically significant NMHC emissions increases of 78% and 102%, respectively, compared to H1, and of 39% and 57%, respectively, compared to H2. Initial testing of the John Deere bus and the C-Gas Plus bus showed differences between H1 and H2 which were statistically significant.

Figure 3-8. Average NMHC Emissions for NG Buses.

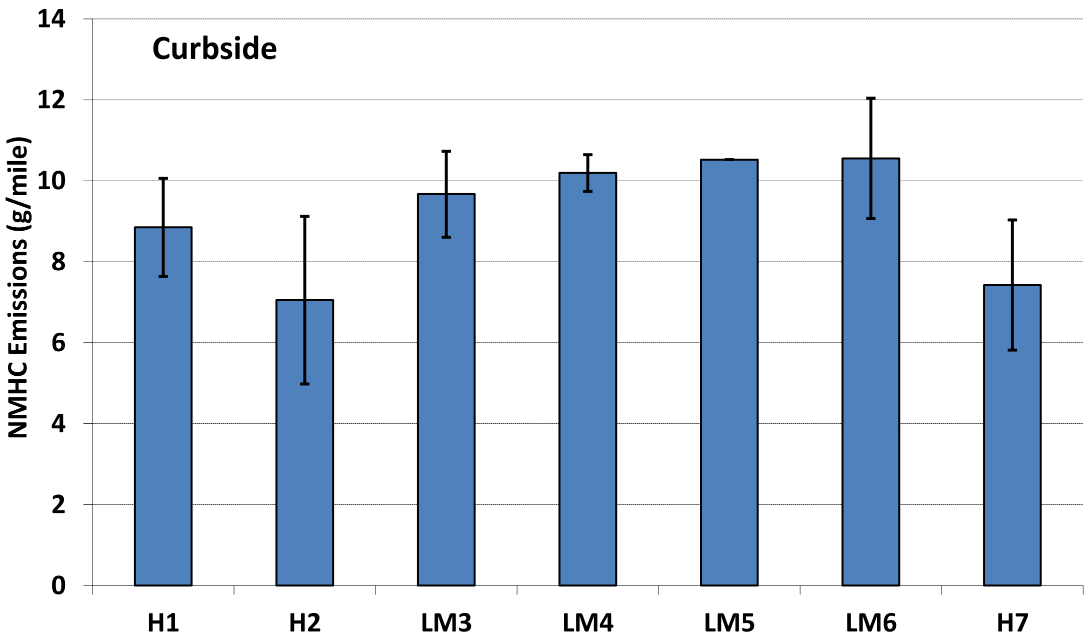


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-9 (a-b). Average NMHC Emissions for Waste hauler Transport and Curbside Segments



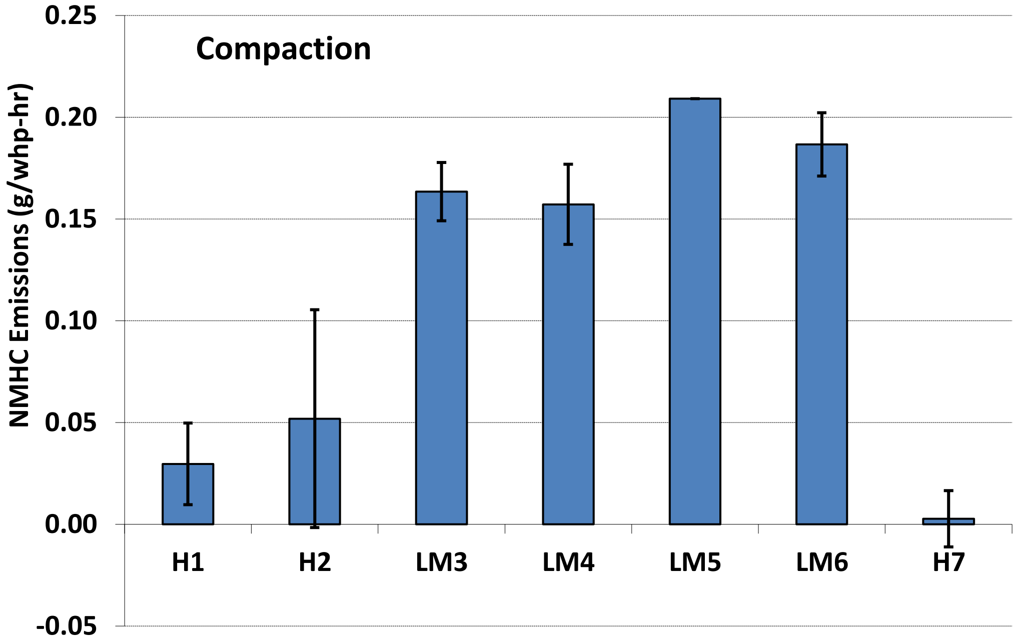
a



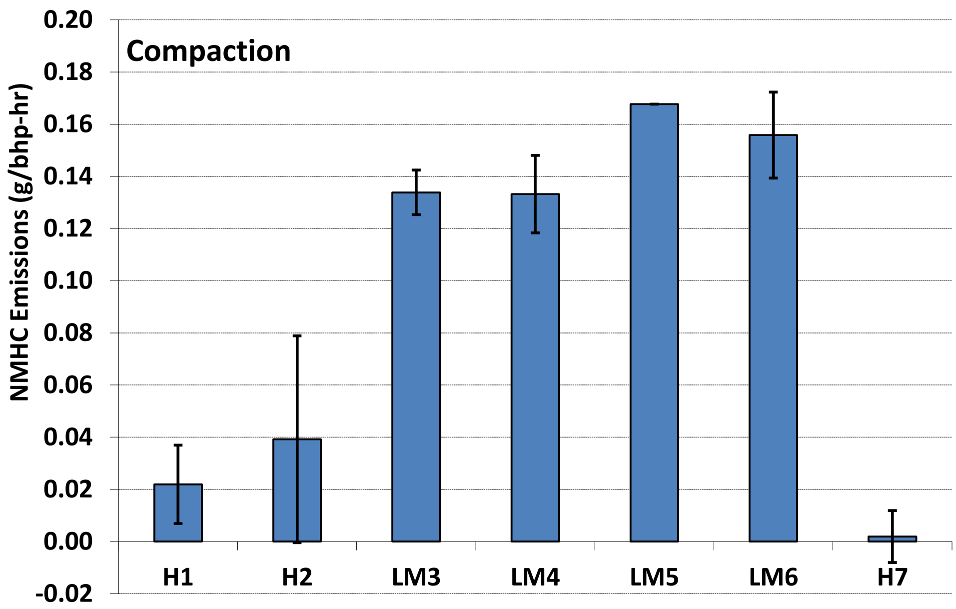
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-10 (a-b). Average NMHC emissions for Waste hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)



a



b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

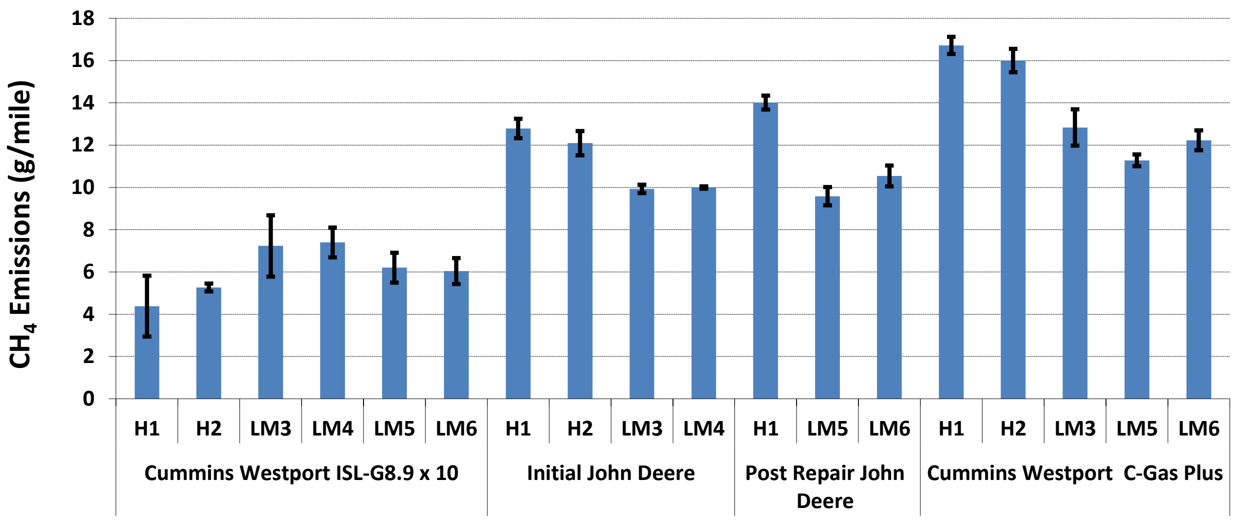
For the waste hauler, the NMHC emissions were also at very low levels. Overall, for both the curbside and compaction segments, NMHC emissions increased as the NMHC fraction of the fuel increased, although this trend was not seen for the transport segment. For the compaction segment, the LM3, LM4, and LM6 gases exhibited increases that were statistically significant and were large on a percentage basis compared to H1, H2, and H7 gases. The percentage differences of these increases were large in magnitude due to low NMHC emissions factors for the compaction segment. Note that for NMHC emissions, only a single test was available for LM5, so no statistical comparisons of the emissions reductions could be made for this fuel. For the curbside segment, the gases of LM3, LM4, and LM6 exhibited statistically significant increases compared to H1, H2, and H7 gases in most cases. These increases were 9.2-19.2%, 37-50%, and 30-42%, respectively, compared to H1, H2, and H7. For the transport segment, interestingly, the low methane gases produced lower NMHC emissions compared to H1 and H2 gases. This result is not in agreement with previous studies showing that NMHC emissions increased with decreasing methane number of the fuel gases [15]. Compared to H1 and H2 gases, the reductions in NMHC emissions for the transport segment for LM4 and LM6 were, respectively, statistically significant and marginally statistically significant compared to H1 and statistically significant compared to H2. These reductions were 34% and 32-33%, respectively, compared to H1 and H2. H7 also showed lower NMHC emissions than H1 and H2, which were marginally statistically significant and statistically significant. For the curbside segment, the difference in NMHC emissions between H1 and H2 was marginally statistically significant.

3.4 CH_4 Emissions

Figure 3-11 shows the CH_4 emissions for the NG buses. The results showed that CH_4 emissions for the Cummins Westport ISL-G bus were about 95% lower than those for the John Deere and C-Gas Plus buses, noting that the CH_4 emissions for the ISL-G are near the background level and are multiplied by 10 so that they can more readily be seen in the figure. The older buses all showed a trend of higher CH_4 emissions for gases with higher methane contents, including H1, H2, and H7. The C-Gas Plus bus showed the highest methane emissions for H1 and H2, with reductions in CH_4 emissions of 4.3%, 23%, 33%, and 27%, respectively, for H2, LM3, LM5, and LM6 compared to H1, with all of the reductions being statistically significant. For the post-repair John Deere bus testing, H1 showed the highest CH_4 emissions, with statistically significant reductions in CH_4 emissions of 32% and 25%, respectively, for LM5 and LM6 compared to H1. For the initial John Deere test, H1 and H2 produced higher CH_4 emissions than those of LM3 and LM4. The Cummins Westport ISL-G showed higher CH_4 emissions for gases LM3 and LM4, but similar to THC, the differences in CH_4 between gases are comparable to the background levels of the system, and hence, are probably more an artifact of measuring at such low levels than real fuel effects. For C-Gas Plus, there were statistically significant differences between H1 and H2. For John Deere, the differences between H1 and H2 were marginally statistically significant.

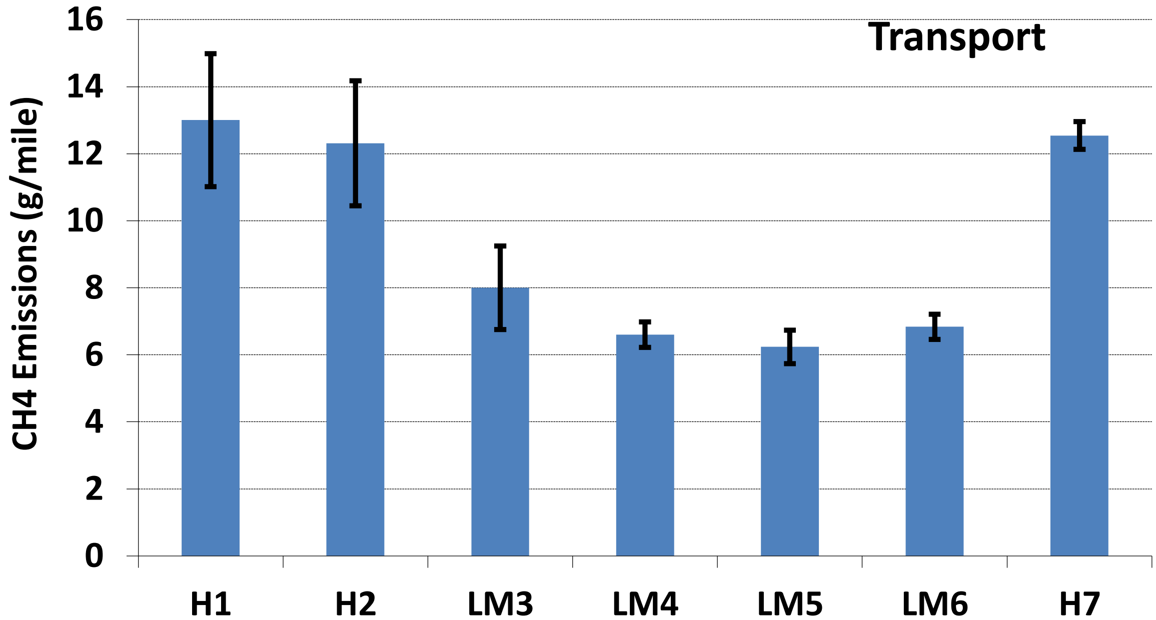
For the waste hauler, CH_4 emissions followed similar patterns for all the three segments of the Refuse Truck Cycle, as shown in Figure 3-12 (a-b) for the transport and curbside segments and in Figure 3-13 (a-b) for the compaction segment on a whp -hr and bhp-hr basis. The fuel effect was consistent, and showed that gases with higher methane contents exhibited higher CH_4 emissions. For the transport, curbside, and compaction segments, CH_4 emissions for the LM3, LM4, LM5, and LM6 gases were lower at a statistically significant level than those of H1, H2, and H7 gases. For the transport segment, these reductions were 38-52%, 35-49%, and 36-50%, respectively, compared to H1, H2, and H7. For the curbside segment, the reductions were 25-34%, 17-27%, and 34-42%, respectively, compared to H1, H2, and H7. For the compaction segment, reductions were 51-60%, 37-48%, and 57-65%, respectively, compared to H1, H2, and H7 on a whp-hr basis and the reductions were 45-54%, 33-44%, and 51-59%, respectively, compared to H1, H2, and H7 on a bhp-hr basis. For the –curbside and compaction segments (whp-hr and bhp-hr basis), the differences observed in CH_4 emissions between H1 and H2 were statistically significant.

Figure 3-11. Average CH_4 Emissions for NG Buses.

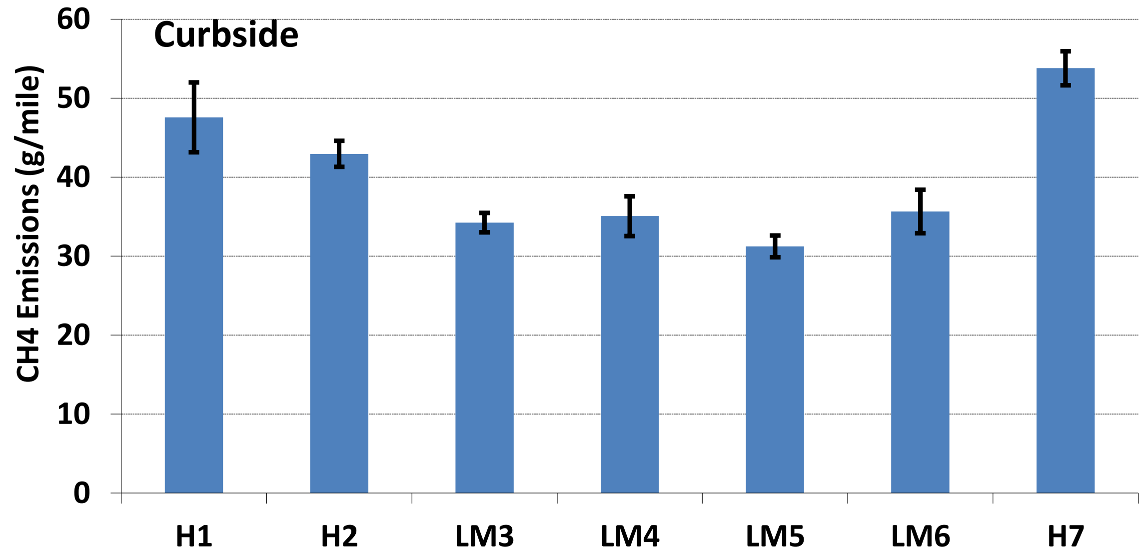


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-12 (a-b). Average CH_4 Emissions for Waste hauler Transport and Curbside Segments



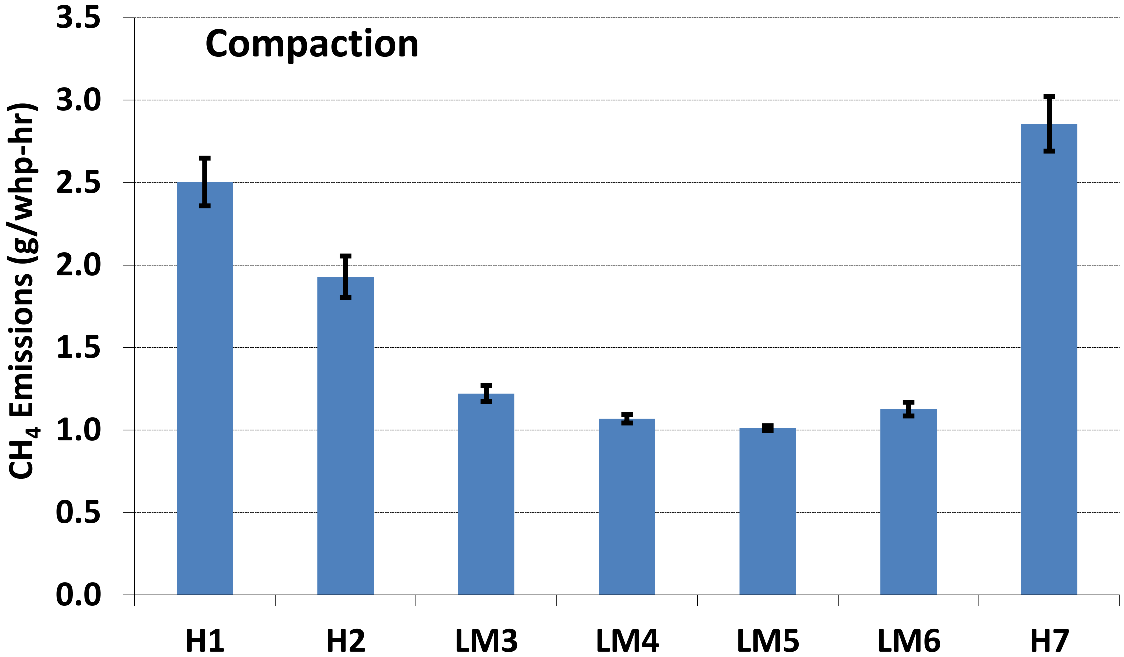
a



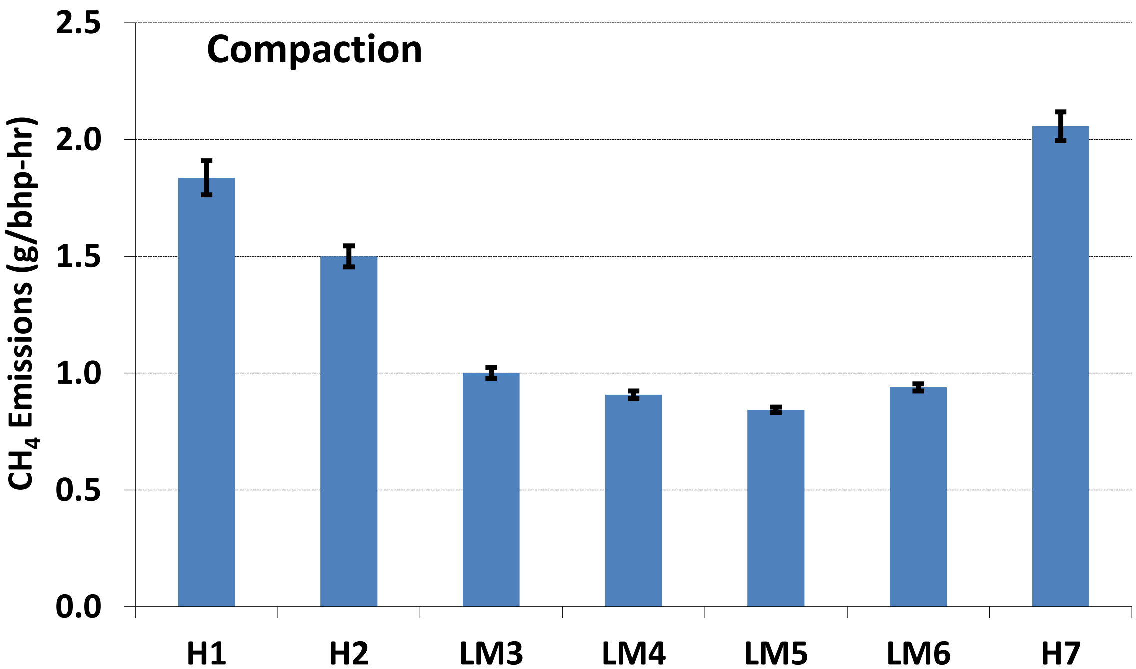
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-13 (a-b). Average CH_4 Emissions for Waste hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)



a



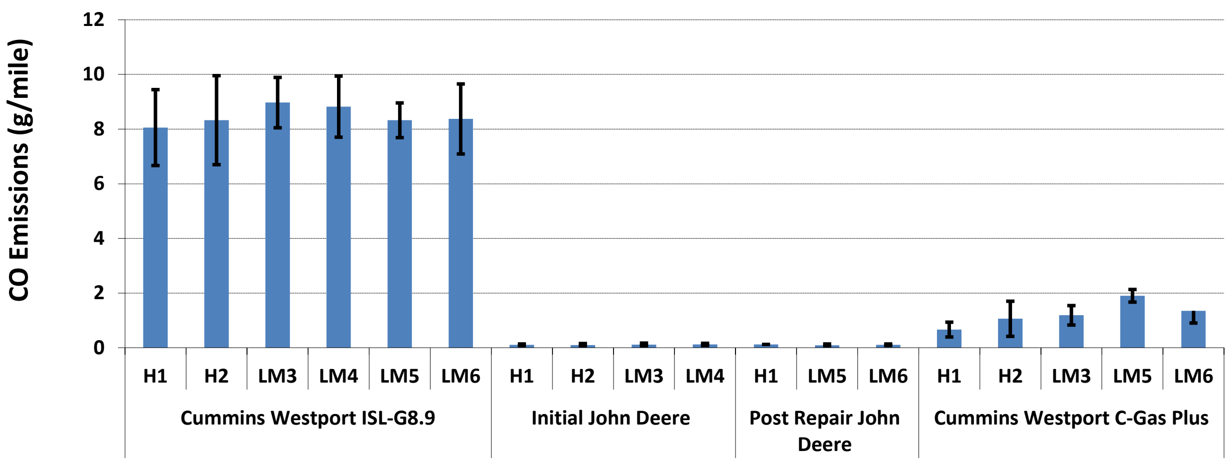
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.5 CO Emissions

Weighted CO emissions for the NG buses are shown in Figure 3-14. The CO emissions for the Cummins Westport ISL-G 8.9 vehicle were significantly higher than those emitted for the John Deere bus during post-repair and initial testing and for the C-Gas Plus bus. This can be attributed to the impact of richer operating conditions for the stoichiometric combustion Cummins Westport ISL-G engine compared to the other lean-burn engines during combustion and across the catalyst. This observation was consistent with the results of previous chassis dynamometer tests as well as a recent engine dynamometer study that also evaluated a Cummins Westport ISL-G engine, a C-Gas Plus engine, a C-Gas engine, and a John Deere engine [15,30,31,34]. In these studies, the Cummins Westport ISL-G also showed the highest CO emissions compared to the other engines. Although the results of these studies are all consistent, these studies and our study all show greater differences in CO emissions between the ISL-G and different lean burn engines than are seen in comparing the certification data for the ISL-G and the C-Gas Plus engines (see Appendix A). CO emissions for the post-repair John Deere test were near the measurement limits. This is consistent with the low CO emission levels found during the certification testing, as shown in Appendix A. Both initial and post repair John Deere testing showed very low CO emissions. For the Cummins Westport ISL-G and John Deere buses, no statistically significant differences in CO emissions between fuels were found. The C-Gas Plus bus showed some increases in CO emissions of 78%, 185% and 103%, respectively, for the low methane LM3, LM5 and LM6 gases compared to H1 that were statistically significant. The CO emissions for H2 were comparable to those of LM3 and LM6, however.

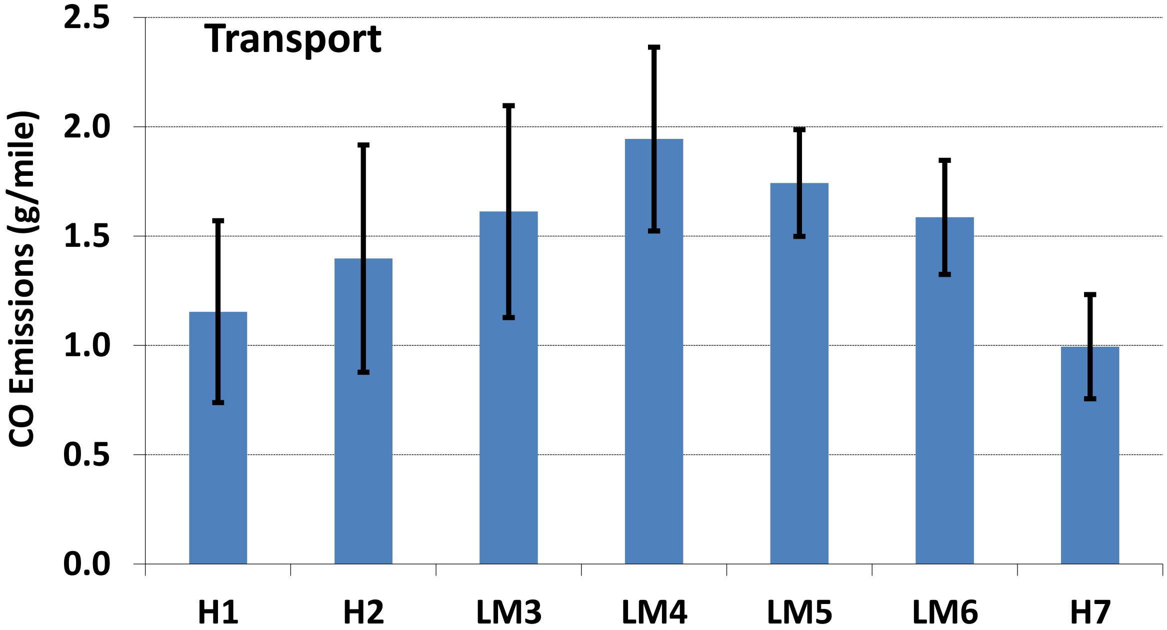
Figure 3-14. Average CO Emissions for NG Buses.



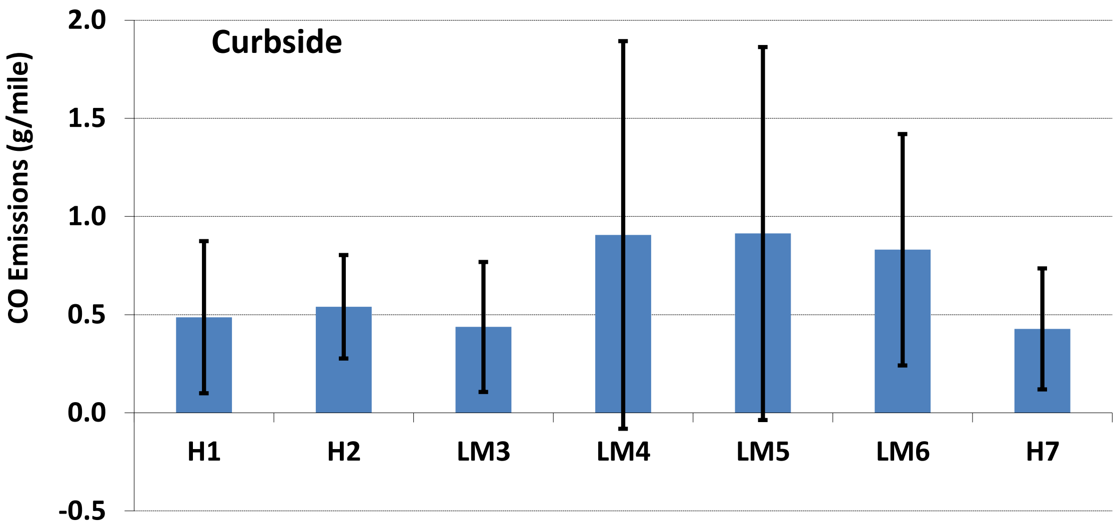
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-15 (a-b) shows the CO emissions for the waste hauler for the transport and curbside segments, while Figure 3-16 (a-b) shows the CO emissions for the compaction segment on a whp-hr and bhp-hr basis. For the waste hauler truck, during the compaction segment of the cycle, the CO emissions for the LM3, LM4, LM5, and LM6 gases were substantially lower than those of H1, H2, and H7 gases, with these reductions being statistically significant. These reductions were 40-55% compared to H1, 35-51% compared to H2, and 35-51% compared to H7 on a whp-hr basis and these reductions were 33-48% compared to H1, 31-47% compared to H2, and 26-43% compared to H7 on a bhp-hr basis. Although some differences between specific fuels were seen for the transport and curbside segments, these were generally not statistically significant. It should be noted that CO emission levels were found to be generally low (less than 1 g/mi for the curbside segment). For comparison with engine certification test results, a conversion factor of 4 bhp-hr/mi can be used [34]. On this basis, the CO emissions are below <1 g/bhp-hr for both the transport and curbside modes, ranging from 0.11-0.48 g/bhp-hr, which is considerably lower than the 15.5 g/bhp-hr certification standard [35]. Comparing the transport and the curbside modes of the cycle, there were slightly higher CO emissions for the transport mode. This is somewhat in contrast to the trends seen for most of the other pollutants. The higher CO emissions for the transport cycle could be due to greater operation under rich conditions, since the transport cycle is characterized by higher speeds and accelerations and higher load operation. For the curbside, on the other hand, the conditions may be so lean that minimal CO is formed, leading to the low CO emission rates seen for the curbside cycle. Irrespective, these differences are relative minor in relation to the certification levels of the engine.

Figure 3-15 (a-b). Average CO Emissions for Waste Hauler Transport and Curbside Segments



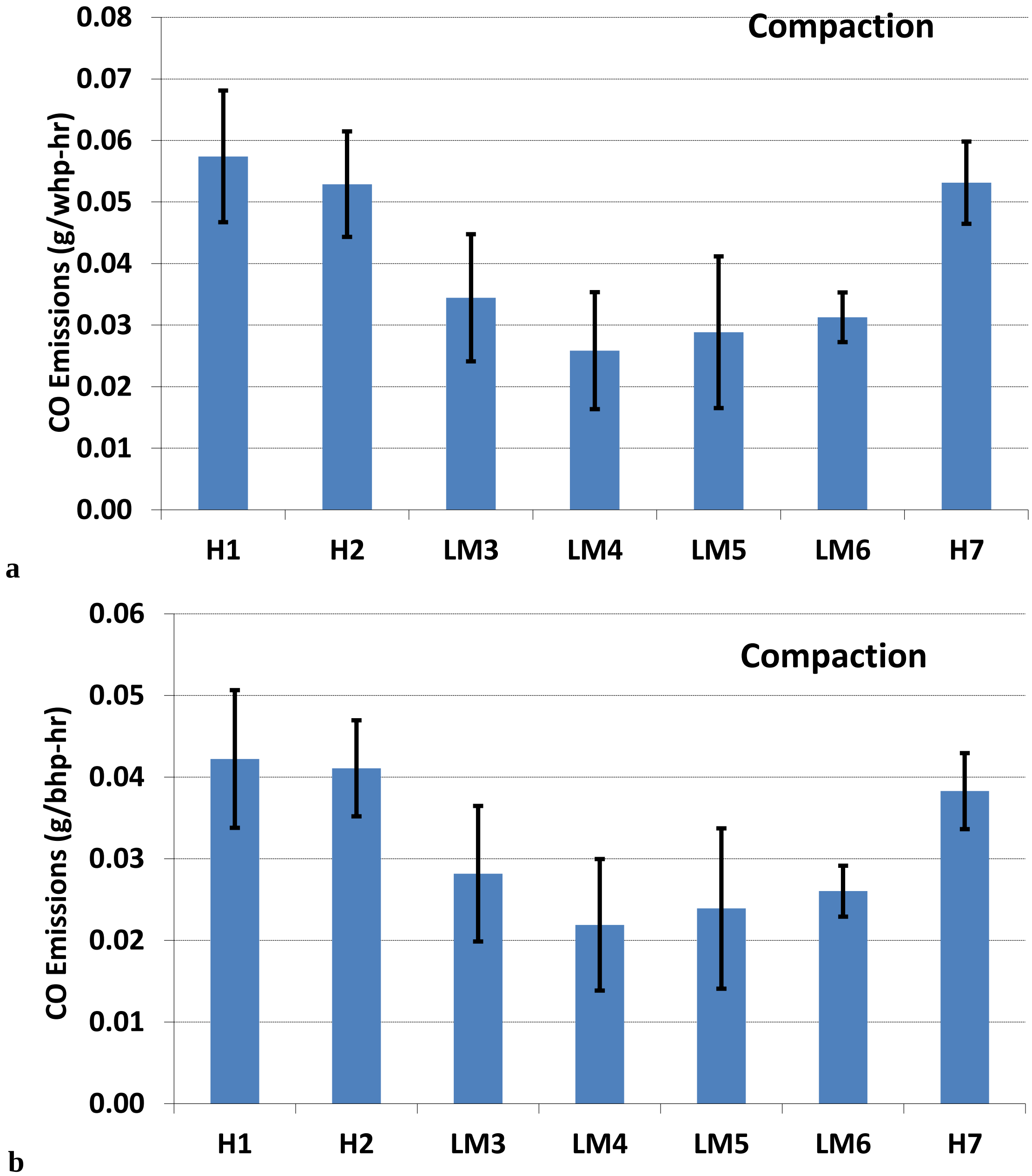
a



b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-16 (a-b). Average CO emissions for Waste Hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis(b)

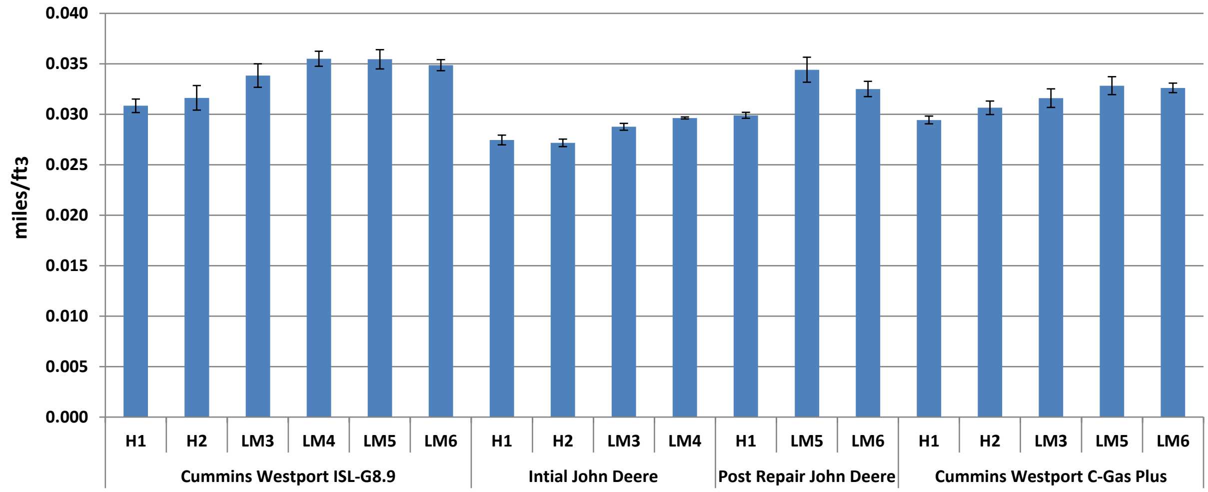


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.6 Fuel Economy/Consumption and CO_2 Emissions

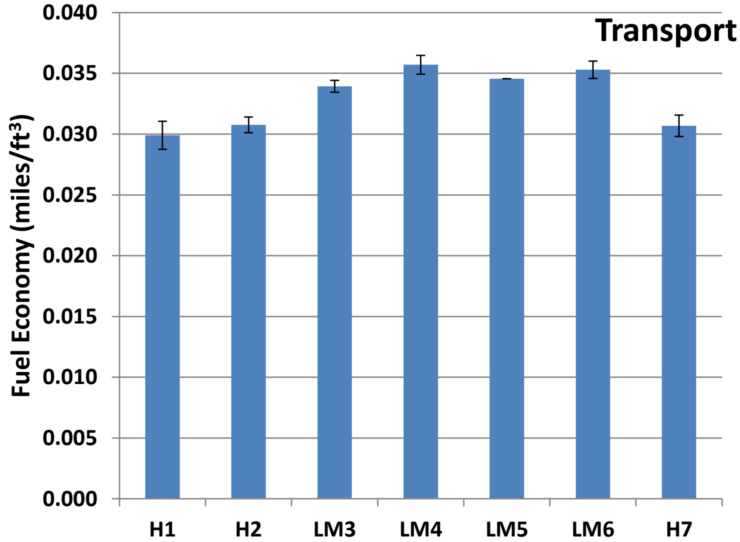
Figure 3-17 and Figure 3-18 (a-b) show the average volumetric fuel economy, respectively, in miles/ft^3 for the buses and the waste hauler truck (the transport and curbside segments). The formulas used to calculate the volumetric fuel economy and the energy equivalent fuel economy are provided in Appendix C. The volumetric fuel economy is a more important measure of fuel economy for the consumer, as fuel is sold volumetrically. Fuel economy was determined using the carbon balance method. This method uses the amount of carbon emitted in the exhaust based on THC, CO, and CO_2 emissions to determine the amount of fuel carbon, and by association the amount of fuel, that was used by the engine. As shown in Figure 3-17 and Figure 3-18, when fuel economy is plotted on a volumetric basis, the differences between the fuel economies of the various test fuels are readily apparent, and in many cases statistically significant, as discussed below. For all the buses, the low methane gases with the higher heating values, i.e., LM3, LM4, LM5, and LM6, showed higher fuel economy compared to H1 and H2. The fuel economy increases for LM3, LM4, LM5, and LM6 compared to H1 were all statistically significant for all the buses. The same trend was also seen for the waste hauler truck for transport and curbside cycles, with LM3, LM4, LM5, and LM6 showing higher volumetric fuel economy compared to H1, H2, and H7. The magnitude of increases was on the order of 5 to 21% and all of them were statistically significant except for the increase seen for LM6 compared to H1 for the curbside cycle which was marginally statistically significant. Interestingly, for the curbside segment, LM5 showed higher fuel economy compared to LM4 and LM6, even though LM5 had a lower energy content than LM4 and LM6. Note that for LM5, the THC emissions were available only as a single test. As such, fuel economy/consumption via carbon balance could only be calculated for a single test on LM5, and no statistical comparisons of fuel economy were made for this fuel. Therefore, no statistical analysis was available for LM5 compared to other fuels. Figure 3-19 (a-b) shows the volumetric fuel consumption for the waste hauler on a ft^3/whp-hr and ft^3/bhp-hr basis. The compaction cycle for the waste hauler showed lower fuel consumption for gases LM3, LM4, and LM6 on a whp-hr basis, consistent with the higher energy contents of these fuels. These reductions were all statistically significant compared to H1, H2, and H7. The fuel consumption showed a somewhat opposite trend on a bhp-hr basis, with fuels H2, LM3, LM4, and LM6 showing higher fuel consumption than H1 and H7. The increases observed for H2, LM3, LM4, and LM6 compared to H1 and H7, were all statistically significant. This can be attributed to the lower bhp ECM readings for the higher energy gases compared to H1 and H7, which produces the trend seen in the graph when the inverse of bhp is considered, as explained in section 3.1.

Figure 3-17. Average Volumetric Fuel Economy for NG Buses.

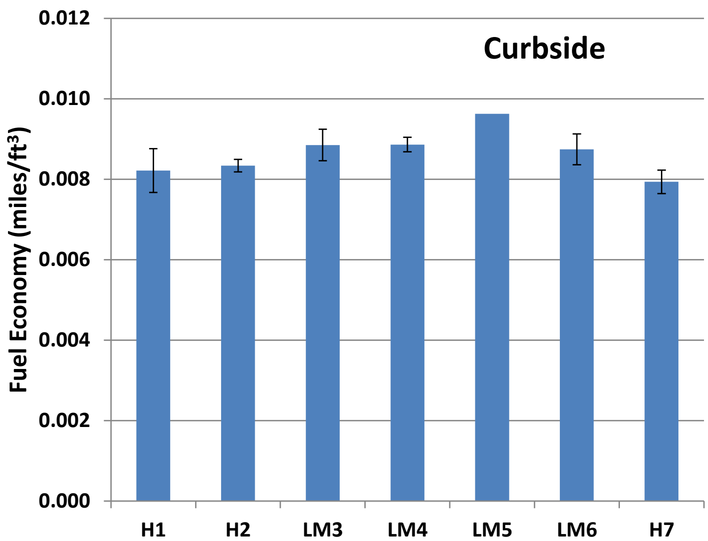


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-18. (a-b). Average Volumetric Fuel Economy for the Waste Hauler Transport and Curbside Segments.



a

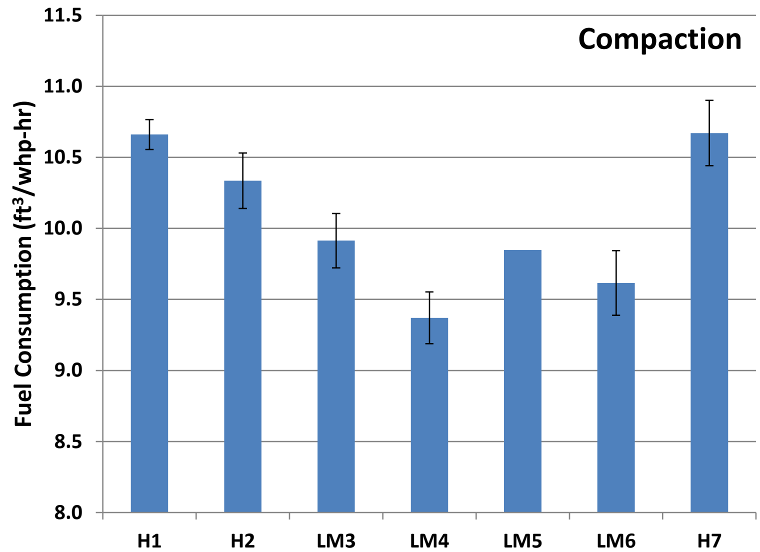


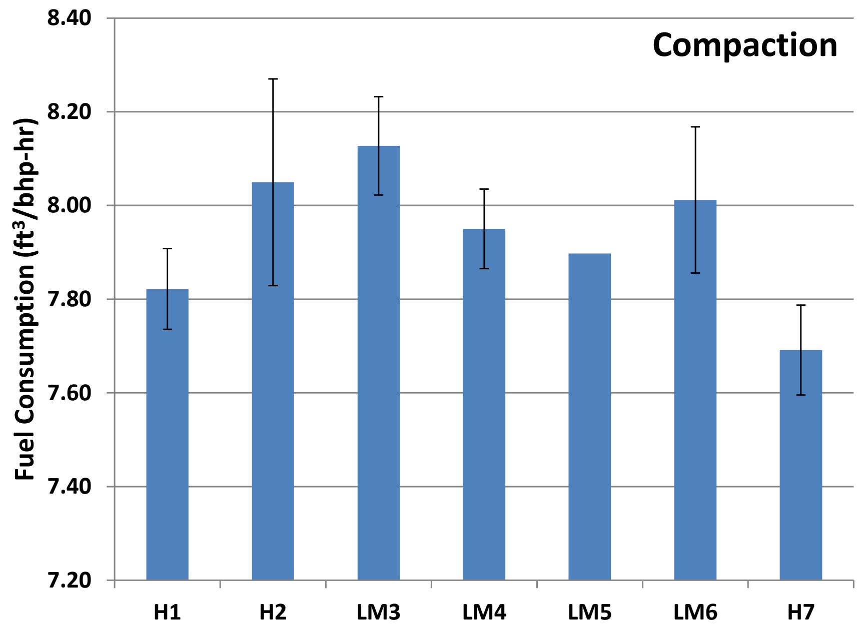
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-19 (a-b). Average Volumetric Fuel Consumption for the Waste Hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)

a



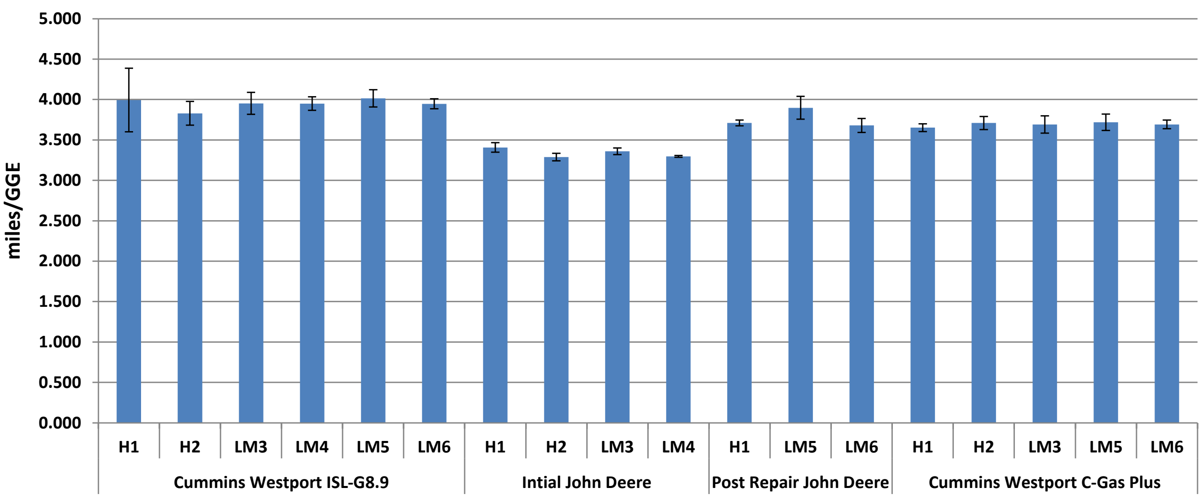


b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Fuel economy can also be examined on an energy equivalent basis. On this basis, the energy differences between the fuels are normalized. This provides an evaluation of fuel economy with the energy differences between fuels eliminated as a factor. The fuel economy results for the three buses powered with the different gas blends over the CBD test cycle are presented in Figure 3-20, on a gasoline gallon equivalent (GGE) energy basis. Overall, the three buses showed comparable fuel economy results between fuels on an energy equivalent basis. The C-Gas Plus and Cummins Westport ISL-G bus did not show any statistically significant fuel effects. The energy equivalent fuel economy differences for the post-repair John Deere were not statistically significant for LM6, but were only marginally statistically significant for LM5. The initial testing results for energy equivalent fuel economy on the John Deere, on the other hand, showed statistically significant decrease in fuel economy for low methane with higher energy content gas LM4, but this could be related to the mechanical failure. For the initial testing of John Deere bus, the difference in fuel economy between H1 and H2 was statistically significant.

Figure 3-20. Average Energy Equivalent Fuel Economy for NG Buses.

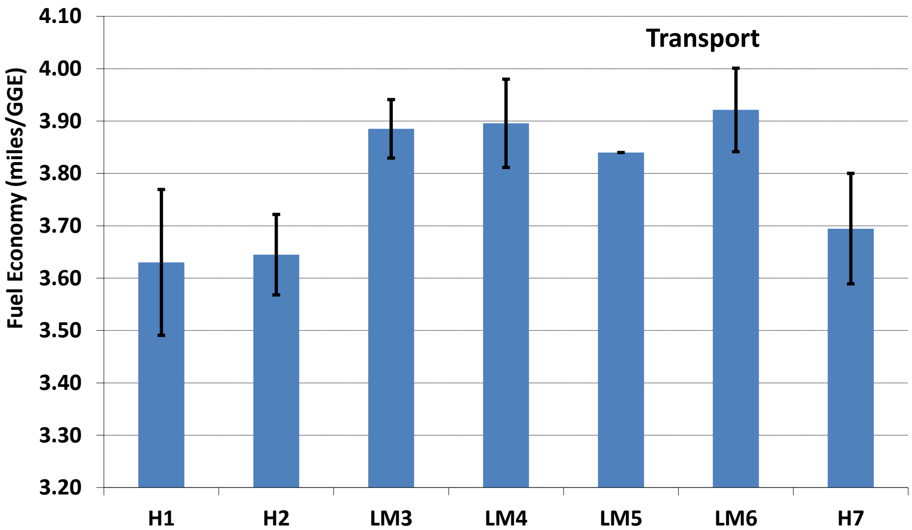


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

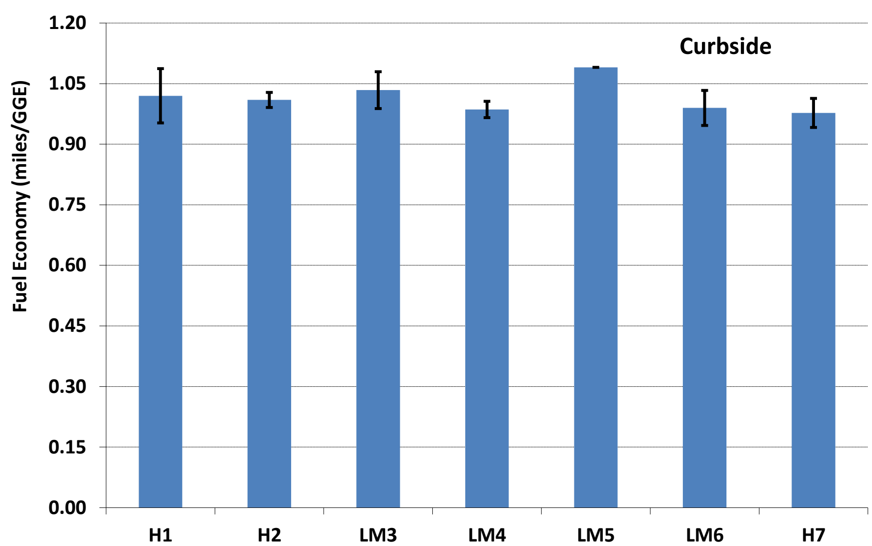
For the waste hauler, fuel economy is shown in Figure 3-21 (a-b) on a gasoline gallon equivalent energy basis for the transport and curbside segments. For the curbside segment, a statistically significant increase in energy equivalent fuel economy was observed for H7 versus LM3 and a marginally statistically significant decrease was observed for H2 versus LM4. For the transport segment, the low methane gases with higher energy contents (LM3, LM4, LM5, and LM6) exhibited higher energy equivalent fuel economy compared to the H1, H2, and H7 blends. The statistically significant increases in energy equivalent fuel economy for LM3, LM4, and LM6 gases were 6.5-7.4% compared to H1, 5.8-6.7% compared to H2, and 4.8-5.7% compared to H7.

For the waste hauler, fuel consumption is shown in Figure 3-22 (a-b) on a gasoline gallon equivalent energy basis for the compaction segment on a whp-hr and bhp-hr basis. On a whp-hr basis, marginally statistically significant reductions in fuel consumption were seen for LM4 compared to H1 and H7. More trends in energy equivalent fuel consumption were found for the compaction segment when the hp from the ECM was used as the basis for comparison. The gases of H1, H2, and H7 exhibited lower energy equivalent fuel consumption compared to the other gases. Specifically, compared with H1, H2, and H7, statistically significant energy equivalent fuel consumption increases of 4.6 to 14.4% were found for the LM3, LM4, and LM6 fuels. The fuel consumption for H2 was also higher than that of H1 at a statistically significant level. Again, as discussed above, this trend is primarily related to the fact that the higher energy fuels recorded lower bhp-hr readings from the ECM, rather than real efficiency differences between the fuels.

Figure 3-21 (a-b). Average Energy Equivalent Fuel Economy for the Waste Hauler Transport and Curbside Segments.



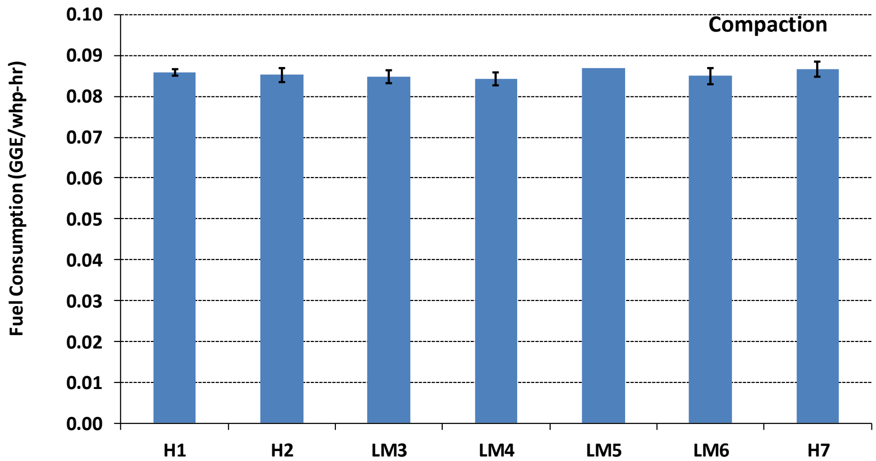
a



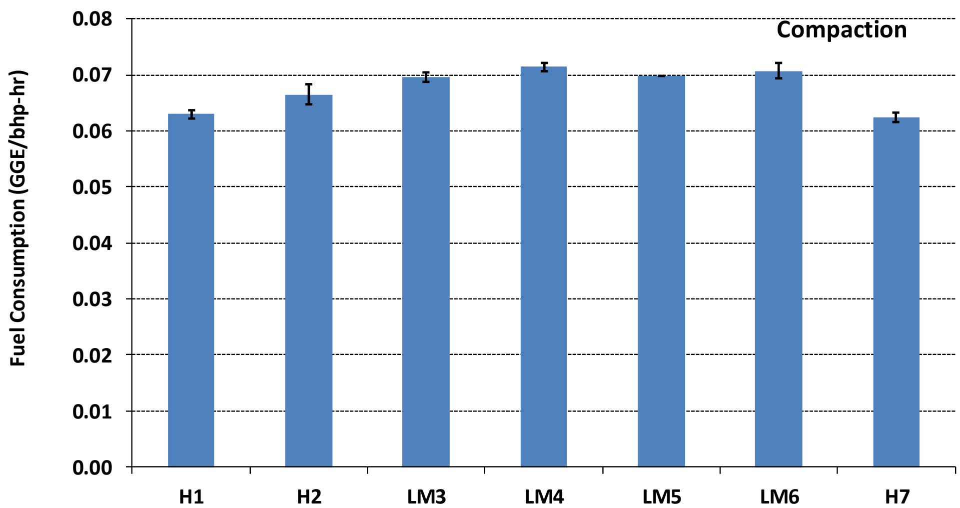
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-22 (a-b). Average Energy Equivalent Fuel Consumption for the Waste Hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)



a



b

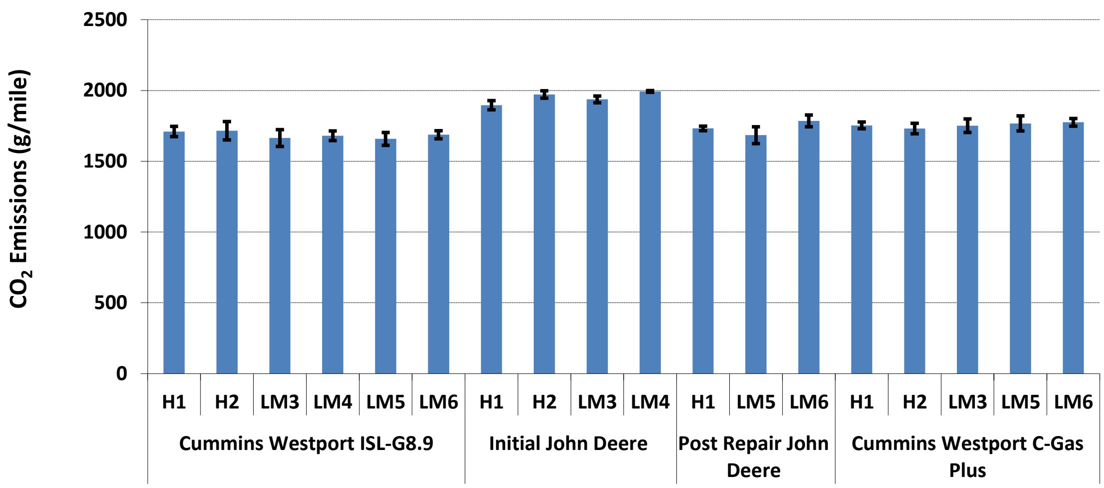
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

CO_2 emissions for the three buses and all fuel/cycle combinations are shown in Figure 3-23. CO_2 emissions from the three buses were comparable. The initial testing on the John Deere bus showed slightly higher CO_2 emissions, which could be related to its mechanical issues. The Cummins Westport ISL-G8.9, post-repair John Deere, and C-Gas Plus buses did not show strong trends in CO_2 emissions between the fuels. The initial testing of the John Deere bus showed slight, but statistically significant, increases in CO_2 emissions for H2 and LM4 compared to H1 and LM3. These differences could be related to the mechanical issue, however. The difference in CO_2 emissions between H1 and H2 for the initial testing of John Deere was statistically significant.

CO_2 emissions for the waste hauler are shown in Figure 3-24 (a-b) for the transport and curbside segments. For the waste hauler, CO_2 emissions for the curbside segment were higher than those for the transport segment on a per mile basis. For the curbside segment, no consistent fuel trends for CO_2 were observed. For the transport segment, interestingly, the results showed lower CO_2 emissions for the low methane gases with lower H/C ratios, compared to H1 and H2 gases, but not compared to H7. Most of the differences between the fuel gases for the transport segment were statistically significant. These differences were -3.6- -4.7% for LM3, LM4, and LM6 compared to H2 and -4.0- -5.0% for LM3, LM4, and LM6 compared to H1.

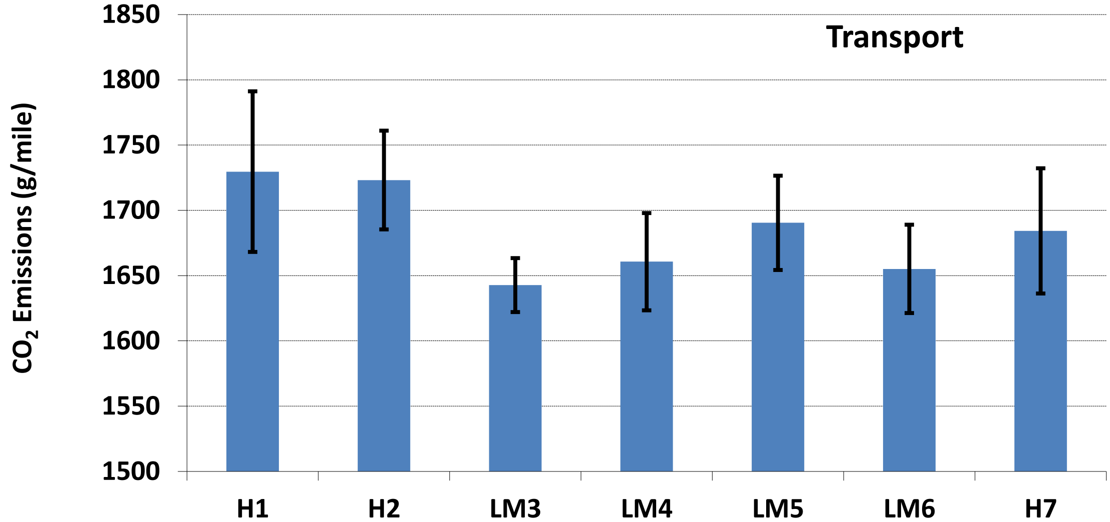
CO_2 emissions for the waste hauler are shown in Figure 3-25 (a-b) for the compaction segment on a whp-hr and bhp-hr basis. On a whp-hr basis, no significant differences were seen in CO_2 emissions between fuels, with the exception that CO_2 emissions for LM5 were higher at a statistically significant level than those for H1, H2, and H7. The compaction segment for the waste hauler showed trends for CO_2 emissions on an engine bhp-hr basis, with CO_2 emissions peaking for fuels LM4, LM5, and LM6. Compared to the baseline H1, H2, and H7, all of the fuel gas blends exhibited statistically significant increases in CO_2 emissions on a bhp-hr basis of between 5.2 to 19.4% compared to H1, H2, and H7. Again, this can be attributed to the lower bhp energy readings for the higher energy gases, as discussed for the fuel consumption.

Figure 3-23. Average CO_2 Emissions for the NG Buses.

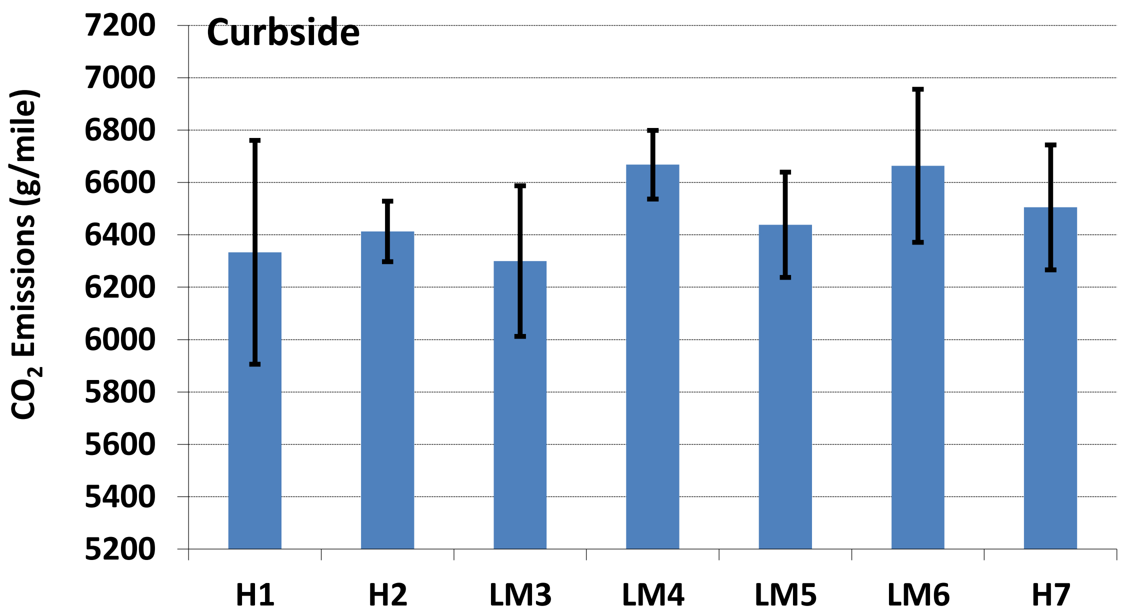


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-24 (a-b). Average CO_2 Emissions for the Waste Hauler Transport and Curbside Segments



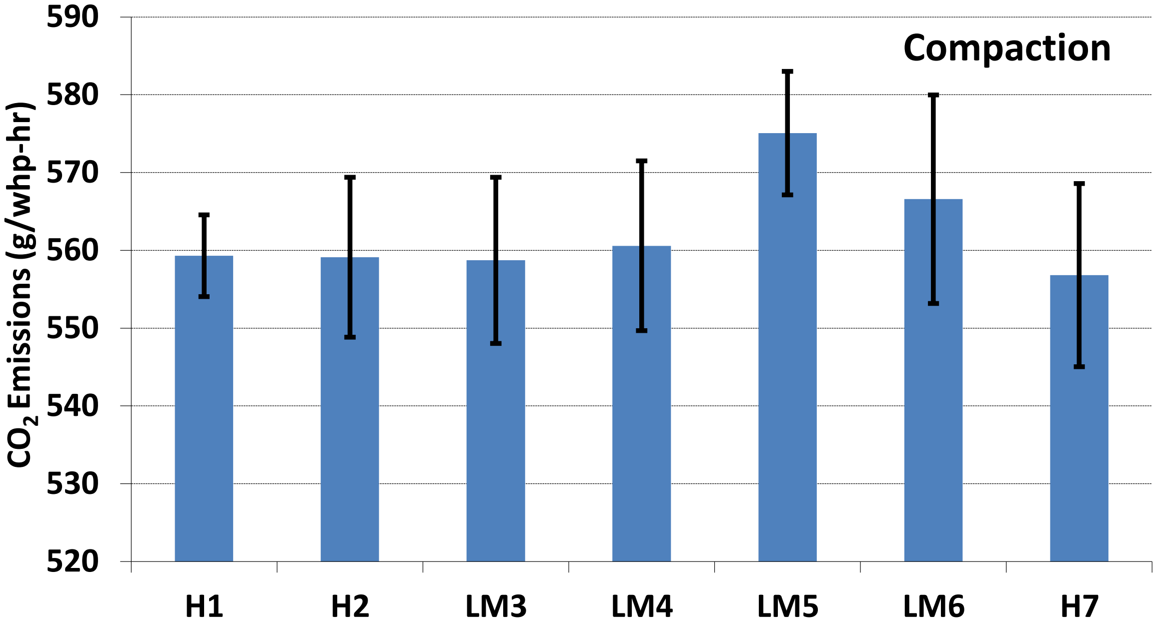
a



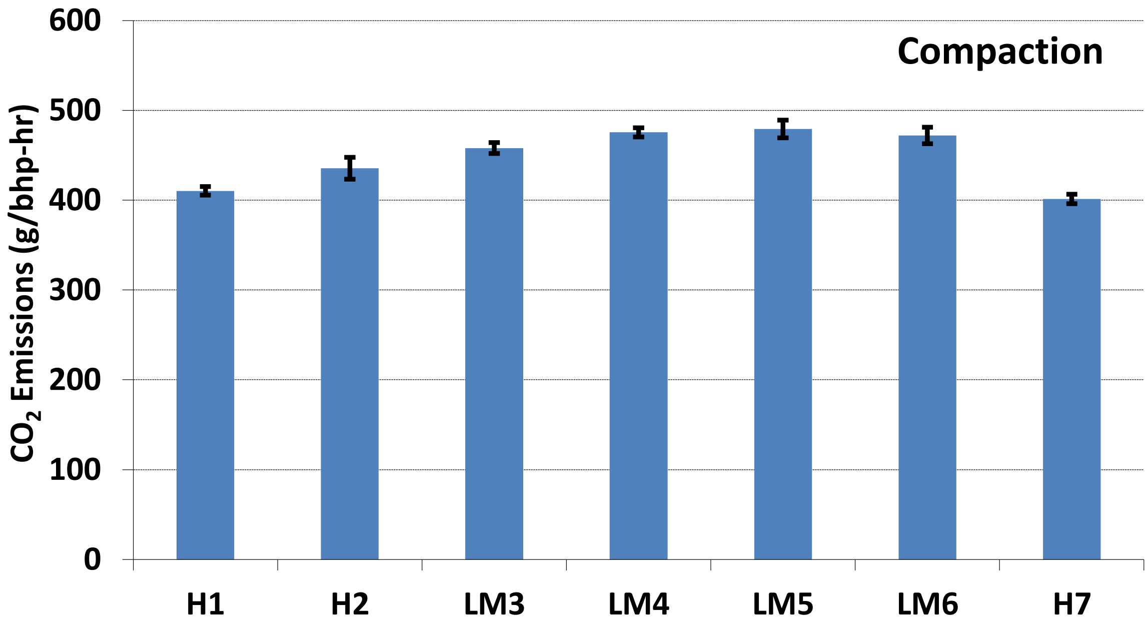
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-25. Average CO_2 Emissions for the Compaction Segment of the Waste Hauler on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b)



a



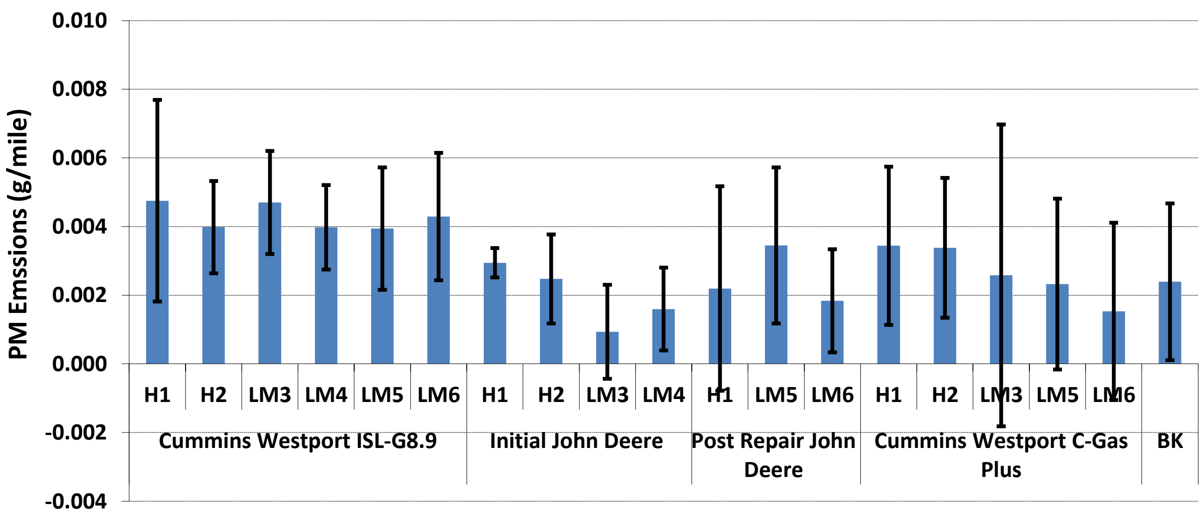
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN

3.7 PM Mass Emissions

Figure 3-26 shows the PM mass emissions for the NG buses over the CBD cycle. The results indicated that total PM mass emissions were low for all three buses on an absolute level, and are at the same levels as the tunnel background. Although some differences were seen between fuels, these differences were all within the range of the tunnel background levels. So, for the post-repair John Deere bus, the Cummins Westport ISL-G bus, and the Cummins Westport C-gas Plus bus testing, there were essentially no differences between PM mass for different fuels.

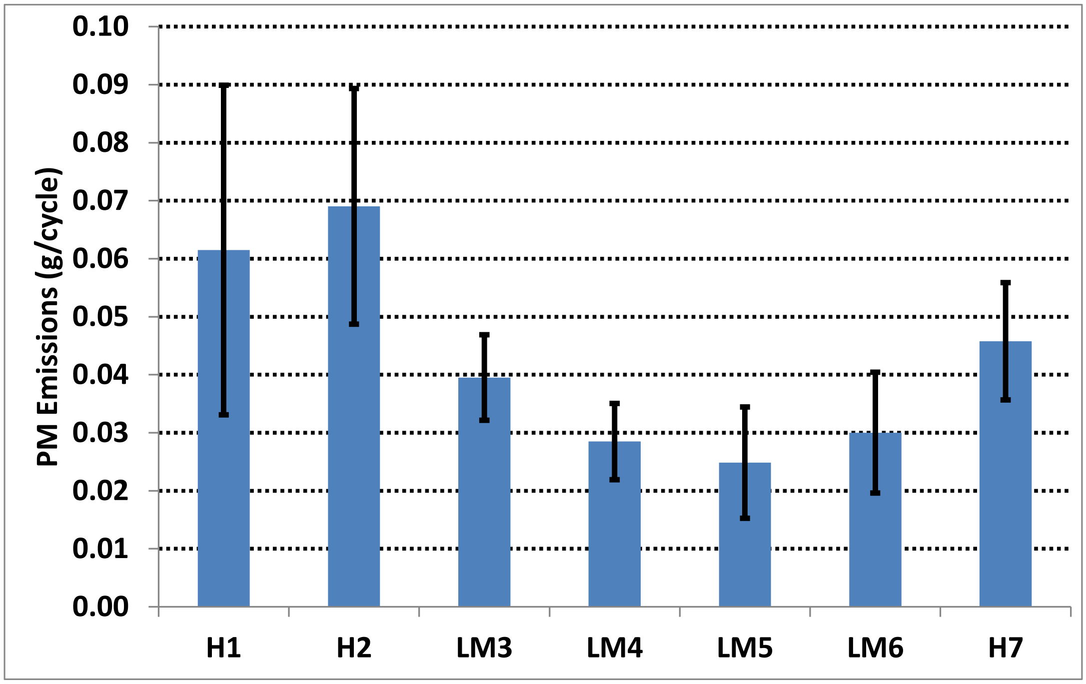
Figure 3-26. Average PM Emissions for NG Buses



H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

For the waste hauler, PM mass emissions are shown in Figure 3-27 for the composite Refuse Truck Cycle. As explained in section 2.4, PM emissions were collected cumulatively over the entire duration of the RTC due to the expectation of low mass levels emitted. Therefore, separate emissions are not available for the curbside, transport, and compaction segments. Instead, PM emissions are shown in terms of g/cycle. Compared to H1, H2, and H7, statistically significant reductions in PM emissions were found for LM4, LM5, and LM6. These reductions ranged from 51-60%, 43-64%, and 34-46%, respectively, compared to H1, H2 and H7. LM3 also demonstrated statistically significant reductions relative to H2, but not compared to H1 and H7. This was consistent with the trends seen for THC emissions and for CO emissions over the compaction cycle for the waste hauler, with the low methane gases showing lower PM levels, while the high methane gases showed higher PM levels.

Figure 3-27. Average PM Emissions for Waste Hauler



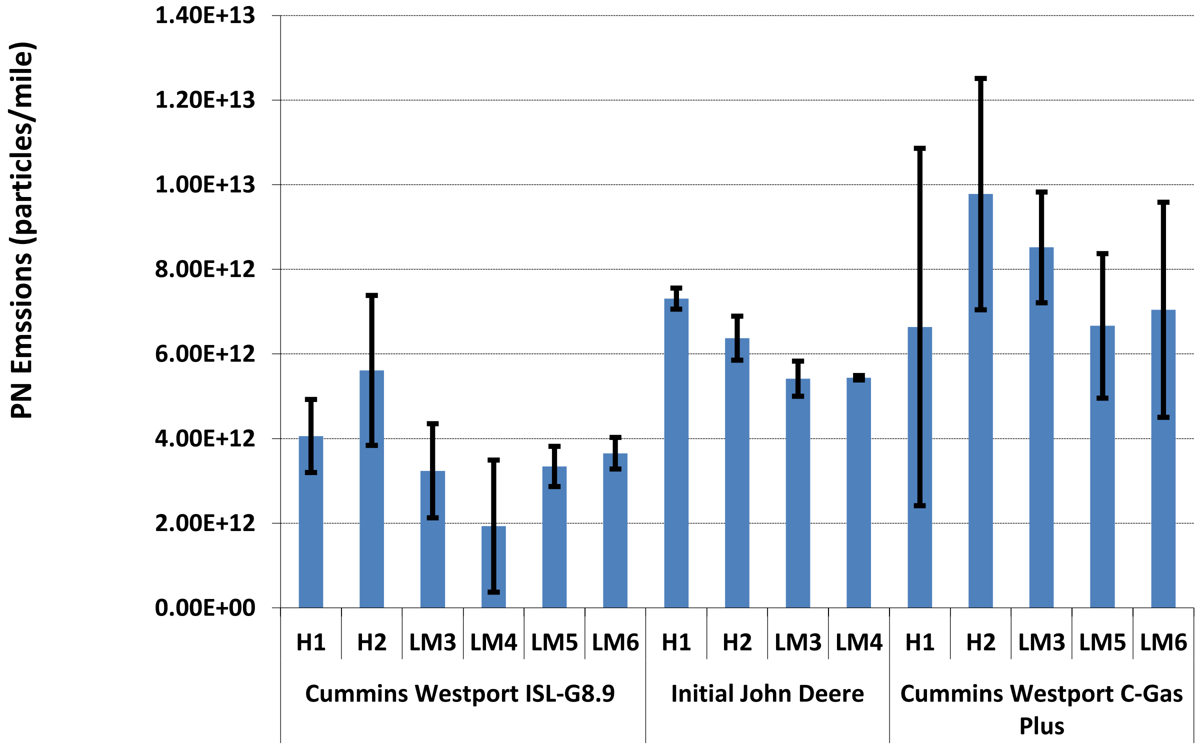
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.8 Particle Number Emissions

Figure 3-28 presents the particle number (PN) emissions for the NG buses over the CBD cycle. For the C-Gas Plus testing, the EEPS instrument was used for particle number measurement as well as particle size distribution. Note that PN results are not available for the post-repair John Deere bus testing because of issues with the data acquisition for the CPC. Also, for the post-repair John Deere Bus testing a nano-SMPS was used to measure size distributions, which measures only the particles in a particular size range at any one particular time. As such, the nano-SMPS cannot be used to obtain total PN. For the initial John Deere bus testing, all test gases exhibited a statistically significant reduction in PN emissions compared to the baseline H1, with LM3 and LM4 showing the largest reductions. For the C-Gas Plus bus, H2 and LM3 showed PN emissions that were higher than H1, but these differences were not statistically significant. The PN measurements for the C-Gas Plus bus with the EEPS were somewhat more variable than the CPC PN measurements for the other vehicles, which could make it more difficult to identify statistical trends. For the Cummins Westport ISL-G bus, some PN differences were seen between different fuels, but most of these differences were not statistically significant. The differences in PN emissions between H1 and H2 for initial John Deere testing were statistically significant. This difference was marginally statistically significant for the 2009 Cummins Westport ISL-G.

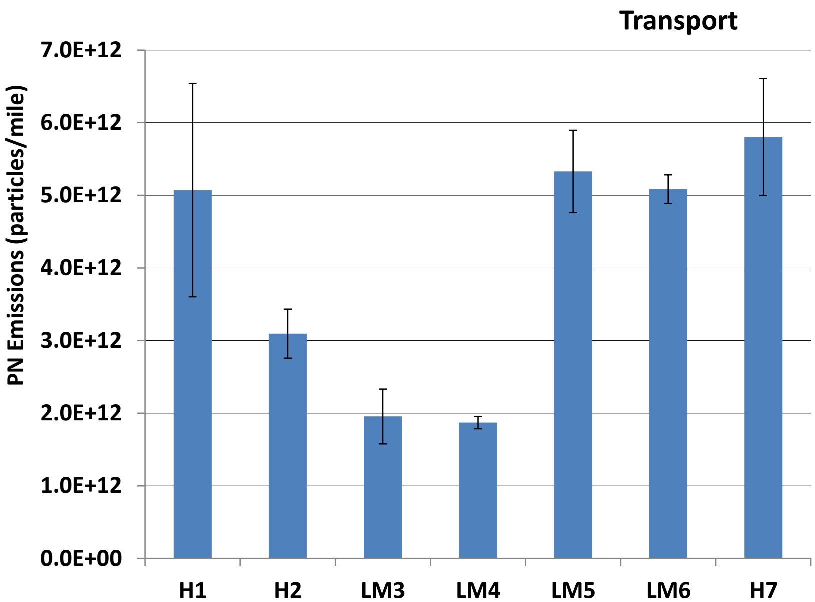
For the waste hauler, PN emissions are shown in Figure 3-29 (a-b) for the transport and curbside segment, and in Figure 3-30 (a-b) for the compaction segment on a whp-hr and bhp-hr basis. The experimental results show that PN emissions followed the same pattern for all three segments for the Refuse Truck Cycle with the H2, LM3, and LM4 showing the lowest PN emissions. These differences were statistically significant. Gases LM3 and LM4 have higher levels of heavier hydrocarbons compared to gases H1, H2, and H7, but not compared to LM5 and LM6. H2 also showed lower PN emissions than H1, LM5, LM6, and H7. The PN emission levels followed the PM mass reductions for LM3 and LM4 gases, but not for H2, LM5 and LM6. It should be noted that PN emissions were approximately an order of magnitude higher for the curbside segment compared to the transport segment of the cycle, as the curbside cycle covers a much shorter distance and is primarily composed of low speed accelerations and idling periods with little steady-state driving. The differences seen between H1 and H2 for all the segments were statistically significant.

Figure 3-28. Average PN Emissions for NG Buses

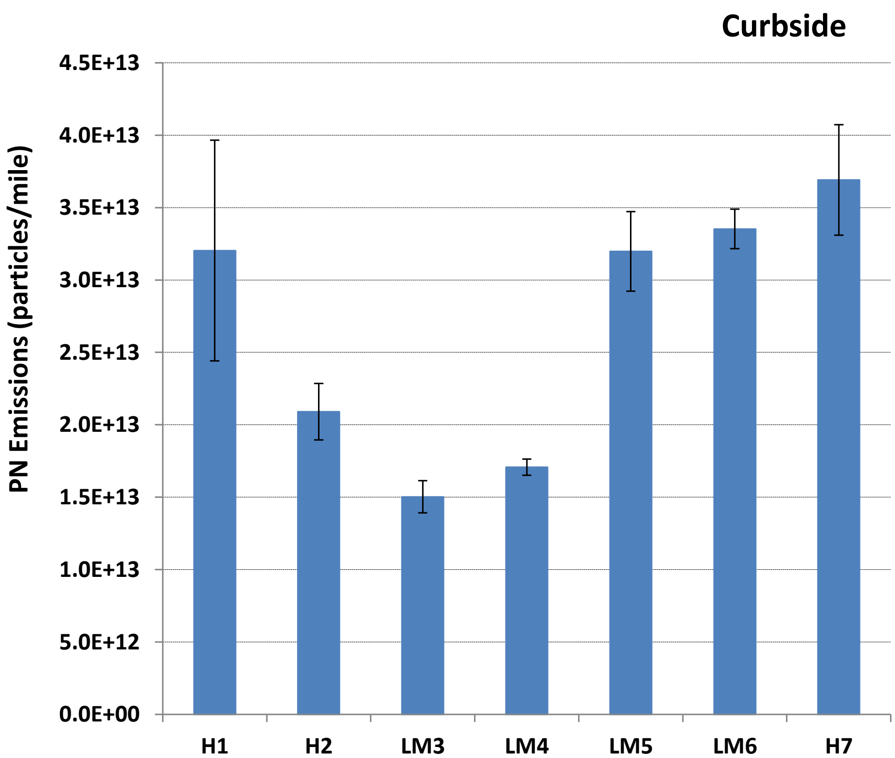


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-29 (a-b). Average PN Emissions for Waste Hauler.



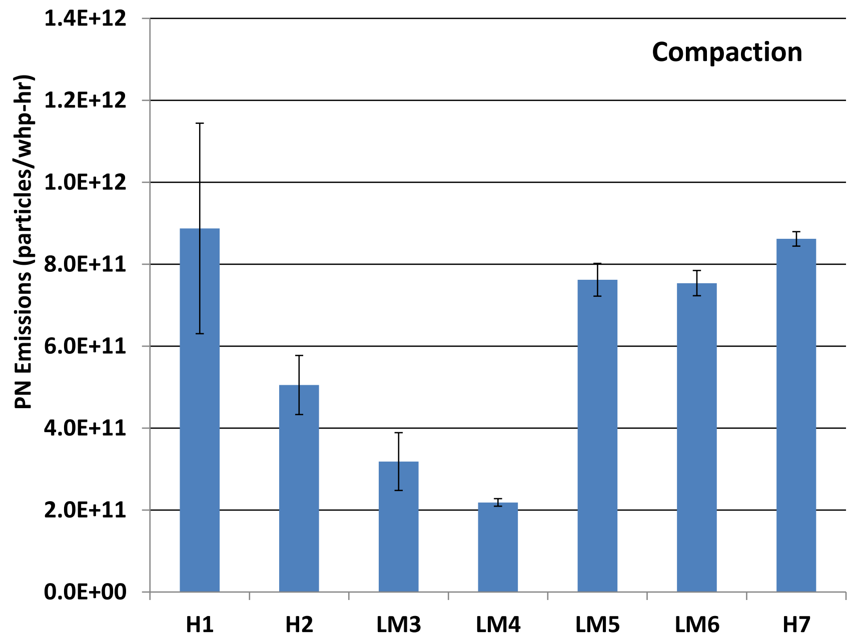
a



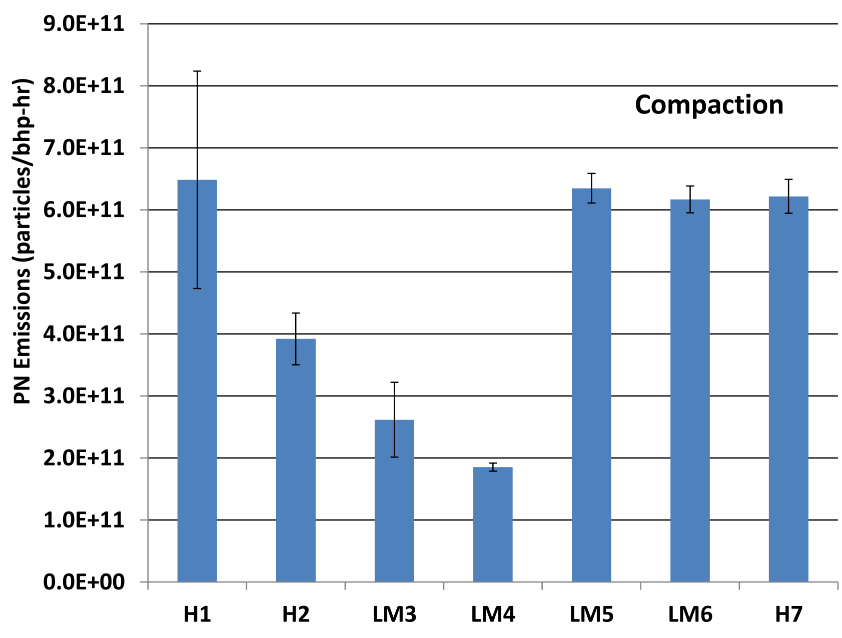
b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-30 (a-b). Average PN Emissions for Waste Hauler.



a



b

H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

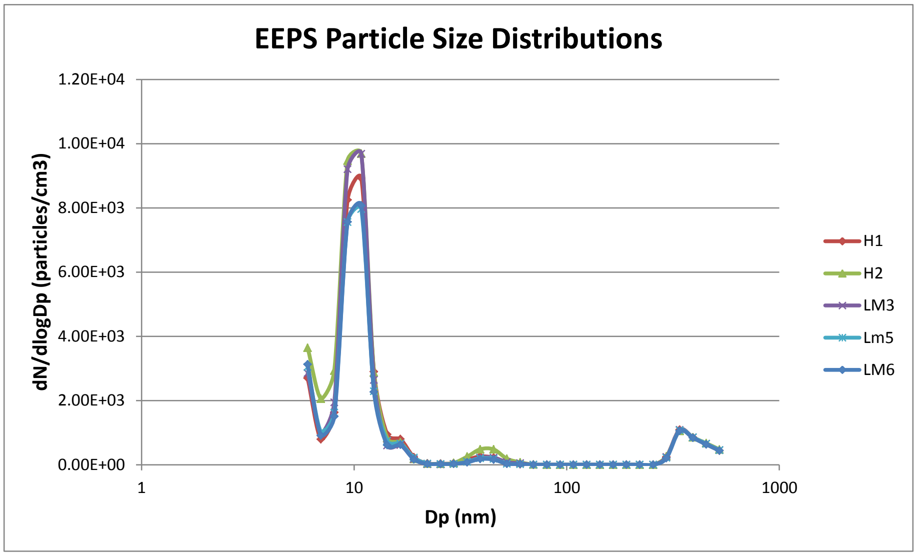
3.9 Particle Size Distributions

Several different instruments were used for determining the size distributions throughout the testing, as discussed in section 2.4. These instruments are summarized in Table 2-4, but are briefly discussed here to provide a context for the discussion below. The most robust and reliable particle size distributions for this test program were obtained for the C-Gas Plus bus, as an Engine Exhaust Particle Sizer (EEPS) with a one second scan time was available during this testing period. A nano scanning mobility particle sizer (nano-SMPS) was used for the 2009 Cummins Westport ISL-G8.9 bus, the waste hauler truck, and both John Deere bus tests to characterize particle size distributions. A regular long-column SMPS was also utilized at the beginning of the testing for the 2009 Cummins Westport ISL-G8.9 bus. It should be noted that due to the relatively long scan time for the nano- and long-column SMPS instruments (118 seconds and 135 seconds, respectively), the measurements from these instruments were predominately useful in determining the general size distribution over the cycle. In particular, since the slower nano- and long-column SMPS only sample a small segment of their size range at any given time, differences seen for tests conducted on different fuels could be an artifact of what part of the size range the instrument is measuring during a particular segment (or acceleration/deceleration) of a cycle. As such, they cannot be accurately characterized as fuel differences. It is also worth noting that the size distribution figures are typically plotted with the x-axis using a logarithmic scale to allow the sizing over a range spanning several orders of magnitude to be shown. The y-axis is typically plotted in dN/dlogDp, where *dN* (or Δ*N*) is the particle concentration in the range and dlogDp (or logDp) is the difference in the log of the channel width, since particle distributions are typically lognormal in character. The area under the curve for these plots represents the total particle concentration [36].

For the C-Gas Plus bus, as shown in Figure 3-31, particle size distributions from EEPS measurements for all gases resulted in a consistent nucleation mode, with a peak particle diameter around 10 nm. This is consistent with other studies showing that particles emitted from NG engines/vehicles are predominantly nucleation particles in the nanometer size range [3,9,37,38]. A smaller peak was also found in the 30-50 nm size range. Since the EEPS measures all the size bins simultaneously, unlike the nano- and long-column SMPS instruments, it can be used to evaluate differences between different fuels. The gases H1, H2, and LM3 exhibited higher nucleation mode particle concentrations compared to gases LM5 and LM6. The higher particle number concentrations for H2 in both the 10 nm and 30-50 nm size ranges is consistent with the higher PN for H2. On the other hand, the particle concentrations for H1 in the 10 nm range are intermediate between those of LM3 and LM5/6. The differences in the trends for particle number and the EEPS data comparing H1 and LM3, LM5, and LM6 could be related to differences in the number of particles that are outside of the 6 to 423 nm size range measured by EEPS, but are still measured by the 3776 CPC, which has a lower cut point of 2.5 nm. This would need to be studied in further detail, however.
The size distributions for the newer technology Cummins Westport ISL-G8.9 bus over the CBD are shown in Figure 3-32 for H1, LM4, LM5, and LM6 using a nano-SMPS and in

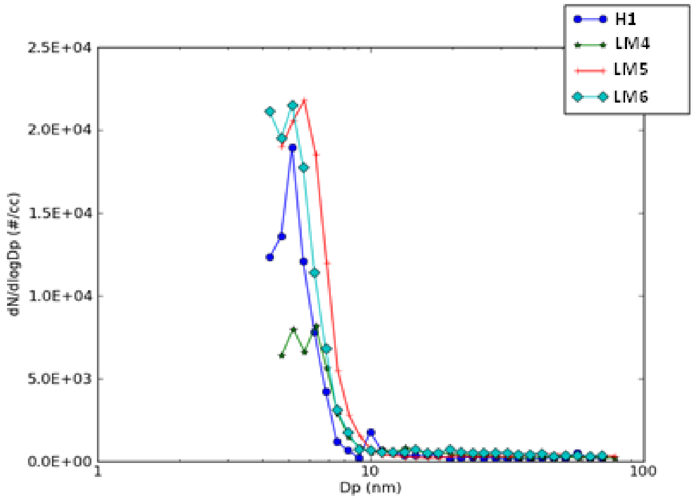
Figure 3-33 for H1, H2, and LM3 using a regular long column SMPS. The nano-SMPS, with a lower cut-off of 4 nm, showed that the size of the particles emitting from the Cummins Westport ISL-G bus were predominately in the sub 10 nm nucleation particle range. The long column SMPS did show a peak in the size distribution around 70-100 nm, but comparing with the nano-SMPS results shows that any such peaks are much smaller than the peaks in the sub 10 nm region. As discussed above, differences in the size distributions for different fuels could be an artifact, so these differences will not be discussed in detail here.

Figure 3-31. Particle Size Distributions for the C-Gas Plus Bus Using the EEPS



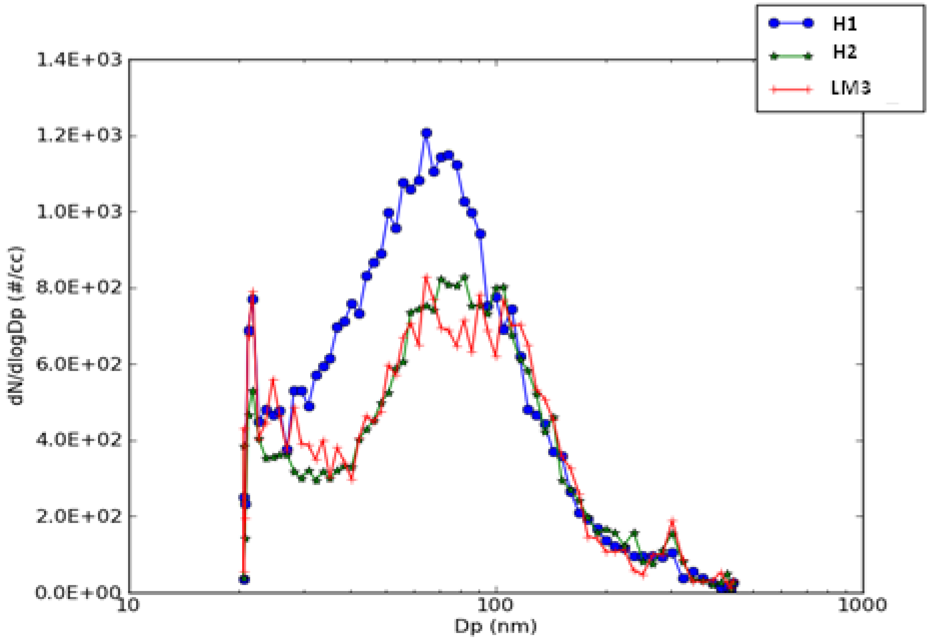
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-32. Particle Size Distributions for the Cummins Westport ISL-G8.9 Bus Using the Nano-SMPS



H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-33. Particle Size Distributions for the Cummins Westport ISL-G8.9 Bus Using a Regular Long Column SMPS.

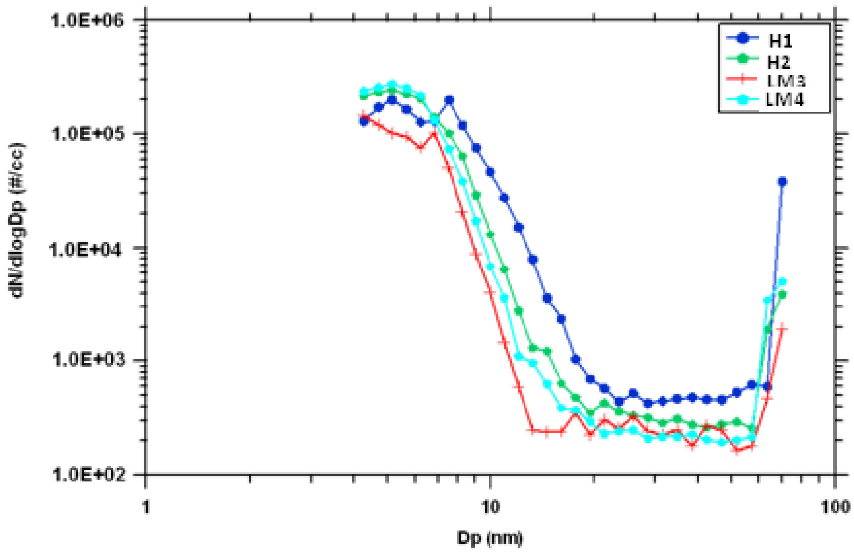


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-34 shows the particle size distributions for the older technology John Deere bus initial testing. Figure 3-35 presents the particle size distribution collected for the post-repair John Deere bus testing. These size distributions were both collected with a nano-SMPS. It should be mentioned that a log-scale for the y-axis was used for both the initial and post-repair John Deere testing, as opposed to the linear-scale figures used for particle size distributions in the rest of this section, to better illustrate the onset of an increase in particles at about 100 nm for the initial John Deere testing. The initial John Deere bus testing showed approximately an order of magnitude more particles compared to post-repair John Deere bus testing, which might be due to the bus' mechanical issue. The sizing results for both the initial and post-repair John Deere tests show a peak in the sub 10 nm range, with the peak being sharper for the initial test results. The results for the initial John Deere bus testing showed the potential formation of accumulation mode particles at around 60 nm. Figure 3-34 and Figure 3-35 clearly show that the size distributions for the various fuels are generally pretty similar. Again, any differences between the fuels could be an artifact of the longer scan time for the nano-SMPS.

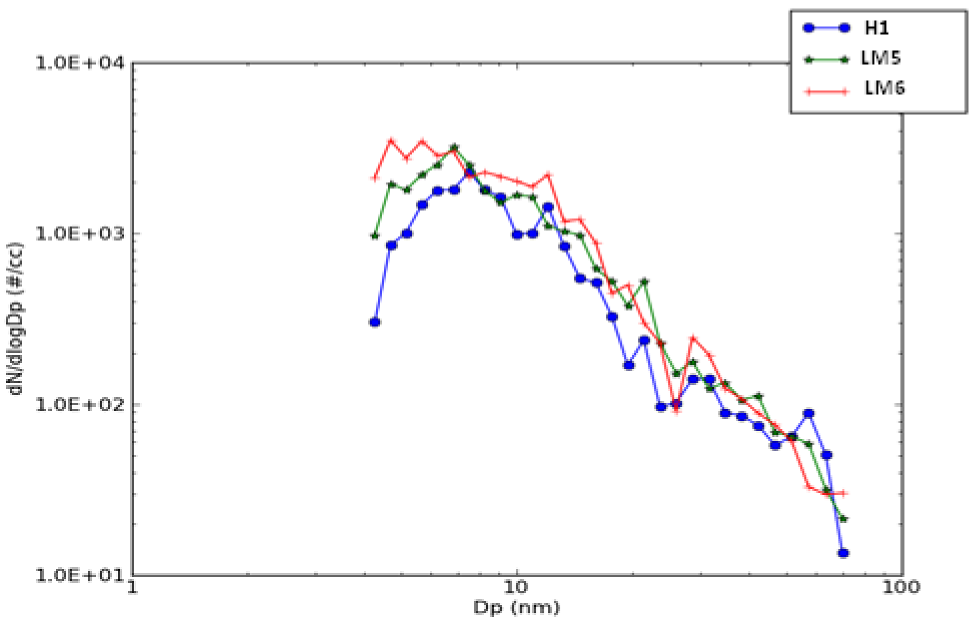
Figure 3-36 presents the particle size distributions for the waste hauler over the Refuse Truck Cycle. The waste hauler showed a peak in the size distribution around 10 nm using the nano SMPS. Again, although there are some differences between the fuels, the differences could be an artifact of the longer scan time for the nano-SMPS.

Figure 3-34. Particle Size Distributions for the Initial John Deere Bus Using the Nano-SMPS



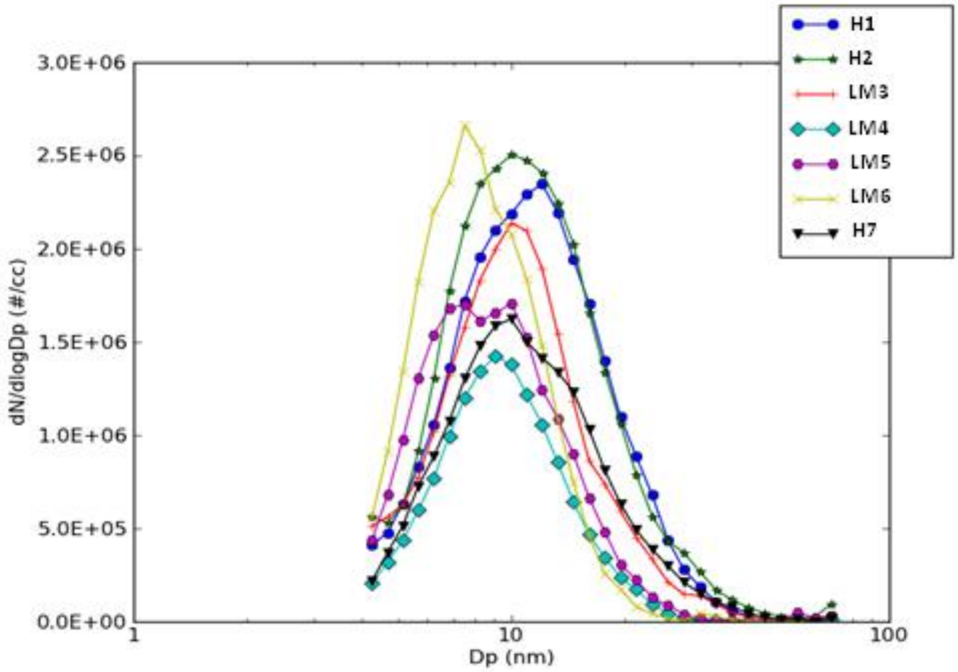
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-35. Particle Size Distributions for the Post-repair John Deere Bus Using the Nano-SMPS



H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-36. Particle Size Distributions for the Waste Hauler Using the Nano-SMPS



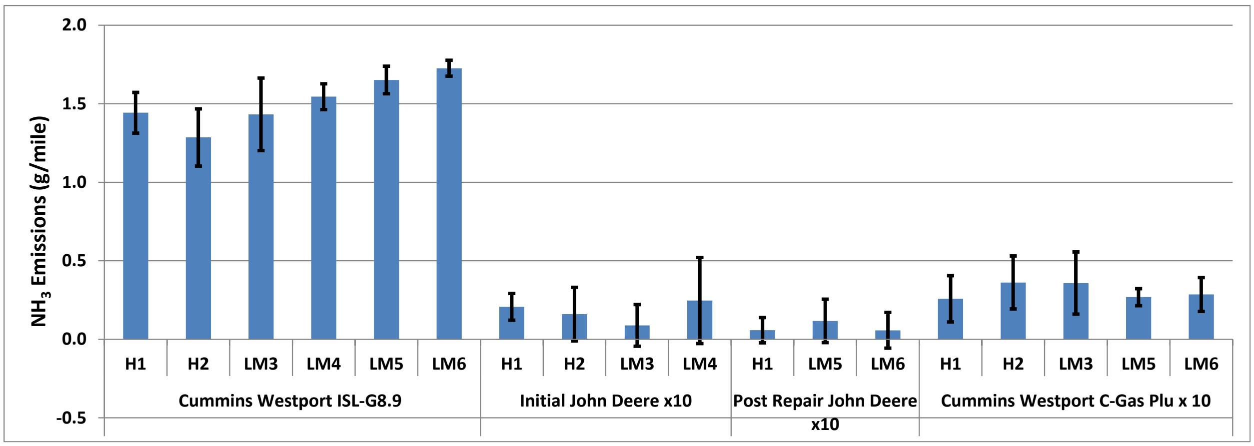
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.10 NH_3 Emissions

Figure 3-37 shows the NH_3 emissions for the NG buses. It should be noted that the NH_3 emissions for the John Deere and Cummins Westport C-Gas Plus buses are multiplied by 10 so that they can be more readily seen in the figure. As can be seen, the Cummins Westport ISL-G bus showed higher NH_3 emissions compared to the John Deere and Cummins Westport C-Gas Plus buses. This is due to the fact that the Cummins Westport ISL-G bus was equipped with a TWC, which can catalyze the formation of NH_3 emissions through a complex series of reactions, including the water-gas shift reaction [39–45]. The NH_3 emissions for the John Deere bus (for both initial and post-repair tests) were very low by comparison with either the ISL-G bus or the waste hauler, as discussed below. The NH_3 emissions for the C-Gas Plus bus were higher than those for the John Deere bus, but were still much lower than those for the Cummins Westport ISL-G bus. In general, no consistent fuel effects were observed for the buses, and most of the emissions differences compared to H1 were not statistically significant.

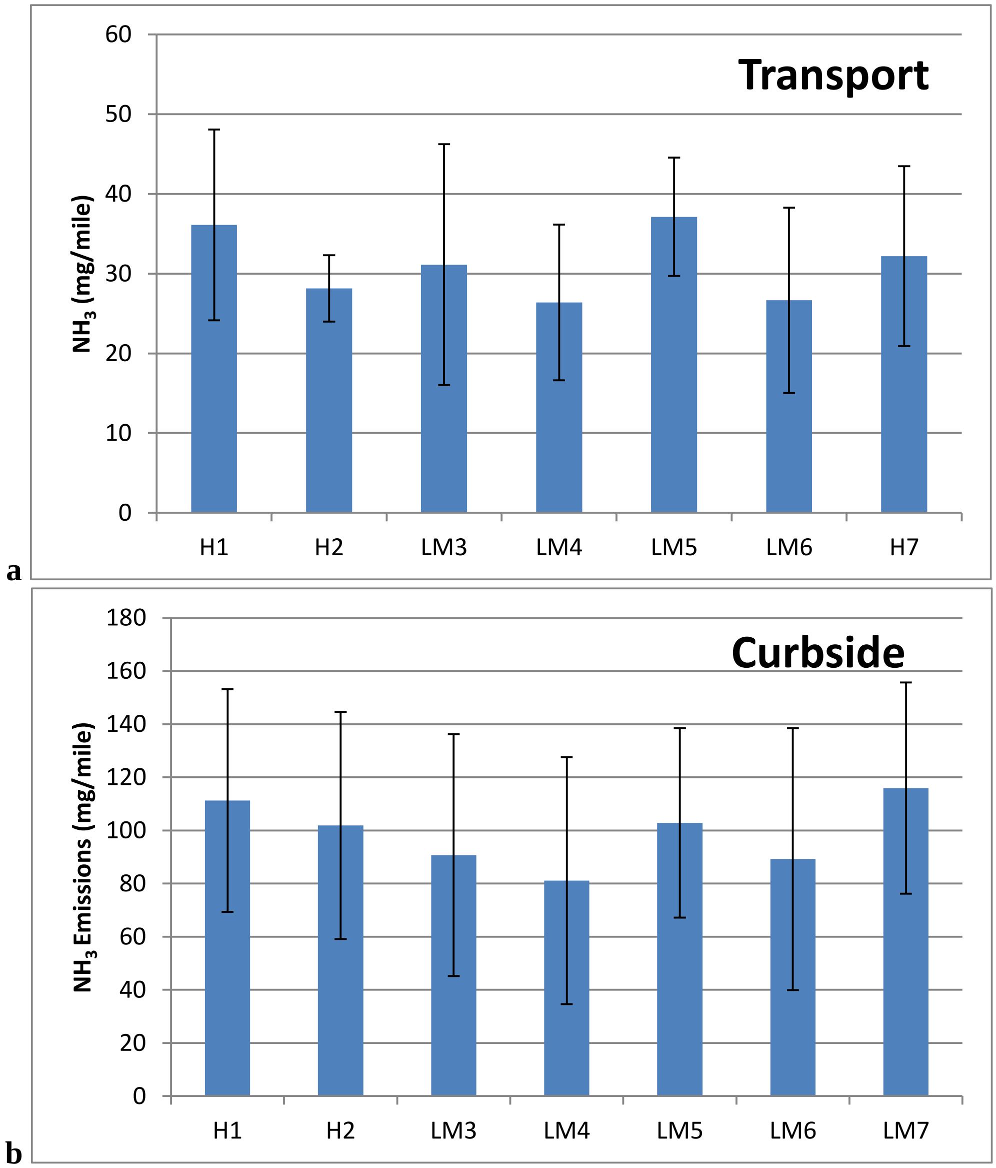
Figure 3-38 shows the NH_3 emissions for the waste hauler for the transport and curbside segments, while Figure 3-39 shows the NH_3 emissions for the compaction segment on a whp-hr and bhp-hr basis. For the waste hauler truck some noticeable fuel differences in NH_3 emissions were seen between test fuels for different cycles, though there were no consistent fuel trends observed. For the compaction segment, some fuel effects were seen for the NH_3 emissions, with H1 showing statistically significant increases relative to H2 and LM6 on a bhp-hr and whp-hr basis and showing a marginally statistically significant increase relative to LM5 on a whp-hr basis. Statistically significant differences were also seen between H2 and LM3 on a bhp-hr and whp-hr basis, and between LM3 and H7 on a bhp-hr basis and between H7 and LM6 on a whp-hr basis. For the transport segment, a statistically significant difference was seen between H2 and LM5. Again, none of these trends were consistent over more than one test cycle segment, and the differences between fuels were not consistent in terms of trends of either high or low methane content fuels. No statistically significant differences between fuels were seen for the curbside segment. The average emissions for all the fuels for both transport and curbside ranged from 49-115 mg/mile with the transport values near the low end and the curbside values near the high end. For the compaction segment (whp-hr and bhp-hr), the differences between NH_3 emissions for H1 and H2 were statistically significant.

Figure 3-37. Average NH_3 Emissions for NG Buses



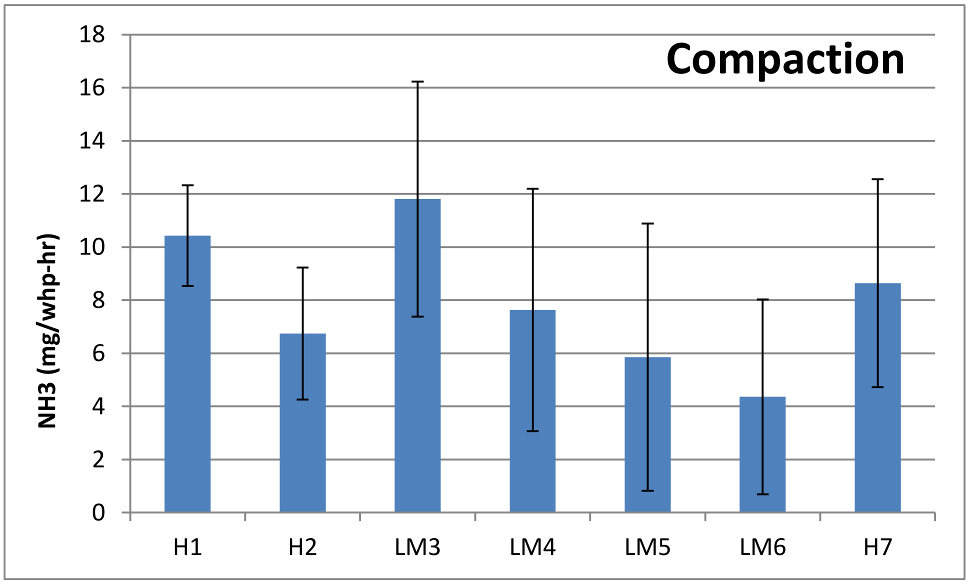
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-38. (a-b). Average NH_3 Emissions for Waste Hauler Transport and Curbside Segments.

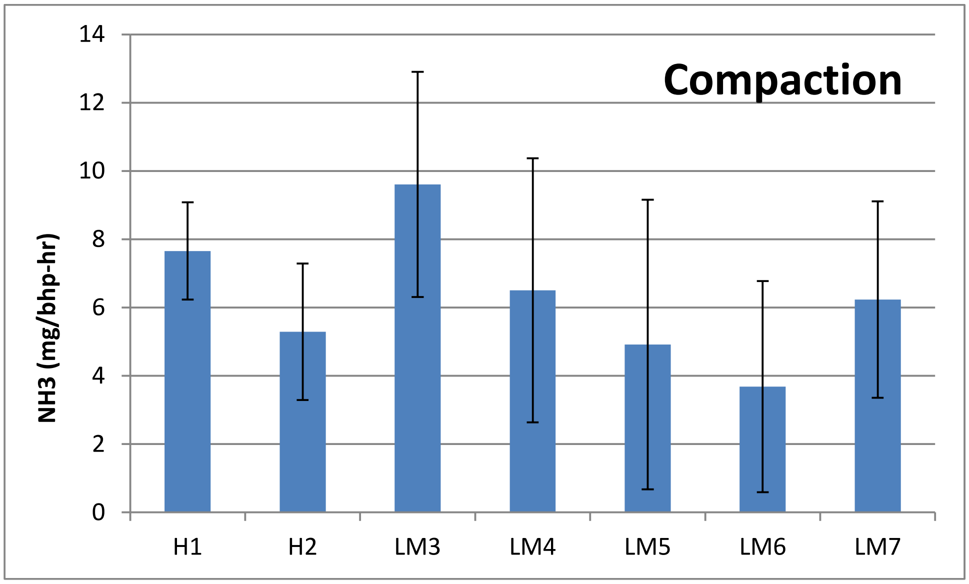


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-39. (a-b). Average NH_3 Emissions for Waste Hauler for the Compaction Segment on a whp-hr Basis (a) and on an Engine bhp-hr Basis (b).



a



b

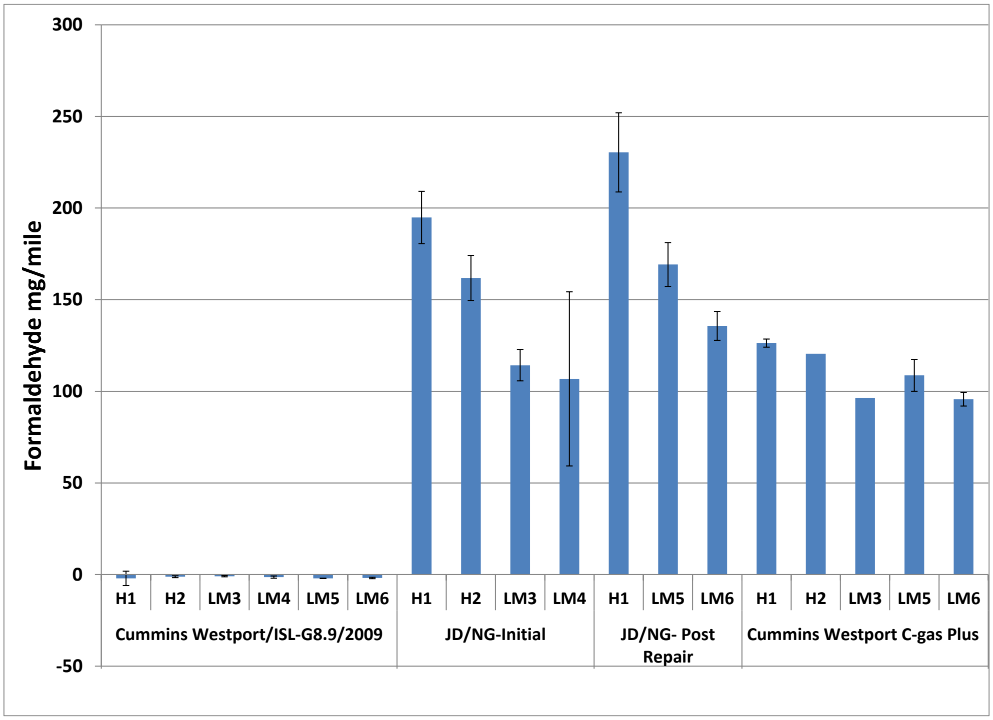
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.11 Carbonyl Emissions

Figure 3-40 and Figure 3-42 show the average formaldehyde and acetaldehyde emissions, respectively, from all three buses. Formaldehyde and acetaldehyde emissions were the most prominent measured carbonyl emissions, with formaldehyde emissions being the highest. Note that formaldehyde and acetaldehyde are the lower molecular weight aldehydes, having one and two carbons, respectively. For the Cummins Westport ISL-G bus, the magnitude of formaldehyde and acetaldehyde emissions were lower than those of the other buses and did not show any fuel trends. In addition, the values for formaldehyde were at the measurement limits. For both the initial and post-repair John Deere bus tests, H1 and H2 showed the highest formaldehyde emissions compared to the other gases. For the post-repair John Deere testing, statistically significant reductions in formaldehyde emissions of 27% for LM5 and 41% for LM6 compared to H1 were found. For the initial John Deere testing, reductions in formaldehyde emissions were statistically significant. These reductions were 16.9% for H2, 41% for LM3, and 45% for LM4 compared to H1. For the John Deere bus, the formaldehyde results follow the same trends as the THC emissions, with the gases with higher methane contents producing higher levels of formaldehyde. The same trend of higher formaldehyde emissions with the high methane gases was seen for the C-Gas Plus bus, although the trend was not as strong as for the John Deere. For the C-Gas Plus bus, H1 and H2 showed the highest formaldehyde emissions. Statistically significant reductions in formaldehyde emissions of 14% for LM5 and 24% for LM6 were found compared to H1 gas. Only a single carbonyl test sample was available for H2 and LM3 due to an issue with the sampling system, so statistical comparisons could not be made for those fuels. For the acetaldehyde emissions, the buses did not show consistent fuel trends. However, for the initial John Deere bus testing, a statistically significant reduction of acetaldehyde emissions was seen for LM3 and LM4 compared to H1. H2 showed a marginally statistically significant reduction in acetaldehyde emissions compared to H1.

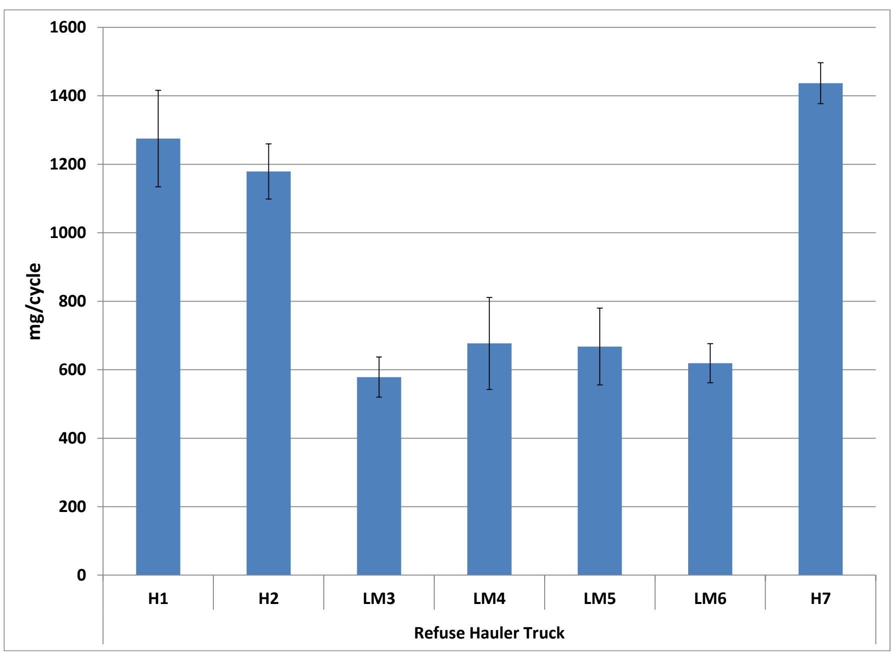
Figure 3-41 and Figure 3-43 show the average composite formaldehyde and acetaldehyde emissions, respectively, from the waste hauler truck. Note that similar to the PM emissions these are presented in terms of grams/cycle, since the emissions for the driving portions of the cycle (i.e., the curbside and transport segments) cannot be separated from the compaction segment, which is not an actual driving event. For the waste hauler, the high methane gases, namely H1, H2, and H7, also showed increased formaldehyde emissions levels compared to the low methane gases, following the same trends as the THC emissions for this vehicle. For the low methane gases, the differences in formaldehyde emissions were statistically significant compared to the H1, H2, and H7 gases. The reductions in formaldehyde emissions for the low methane gases (LM3-LM6) when compared to H1, H2, and H7 range from 47-55%, 43-51%, 53-60%, respectively. Similar trends were observed for acetaldehyde emissions, with the high methane gases having higher emissions levels than the low methane gases. The reductions in acetaldehyde emissions were statistically significant for the low methane gases. The reductions for the low methane gases (LM3-LM6) when compared to H1, H2, and H7 range from 53-63%, 54-64%, 38-51%, respectively.

Figure 3-40. Average Formaldehyde Emissions for Buses.



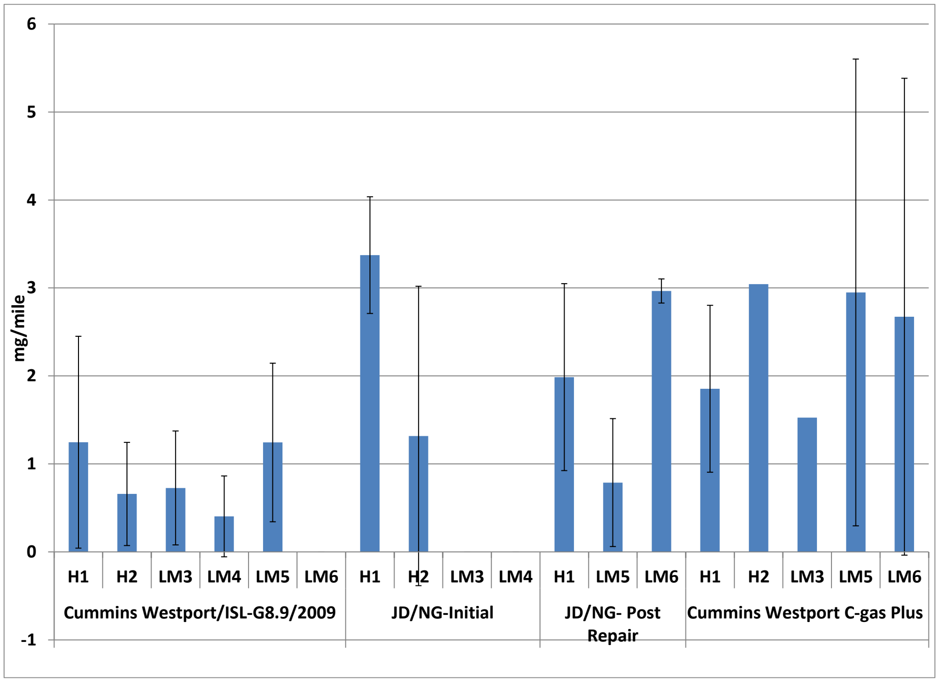
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-41. Average Formaldehyde Emissions for Waste Hauler.



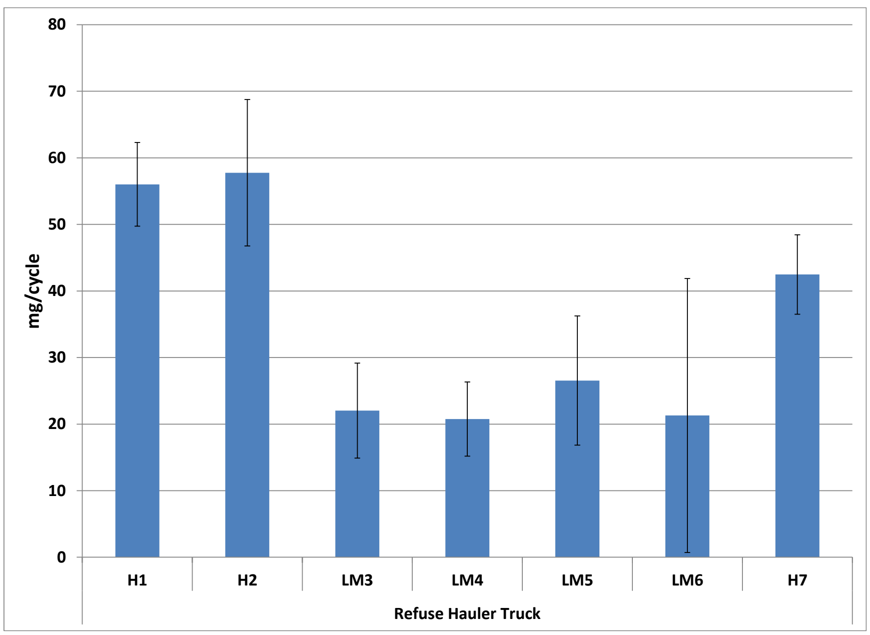
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-42. Average Acetaldehyde Emissions for Buses.



H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-43. Average Acetaldehyde Emissions for Waste Hauler Truck.



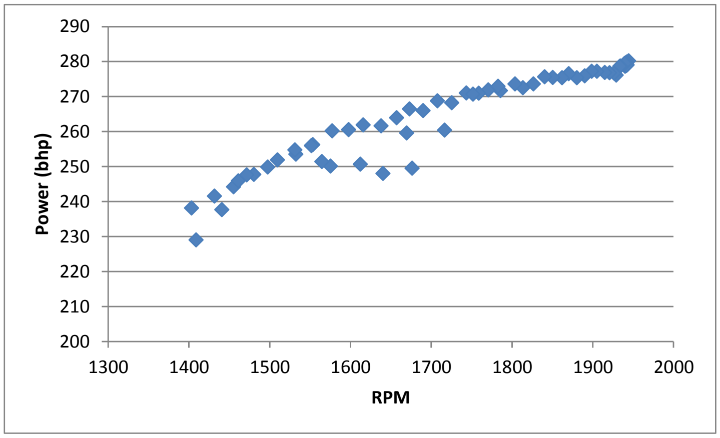
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN) LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

3.12 Power Maps

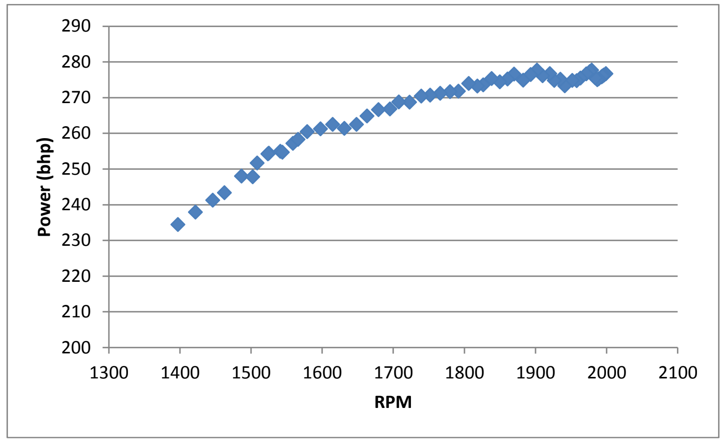
Figure 3-44 to Figure 3-47 present the power map plots for different CNG gases for the Cummins Westport ISL-G bus, the initial and post-repair testing for the John Deere bus, and the waste hauler truck. In all these plots the power of the engine in horsepower (hp) is plotted versus engine speed in revolution per minute (rpm). There were several issues in doing the power maps on these vehicles that complicated the analysis. Unlike an engine dynamometer power map that is obtained through a direct connection with an engine dynamometer, the vehicles were all equipped with transmissions with different configurations and gearing ratios. Issues with the transmissions shifting in and out of gear and other instabilities caused fluctuations in the hp readings over the course of the tests. These fluctuations are seen to different degrees in the data plots provided below. In the case of the C-Gas Plus, there were issues with the loading of the engine/vehicle, which could be due to being in the wrong gear or some other reason, so these data are not presented. Additionally, as discussed in section 3.1, the hp readings from the engine do not account for the differences in the fuel properties of the different gases. Given the complications inherent with doing this type of testing with a vehicle, it does not appear that these series of tests provided an adequate comparison of what the expected power differences would be between the fuels in use. It should be noted that the initial testing for the John Deere bus also showed relatively low power levels. This could be related to the mechanical issue that was identified for that bus.

Figure 3-44. Power Map for Different CNG Gases for Cummins Westport ISL-G8.9 Bus Testing

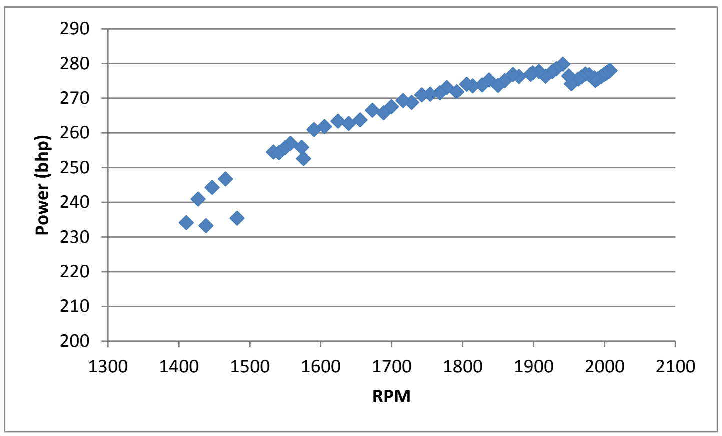
H1



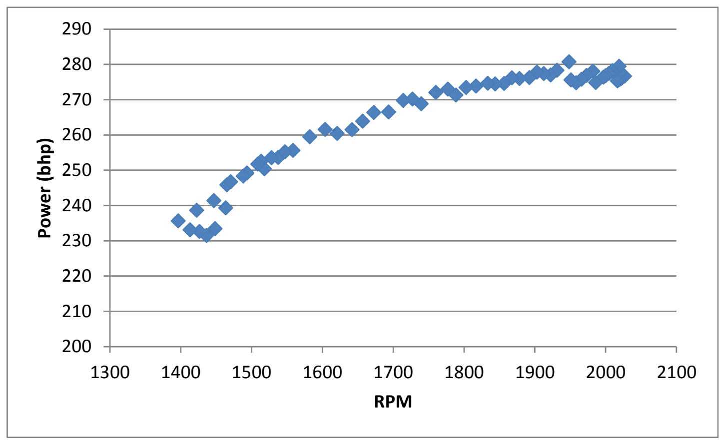
H2



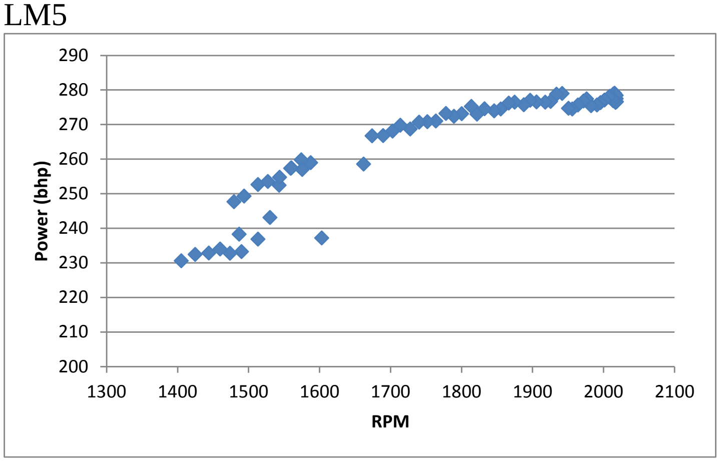
LM3



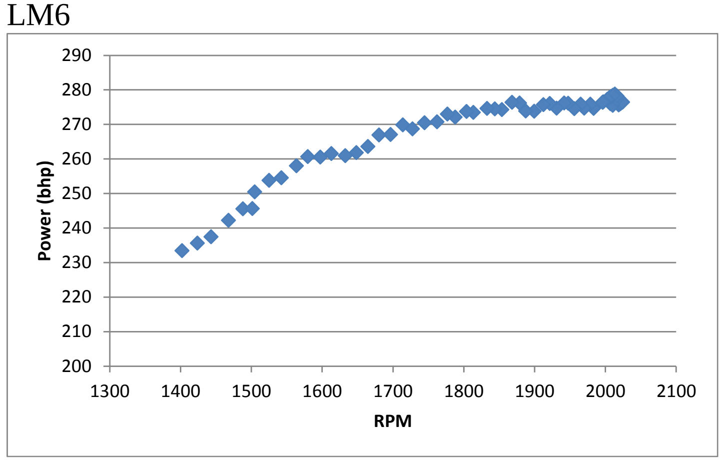
LM4



LM5

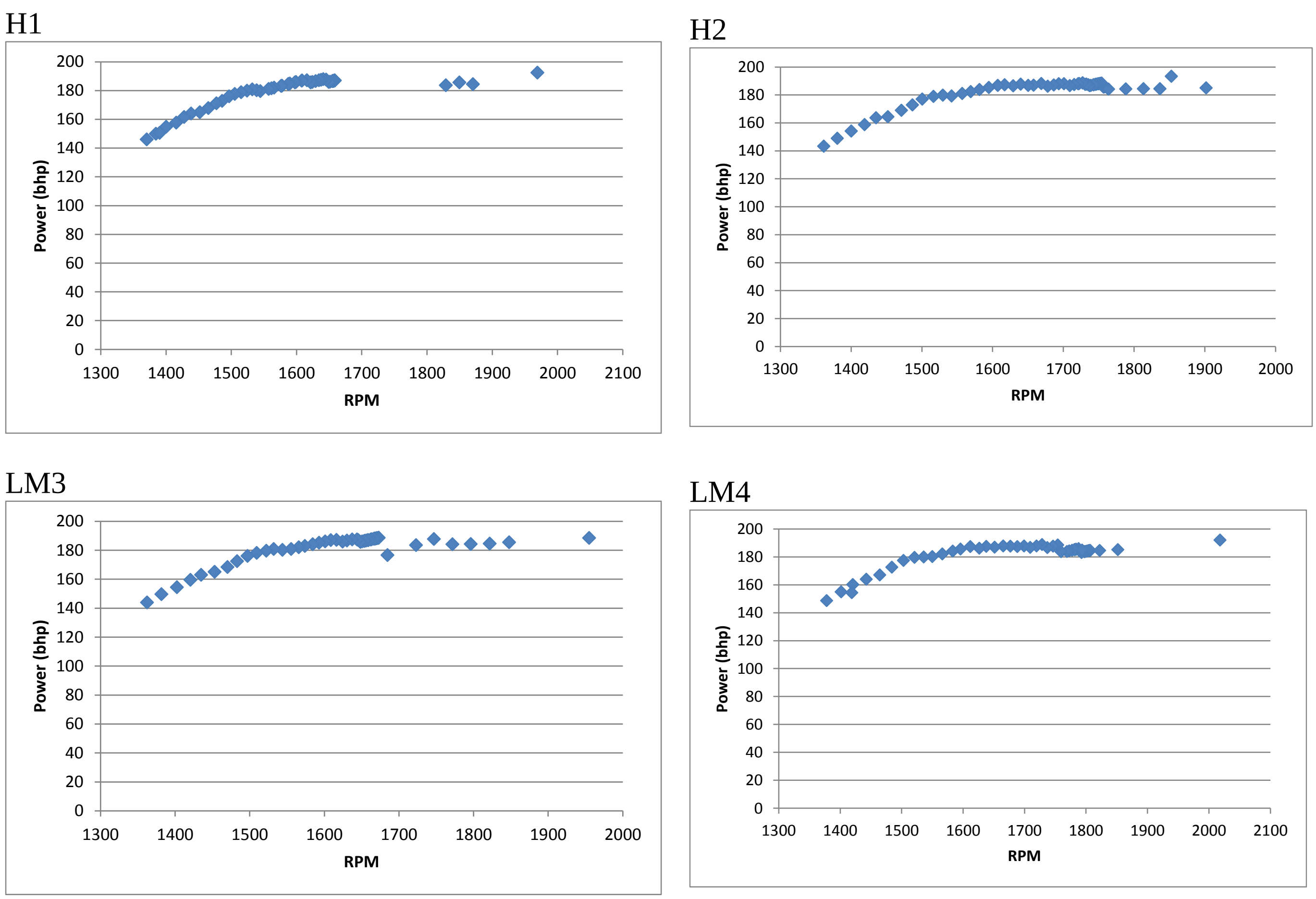


LM6



H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

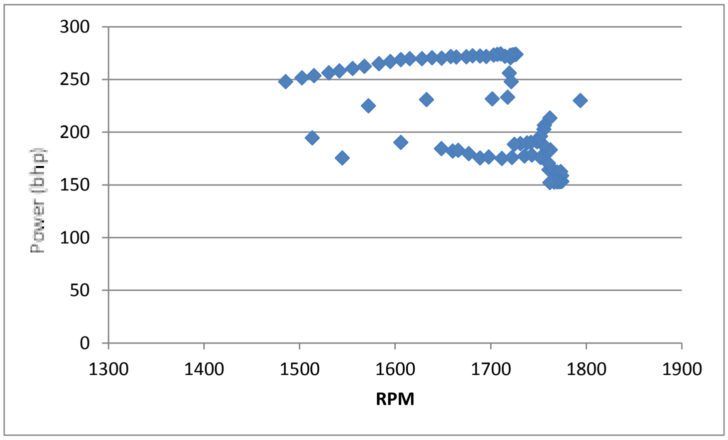
Figure 3-45. Power Map for Different CNG Gases for the Initial John Deere Bus Testing



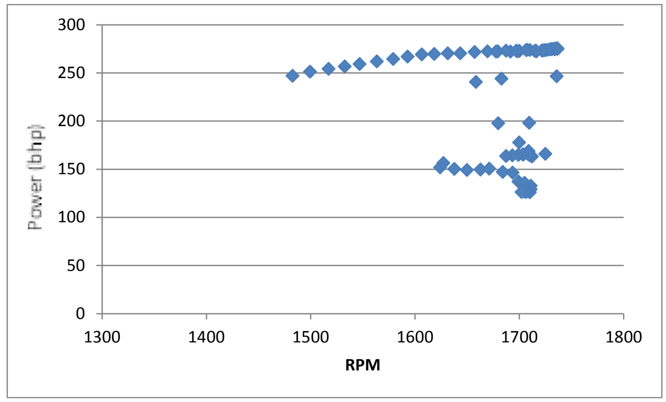
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-46. Power Map for Different CNG Gases for the Post-repair John Deere Bus Testing

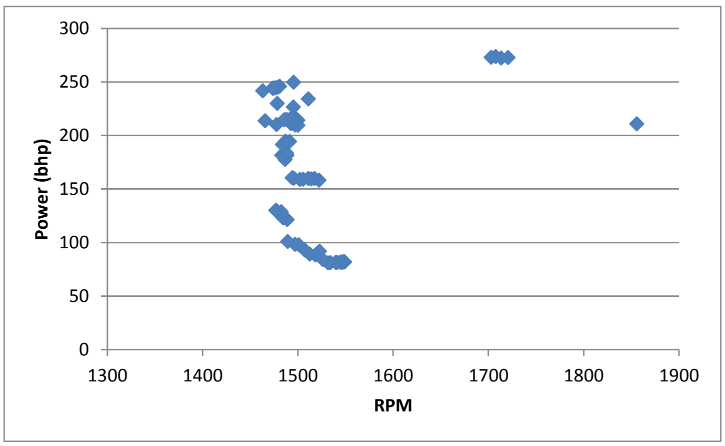
H1



LM5



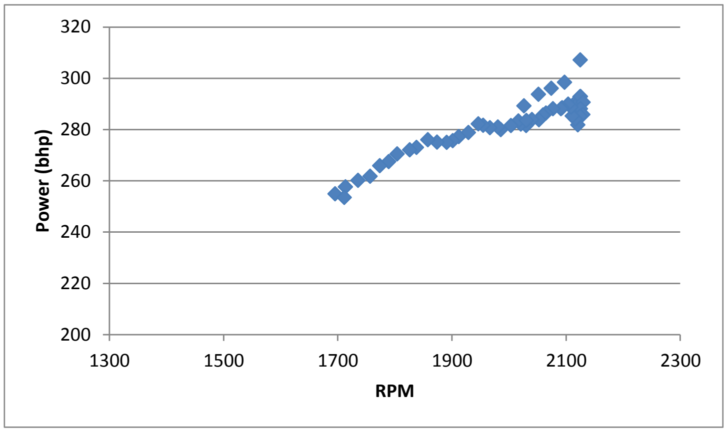
LM6



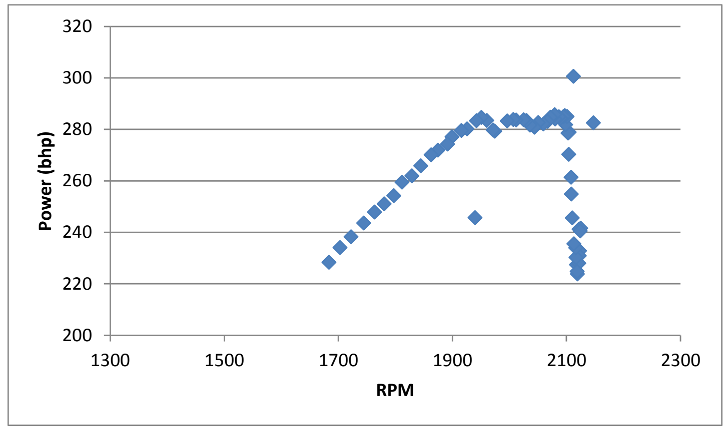
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Figure 3-47. Power Map for Different CNG Gases for Waste Hauler Truck Testing

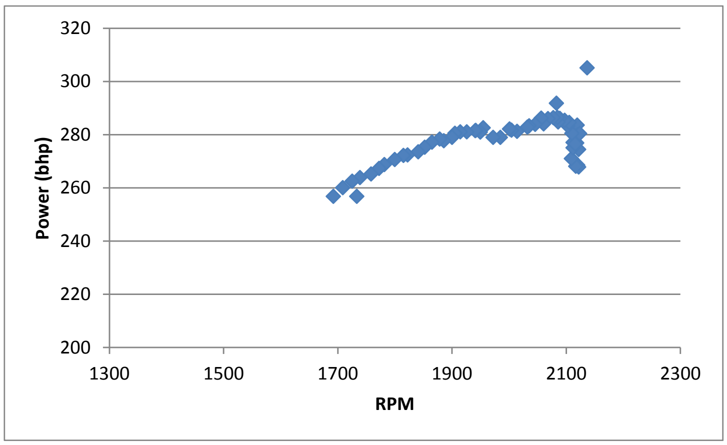
H1



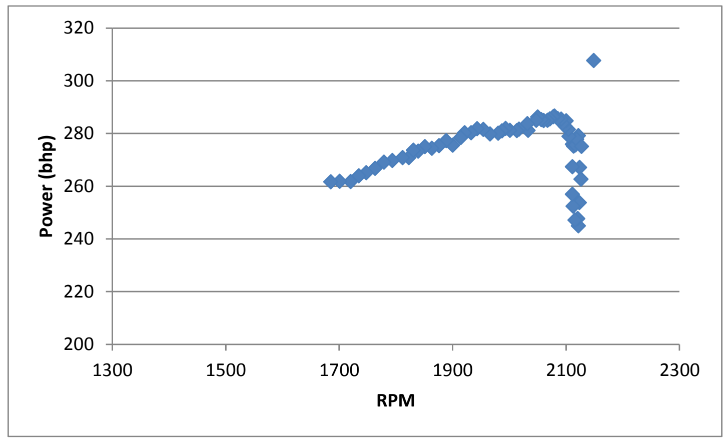
H2



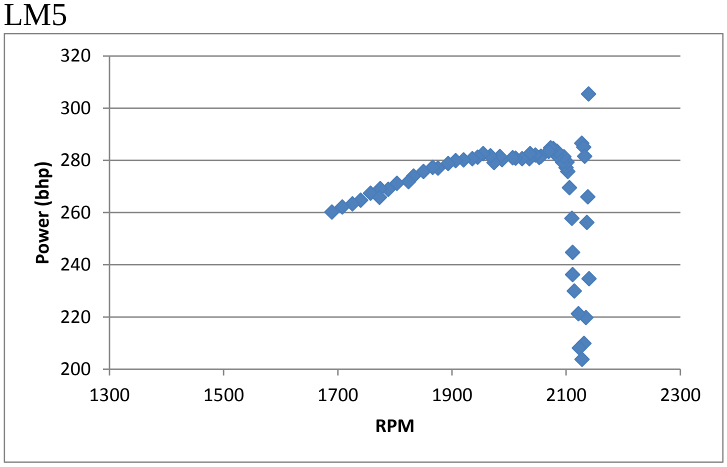
LM3



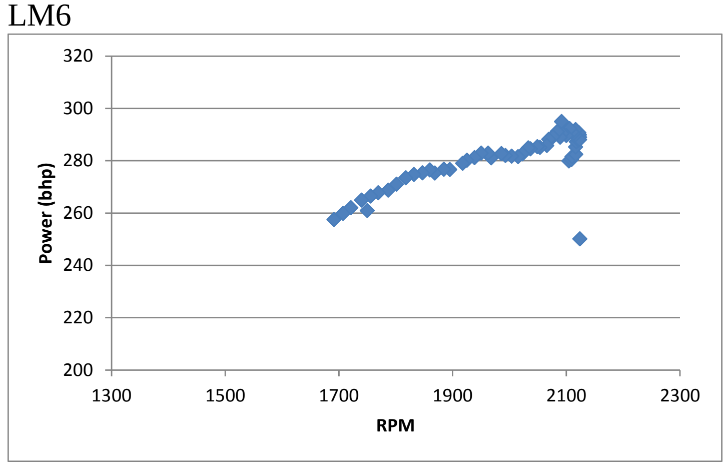
LM4



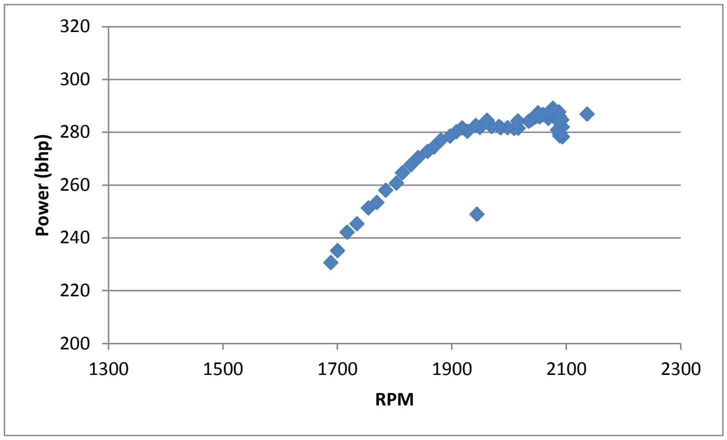
LM5



LM6



H7



H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN)
LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

4 Summary

As the demand for NG in California and the production of NG throughout the U.S. both expand, there is potential for a wider range of natural gas compositions to be used in NGVs. It is important to evaluate whether changing compositions of NG will have adverse impacts on the emissions or performance of NGVs. The current study was designed to address this issue. These results may also be used in CARB's ongoing process to amend the California NG fuel standards for motor vehicles.

In this study, five to seven blends of natural gas with different fuel compositions were tested. The gases represent a range of compositions from gases with high levels of methane and correspondingly lower energy contents/Wobbe numbers to gases with higher levels of heavier hydrocarbons and correspondingly higher energy contents/Wobbe numbers. Emissions testing was performed on three transit buses (a bus with a 2009 stoichiometric combustion spark ignited engine with cooled EGR and a TWC, and two buses with older 2002 and 2003 engines), and a waste hauler with a 2002 engine) on CE-CERT's heavy-duty chassis dynamometer. The latter three vehicles all have lean burn spark ignition engines that are equipped with OCs. The bus with a 2004 lean burn engine was tested on two separate occasions due to a mechanical failure during the initial testing. The results of the test program showed that fuel composition, engine operating conditions, and driving cycle had effects on the formation of exhaust emissions for the older technology vehicles. Consistent fuel effects were not seen for the newest technology bus with the stoichiometric combustion engine with a TWC, however.

The results of this study are summarized below. Results are generally statistically significant, except as noted.

2002 Cummins Westport 8.3L C-Gas Plus Waste Hauler

Waste hauler truck emissions were evaluated over a refuse truck cycle that included, transport, compaction, and curbside segments. Overall, the waste hauler showed the strongest fuel effects for most of the pollutants compared to the buses. Almost all the pollutants showed some fuel effects for at least one of the cycle segments. The low methane gases showed higher NO_x emissions for all three segments of the cycle. Low methane gases showed lower THC, CH_4, formaldehyde and acetaldehyde emissions. For the compaction and curbside phases, higher NMHC emissions were seen for the low methane gases, but for the transport phase the opposite trend was observed. Cumulative PM emissions and CO emissions for the compaction cycle showed a trend of lower emissions for the low methane gases. Fuel economy/consumption on a volumetric basis showed increases for the low methane gases with higher energy contents for the transport and curbside phases of the cycle and decreases for the compaction cycle. On an energy equivalent basis, fuel economy/consumption showed no fuel differences for the curbside and mixed results for the compaction cycles, but higher energy equivalent fuel economy was seen for the low methane gases with higher energy contents for the transport phase. Particle number showed similar fuel trends over the three cycle segments, but the gases showing lower particle numbers included some with higher levels of methane (i.e., H2) and some with lower levels of methane (i.e., LM3 and LM4). CO_2 emissions did not show strong trends for the curbside phase, but the transport phase showed lower CO_2 emissions for the low methane gases with lower H/C ratios, compared to H1 and H2 gases, but not compared to H7. For the compaction segment, CO_2 emissions for LM5 were higher at a statistically significant level than those for H1, H2, and H7 on a whp-hr basis for the compaction segment. On a bhp-hr basis for the compaction segment, CO_2 emissions for all of the low methane fuel gas blends exhibited statistically significant increases in CO_2 emissions of between 5.2 to 19.4% compared to H1, H2, and H7. This can be attributed to the bhp energy readings being lower for the higher energy gases, because the ECM bhp reading does not take into account the differences between fuels. NH_3 emissions showed some fuel differences, but no consistent fuel trends over the three segments of the cycle. The particle size distributions showed a peak in the 10 nm range.

2004 John Deere 8.1L 6081H transit bus

The John Deere bus was tested on two separate occasions due to a mechanical failure during the initial testing. The post-repair John Deere bus tests showed a number of fuel effects. These tests were conducted for only three of the main test gases. Fuels with higher methane contents showed higher THC, CH_4, and formaldehyde emissions, but lower NMHC emissions. The low methane gases showed higher NO_x emissions, although these increases were not statistically significant for all fuel combinations. Low methane gases with higher energy contents showed higher fuel economy on a volumetric basis. One of the low methane gases also showed higher fuel economy on an energy equivalent basis. PM mass, acetaldehyde, CO, CO_2, and NH_3 emissions did not show any significant fuel trends. PM mass, CO and NH_3 emissions were very low for the post-repair bus. The particle size distributions showed a broad peak stretching from sub 10 nm into the 70 nm range.

Some fuel effects were also seen for the initial testing of the John Deere bus. These tests were conducted for only four of the main test gases. Trends for THC, CH_4, formaldehyde, and NO_x were consistent with the post-repair results. Higher methane content gases resulted in higher THC, CH_4, and formaldehyde emissions and particle number counts, but lower NMHC emissions. NO_x emissions showed increases for the highest WN gas compared to the baseline gas. The low methane gases with higher energy contents showed higher fuel economy on a volumetric basis, but slight trends of decreasing fuel economy on an energy equivalent basis. CO_2 showed some statistically significant differences between fuels, but no real trends. CO and NH_3 emissions did not show any specific trends. PM mass emissions were very low and did not show consistent trends with fuel properties, although some differences between different fuel combinations were seen. Acetaldehyde emissions showed a statistically significant reduction for LM3 and LM4 compared to H1, and a marginally statistically significant reduction of H2 compared to H1. The particle size distributions also showed a peak in the sub 10 nm range, but this peak was sharper compared to the post-repair testing.

2003 Cummins Westport 8.3L C-Gas Plus engine transit bus

For the 2003 Cummins Westport 8.3L C-Gas Plus bus, NO_x and NMHC emissions and volumetric fuel economy were higher, and THC, CH_4, and formaldehyde emissions were lower for the low methane gases. CO emissions showed some statistically significant increases with some of the low methane gases. Energy equivalent fuel economy, CO_2, PM, and NH_3, and acetaldehyde emissions did not show any strong fuel effects, and particle number showed inconsistent fuel trends. The particle size distributions showed a peak around 10 nm.

2009 Cummins Westport ISL-G 8.9 L transit bus

The bus with a 2009 Cummins Westport ISL-G stoichiometric combustion engine with cooled EGR and a TWC was the newest technology tested during this program. In general, for this bus, most of the pollutants did not show any specific fuel effects. THC, NMHC, CH_4, NO_x, and formaldehyde emissions for the Westport ISL-G bus were considerably lower than for the other buses. The Cummins Westport ISL-G bus did, however, show higher CO and NH_3 emissions compared to the other buses. This could be attributed to the richer operation for the stoichiometric combustion engine compared to the lean burn engines, as well as the TWC for the NH_3 emissions. Some fuel effects were seen for fuel economy, but not for the other pollutants. The low methane gases with higher energy contents showed higher fuel economy on a volumetric basis but not on an energy equivalent basis. Some differences between fuels were seen for THC and CH_4 emissions, but these differences were on the order of the background levels. The size distributions of the particles emitted from this bus were mainly in the sub 10 nm nucleation particle range.

General

The results showed that fuel composition, engine operating conditions, and driving cycle had effects on the formation of exhaust emissions from all the older heavy-duty vehicles. The older vehicles showed trends that were generally consistent with those of previous studies. Gases with low methane contents showed higher NO_x and NMHC emissions and improved fuel economy on a volumetric basis, but lower emissions of THC, CH_4, and formaldehyde emissions. In some, but not all cases, the magnitudes of these fuel trends were greater than those found in other studies. The trends for the other emissions were not as consistent. The newer technology bus with the stoichiometric combustion engine and with a TWC did not show any specific fuel effects.

Although trends were found between gases with higher vs. lower methane contents, other trends between gases were not as strong. For example, although H7 has a WN that is much higher than H1 and H2, these gases show similar emissions. Similarly LM4, which has a high WN but an intermediate MN, has emissions similar to LM5 and LM6. Additionally, gases LM5 and LM6, which have varying contents of ethane and propane and butane have similar emissions.

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Appendix A. Engine Certification Values

2004 John Deer 8.1L 6081H transit bus

California Environmental Protection Agency AIR RESOURCES BOARD	DEERE POWER SYSTEMS GROUP OF DEERE & COMPANY	EXECUTIVE ORDER A-108-0033 New On-Road Heavy-Duty Engines

Pursuant to the authority vested in the Air Resources Board by Health and Safety Code (HSC) Division 26, Part 5, Chapter 2; and pursuant to the authority vested in the undersigned by HSC Sections 39515 and 39516 and Executive Order G-02-003;

IT IS ORDERED AND RESOLVED: That the engine and emission control systems produced by the manufacturer are certified as described below for use in on-road motor vehicles with a manufacturer's gross vehicle weight rating (GVWR) over 14,000 pounds. Production engines shall be in all material respects the same as those for which certification is granted.

MODEL YEAR	ENGINE FAMILY	ENGINE SIZE (liter)	FUEL TYPE (CNG/LNG=compressed/liquefied natural gas; LPG=liquefied petroleum gas)	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS (L/M/H HDD=light/medium/heavy heavy-duty [HD] diesel; UB=urban bus; HDO=HD Otto)
2004	4JDXH08.1066	8.1	CNG or LNG	Diesel	UB

SPECIAL FEATURES & EMISSION CONTROL SYSTEMS	ENGINE MODELS / CODES (rated power in horsepower, hp)
TBI, OC, O2S, TC, CAC, ECM	6081H / 6081HFN04P (280 hp) 6081H / 6081HFN04Q (280 hp) 6081H / 6081HFN04M(275 hp) 6081H / 6081HFN04R (250 hp) 6081H / 6081HFN04N(275 hp) 6081H / 6081HFN04S (250 hp)

TWC/OC=three-way/oxidizing catalyst WU (prefix) =warm-up cat. O2S=oxygen sensor HO2S=heated O2S TBI=throttle body fuel injection MFI=multi port fuel injection SFI=sequentialMFI DDI/IDI=direct /indirect diesel injection TC/SC=turbo/super charger CAC=charge air cooler EGR=exhaust gas recirculation AIR=secondary air injection PAIR=pulsed AIR SPL=smoke puff limiter ECM/PCM=engine /powertrain control module EM=engine modification 2 (prefix)=parallel (2) (suffix)=in series

The following are the exhaust emission standards (CERT), or family emission limit(s) (FEL) as applicable, and certification levels (CERT) in grams per brake horsepower-hour (g/bhp-hr) for this engine family for hydrocarbon (HC) or non-methane HC (NMHC), oxides of nitrogen (NOx), or NMHC+NOx, carbon monoxide (CO) [except that "diesel" CO certification compliance may have been demonstrated pursuant to Code of Federal Regulations, Title 40, Part 86, Subpart A, Section 86.091-23(c)(2)(i) in lieu of testing], particulate matter (PM), and formaldehyde (HCHO) under the "Federal Test Procedure" (FTP) (Title 13, California Code of Regulations, (13 CCR) Section 1956.1 (urban bus) or 1956.8 (other than urban bus)): (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR Section 1956.1 or 1956.8 are in parentheses.)

* = not applicable [g/bhp-hr]	HC	NMHC	NOx	NMHC+NOx	CO	PM	HCHO
(DIRECT) STANDARD	*	*	*	1.8	15.5	0.01	*
CORPORATE AVERAGE STANDARD	*	*	*	*	*	*	*
FAMILY EMISSION LIMIT (FEL)	*	*	*	*	*	*	*
CERTIFICATION LEVEL	*	*	*	1.5	0.1	0.01	*

BE IT FURTHER RESOLVED: That certification to the FEL(s) listed above, as applicable, is subject to the following terms, limitations and conditions. The FEL(s) is the emission level declared by the manufacturer and serves in lieu of an emission standard for certification purposes in any averaging, banking, or trading (ABT) programs. It will be used for determining compliance of any engine in this family and compliance with such ABT programs.

BE IT FURTHER RESOLVED: That the listed engine models have been certified to the FTP optional NMHC+NOx and PM emission standard(s) listed above pursuant to 13 CCR Section 1956.1 or 1956.8.

BE IT FURTHER RESOLVED: That for the listed engine models, the manufacturer has submitted the materials to demonstrate certification compliance with 13 CCR Sections 1965 (emission control labels), and 2035 et seq. (emission control warranty).

Engines certified under this Executive Order shall conform to all applicable California emission regulations.

The Bureau of Automotive Repair will be notified by copy of this Executive Order.

Executed at El Monte, California on this 4TH day of September 2003.

Allen Lyons, Chief
Mobile Source Operations Division

2009 Cummins Westport ISL-G 8.9L transit bus

California Environmental Protection Agency AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0492-1 New On-Road Heavy-Duty Engines Page 1 of 1 Pages

Pursuant to the authority vested in the Air Resources Board by Health and Safety Code Division 26, Part 5, Chapter 2; and pursuant to the authority vested in the undersigned by Health and Safety Code Sections 39515 and 39516 and Executive Order G-02-003;

IT IS ORDERED AND RESOLVED: The engine and emission control systems produced by the manufacturer are certified as described below for use in on-road motor vehicles with a manufacturer's GVWR over 14,000 pounds. Production engines shall be in all material respects the same as those for which certification is granted.

MODEL YEAR	ENGINE FAMILY	ENGINE SIZES (L)	FUEL TYPE [1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS [2]	ECS & SPECIAL FEATURES [3]	DIAGNOSTIC [5]
2009	9CEXH0540LBD	8.9	CNG/LNG	Diesel	UB	TBI, TC, CAC, ECM, EGR, TWC, HO2S	N/A

PRIMARY ENGINE'S IDLE EMISSIONS CONTROL [5]	ADDITIONAL IDLE EMISSIONS CONTROL [5]
EXEMPT	N/A

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
8.9	ISL G 320 / 0897;FR91958 (320), ISL G 300 / 0897;FR93055 (300), ISL G 280 / 0897;FR91959 (280), ISL G 250 / 0897;FR92740 (250)
*	*
*	*
*	*

* =not applicable; GVWR=gross vehicle weight rating; 13 CCR xyz=Title 13, California Code of Regulations, Section xyz; 40 CFR 86.abc=Title 40, Code of Federal Regulations, Section 86.abc; L=liter; hp=horsepower; kw=kilowatt; hr=hour;

1 CNG/LNG=compressed/liquefied natural gas; LPG=liquefied petroleum gas; E85=85% ethanol fuel; MF=multi fuel a.k.a. BF=bi fuel; DF=dual fuel; FF=flexible fuel;

2 L/M/H HDD=light/medium/heavy heavy-duty diesel; UB=urban bus; HDO=heavy duty Otto;

3 ECS=emission control system; TWC/OC=three-way/oxidizing catalyst; NAC=NOx adsorption catalyst; SCR-U / SCR-N=selective catalytic reduction – urea / – ammonia; WU (prefix) =warm-up catalyst; DPF=diesel particulate filter; PTOX=periodic trap oxidizer; HO2S/O2S=heated/oxygen sensor; HAFS/AFS=heated/air-fuel-ratio sensor (a.k.a., universal or linear oxygen sensor); TBI=throttle body fuel injection; SFI/MFI=sequential/multi port fuel injection; DGI=direct gasoline injection; GCARB=gaseous carburetor; IDI/DDI=indirect/direct diesel injection; TC/SC=turbo/super charger; CAC=charge air cooler; EGR / EGR-C=exhaust gas recirculation / cooled EGR; PAIR/AIR=pulsed/secondary air injection; SPL=smoke puff limiter; ECM/PCM=engine/powertrain control module; EM=engine modification; 2 (prefix)=parallel; (2) (suffix)=in series;

5 ESS=engine shutdown system (per 13 CCR 1956.8(a)(6)(A)(1); 30g=30 g/hr NOx (per 13 CCR 1956.8(a)(6)(C); APS =internal combustion auxiliary power system; ALT=alternative method per 13 CCR 1956.8(a)(6)(D); Exempt=exempted per 13 CCR 1956.8(a)(6)(B) or for CNG/LNG fuel systems; N/A=not applicable (e.g., Otto engines and vehicles);

6 EMD=engine manufacturer diagnostic system (13 CCR 1971); OBD=on-board diagnostic system (13 CCR 1971.1);

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.8; 2) the EURO and NTE limits under the applicable California exhaust emission standards and test procedures for heavy-duty diesel engines and vehicles (Test Procedures); and 3) the corresponding certification levels, for this engine family. "Diesel" CO, EURO and NTE certification compliance may have been demonstrated by the manufacturer as provided under the applicable Test Procedures in lieu of testing. (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR 1956.8 are in parentheses.). [4]

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO
STD	0.14	0.14	0.20	0.20	*	*	15.5	15.5	0.01	0.01	*	*
FEL	*	*	*	*	*	*	*	*	*	*	*	*
CERT	0.13	0.04	0.10	0.01	*	*	1.2	0.4	0.009	0.000	*	*
NTE	0.21		0.30		*		19.4		0.02		*	

4 g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; EURO=Euro III European Steady-State Cycle, including RMCSET=ram mode cycle supplemental emissions testing; NTE=Not-to-Exceed; STD=standard or emission test cap; FEL=family emission limit; CERT=certification level; NMHC/HC=non-methane/hydrocarbon; NOx=oxides of nitrogen; CO=carbon monoxide; PM=particulate matter; HCHO=formaldehyde;

(Rev.: 2007-02-26)

BE IT FURTHER RESOLVED: Certification to the FEL(s) listed above, as applicable, is subject to the following terms, limitations and conditions. The FEL(s) is the emission level declared by the manufacturer and serves in lieu of an emission standard for certification purposes in any averaging, banking, or trading (ABT) programs. It will be used for determining compliance of any engine in this family and compliance with such ABT programs.

BE IT FURTHER RESOLVED: For the listed engine models the manufacturer has submitted the materials to demonstrate certification compliance with 13 CCR 1965 (emission control labels) and 13 CCR 2035 et seq. (emission control warranty).

Engines certified under this Executive Order must conform to all applicable California emission regulations.

The Bureau of Automotive Repair will be notified by copy of this Executive Order.

This Executive Order hereby supersedes Executive Order A-021-0492 dated February 3, 2009.

Executed at El Monte, California on this 30th day of March 2009.

Annette Hebert, Chief
Mobile Source Operations Division

2003 Cummins Westport 8.3L C-Gas Plus engine transit bus

California Environmental Protection Agency AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0340-1 New On-Road Heavy-Duty Engines

Pursuant to the authority vested in the Air Resources Board (ARB) by Health and Safety Code (HSC) Division 26, Part 5, Chapter 2; and pursuant to the authority vested in the undersigned by HSC Sections 39515 and 39516 and Executive Order (EO) G-02-003; and

Pursuant to the December 15, 1998 Settlement Agreement (SA) between ARB and the manufacturer, and any modifications thereof to the Settlement Agreement;

IT IS ORDERED AND RESOLVED: That the engine and emission control systems produced by the manufacturer are certified as described below for use in on-road motor vehicles with a manufacturer's GVWR over 14,000 pounds. Production engines shall be in all material respects the same as those for which certification is granted.

MODEL YEAR	ENGINE FAMILY	ENGINE SIZE (liter)	FUEL TYPE (CNG/LNG=compressed/liquefied natural gas; LPG=liquefied petroleum gas)	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS (L/M/H HDD=light/medium/heavy heavy-duty [HD] diesel; UB=urban bus; HDO=HD Otto)
2003	3CEXH0505CBK	8.3	CNG / LNG	Diesel	UB
SPECIAL FEATURES & EMISSION CONTROL SYSTEMS		ENGINE MODELS / CODES (rated power in horsepower, hp)			
TBI, OC, HO2S, TC, CAC, PCM		CG-280 / 8012 (280 hp), CG-275 / 8009 (275 hp), CG-250 / 8006 (250 hp), CG-250 / 8003 (250 hp)			

GVWR=gross vehicle weight rating TWC/OC=three-way/oxidizing catalyst WU (prefix) =warm-up cat. O2S=oxygen sensor HO2S=heated O2S TBI=throttle body fuel injection MFI=multi port fuel injection SFI=sequentialMFI DDI/IDI=direct /indirect diesel injection TC/SC=turbo/super charger CAC=charge air cooler EGR=exhaust gas recirculation AIR=secondary air injection PAIR=pulsed AIR SPL=smoke puff limiter ECM/PCM=engine /powertrain control module EM=engine modification 2 (prefix)=parallel (2) (suffix)=in series HC=hydrocarbon NMHC=non-methane HC NOx=oxides of nitrogen CO=carbon monoxide PM=particulate matter HCHO=formaldehyde g/bhp-hr=grams per brake horsepower-hour

The following are the exhaust emission standards (STD), or family emission limit(s) (FEL) as applicable, and certification levels (CERT) for this engine family under the "Federal Test Procedure" (FTP) (Title 13, California Code of Regulations, (13 CCR) Section 1956.1 (urban bus) or 1956.8 (other than urban bus)), and under the "Euro III Test Procedure" (EURO) in the Settlement Agreement, including EURO's "Not-to-Exceed" standard(s). "Diesel" CO certification compliance may have been demonstrated pursuant to Code of Federal Regulations, Title 40, Part 86, Subpart A, Section 86.091-23(c)(2)(i) in lieu of testing. (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR Section 1956.1 or 1956.8 are in parentheses.)

			EURO'S NOT-TO-EXCEED STD				NMHC: *		NOx: *		NMHC+NOx: 2.25		PM: 0.0375	
* = not applicable	HC		NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO
(DIRECT) STD	*	*	*	*	*	*	1.8	1.8	15.5	15.5	0.03	0.03	*	*
AVERAGE STD	*	*	*	*	*	*	*	*	*	*	*	*	*	*
FEL	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CERT	*	*	*	*	*	*	1.7	1.4	2.0	1.3	0.01	0.005	*	*

BE IT FURTHER RESOLVED: That certification to the FEL(s) listed above, as applicable, is subject to the following terms, limitations and conditions. The FEL(s) is the emission level declared by the manufacturer and serves in lieu of an emission standard for certification purposes in any averaging, banking, or trading (ABT) programs. It will be used for determining compliance of any engine in this family and compliance with such ABT programs.

BE IT FURTHER RESOLVED: That the listed engine models have been certified to the FTP optional NOx, or NMHC+NOx as applicable, and PM emission standard(s) listed above pursuant to 13 CCR Section 1956.1 or 1956.8.

BE IT FURTHER RESOLVED: That for the listed engine models, the manufacturer has submitted the materials to demonstrate certification compliance with 13 CCR Sections 1965 (emission control labels), and 2035 et seq. (emission control warranty).

BE IT FURTHER RESOLVED: That the listed engine models are conditionally certified subject to the following conditions: **(1)** The SA is in effect; and **(2)** The manufacturer is in compliance with all applicable California emission regulations, and all SA's applicable requirements and any modifications thereof.

Engines certified under this Executive Order shall conform to all applicable California emission regulations and all requirements under the Settlement Agreement and any modifications thereof.

This Executive Order hereby supersedes Executive Order A-021-0340 dated October 2, 2002.
The Bureau of Automotive Repair will be notified by copy of this Executive Order.

Executed at El Monte, California on this 20th day of December 2002.

Raphael Susnowitz

Allen Lyons, Chief
Mobile Source Operations Division

2002 Cummins Westport 8.3L C-Gas Plus Waste Hauler

California Environmental Protection Agency AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0316-2 New On-Road Heavy-Duty Engines

Pursuant to the authority vested in the Air Resources Board by Health and Safety Code (HSC) Division 26, Part 5, Chapter 2; and pursuant to the authority vested in the undersigned by HSC Sections 39515 and 39516 and Executive Order G-45-9; and

Pursuant to the December 15, 1998 Settlement Agreement between the Air Resources Board and the manufacturer, and any modifications thereof to the Settlement Agreement;

IT IS ORDERED AND RESOLVED: That the engine and emission control systems produced by the manufacturer are certified as described below for use in on-road motor vehicles with a manufacturer's gross vehicle weight rating (GVWR) over 14,000 pounds. Production engines shall be in all material respects the same as those for which certification is granted.

MODEL YEAR	ENGINE FAMILY	ENGINE SIZE (liter)	FUEL TYPE (CNG/LNG=compressed/liquefied natural gas; LPG=liquefied petroleum gas)	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS (L/M/H HDD=light/medium/heavy heavy-duty [HD] diesel; UB=urban bus; HDO=HD Otto)
2002	2CEXH0505CBH	8.3	CNG / LNG	Diesel	MHDD
SPECIAL FEATURES & EMISSION CONTROL SYSTEMS		ENGINE MODELS / CODES (rated power in horsepower, hp)			
OC, HO2S, TC, CAC, PCM, TBI		C+8.3-280G / CPL8013 (280 hp), C+8.3-275G / CPL8010 (275 hp), C+8.3-250G / CPL8007 (250 hp), C+8.3-250G / CPL8004 (250 hp), CG-280 / CPL8013 (280 hp), CG-275 / CPL8010 (275 hp), CG-250 / CPL8007 (250 hp), CG-250 / CPL8004 (250 hp)			

TWC/OC=three-way/oxidizing catalyst WU (prefix) =warm-up cat. O2S=oxygen sensor HO2S=heated O2S TBI=throttle body fuel injection MFI=multi port fuel injection SFI=sequentialMFI DDI/IDI=direct /indirect diesel injection TC/SC=turbo/super charger CAC=charge air cooler EGR=exhaust gas recirculation AIR=secondary air injection PAIR=pulsed AIR SPL=smoke puff limiter ECM/PCM=engine /powertrain control module EM=engine modification 2 (prefix)=parallel (2) (suffix)=in series

The following are the exhaust emission standards (STD), or family emission limit(s) (FEL) as applicable, and certification levels (CERT) in grams per brake horsepower-hour (g/bhp-hr) for this engine family for hydrocarbon (HC) or non-methane HC (NMHC), oxides of nitrogen (NOx), or NMHC+NOx, carbon monoxide (CO) [except that "diesel" CO certification compliance may have been demonstrated pursuant to Code of Federal Regulations, Title 40, Part 86, Subpart A, Section 86.091-23(c)(2)(i) in lieu of testing], particulate matter (PM), and formaldehyde (HCHO) under the "Federal Test Procedure" (FTP) (Title 13, California Code of Regulations, (13 CCR) Section 1956.1 (urban bus) or 1956.8 (other than urban bus)), and under the "Euro III Test Procedure" (EURO) in the Settlement Agreement, including a EURO's "Not-to-Exceed" NOx standard: (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR Section 1956.1 or 1956.8 are in parentheses.)

* = not applicable	HC		NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
									EURO'S NOT-TO-EXCEED NOx STD				*	
	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO
(DIRECT) STD	*	*	1.2	*	2.0	*	*	*	15.5	*	0.10	*	*	*
AVERAGE STD	*	*	*	*	*	*	*	*	*	*	*	*	*	*
FEL	*	*	*	*	*	*	*	*	*	*	*	*	*	*
CERT	*	*	0.2	*	1.5	*	*	*	1.3	*	0.01	*	*	*

BE IT FURTHER RESOLVED: That certification to the FEL(s) listed above, as applicable, is subject to the following terms, limitations and conditions. The FEL(s) is the emission level declared by the manufacturer and serves in lieu of an emission standard for certification purposes in any averaging, banking, or trading (ABT) programs. It will be used for determining compliance of any engine in this family and compliance with such ABT programs.

BE IT FURTHER RESOLVED: That the listed engine models have been certified to the FTP optional NOx, or NMHC+NOx as applicable, emission standard listed above pursuant to 13 CCR Section 1956.1 or 1956.8.

BE IT FURTHER RESOLVED: That for the listed engine models, the manufacturer has submitted the materials to demonstrate certification compliance with 13 CCR Sections 1965 (emission control labels), and 2035 et seq. (emission control warranty).

BE IT FURTHER RESOLVED: That the listed engine models are conditionally certified subject to the following conditions: (1) The Settlement Agreement is in effect; and, (2) The manufacturer is in compliance with all applicable certification requirements of the Settlement Agreement and any modifications thereof.

Engines certified under this Executive Order shall conform to all applicable California emission regulations and all requirements under the Settlement Agreement and any modifications thereof.

The Bureau of Automotive Repair will be notified by copy of this Executive Order.
This Executive Order hereby supersedes Executive Order A-021-0316-1 dated November 7, 2001.
This Executive Order is not valid for engines produced on or after October 1, 2002.

Executed at El Monte, California on this 29th day of March 2002.

Allen Lyons, Chief
New Vehicle / Engine Programs Branch

Appendix B. Emissions Test Results

a) Averages, percentage differences, and P-values

2004 John Deere 8.1L 6081H transit bus

John Deere			THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	PM g/mile	miles/GGE	Miles/ft^3	PN #/mile	Formaldehyde mg/mile	Acetaldehyde mg/mile
		Average													
Initial testing		H1	16.4	12.8	1.74	0.11	67.2	20.7	1895.8	0.0029	3.407	0.0274	7.31E+12	194.83	3.37
		H2	16.1	12.1	2.23	0.10	71.7	16.1	1971.7	0.0025	3.289	0.0272	6.37E+12	161.92	1.32
		LM3	14.4	9.9	3.09	0.11	74.5	8.8	1937.3	0.0009	3.360	0.0288	5.41E+12	114.20	0.00
		LM4	14.9	10.0	3.51	0.12	79.8	24.7	1993.7	0.0016	3.297	0.0296	5.44E+12	106.79	0.00
Post-repair testing		H1	18.3	14.0	2.26	0.12	41.1	5.8	1732.1	0.0022	3.710	0.0299	-	230.38	1.99
		LM5	15.2	9.6	4.25	0.09	50.9	11.7	1684.5	0.0034	3.897	0.0344	-	169.23	0.79
		LM6	15.9	10.5	3.89	0.11	61.5	5.7	1785.3	0.0018	3.679	0.0325	-	135.80	2.97
	Vs.	% difference													
Initial testing	H1	H2	-1.9%	-5.4%	28.4%	-3.3%	6.7%	-22.4%	4.0%	-15.9%	-3.5%	-1.0%	-13%	-16.9%	-60.9%
		LM3	-11.8%	-22.4%	78.0%	8.6%	10.8%	-57.4%	2.2%	-68.3%	-1.4%	4.8%	-26%	-41.4%	-100.0%
		LM4	-8.8%	-21.8%	101.8%	13.9%	18.8%	19.3%	5.2%	-45.8%	-3.2%	8.0%	-26%	-45.2%	-100.0%
	H2.	H1	1.9%	5.7%	-22.1%	3.4%	-6.3%	28.9%	-3.8%	19.0%	3.6%	1.0%	-	-	-
		LM3	-10.2%	-17.9%	38.6%	12.3%	3.9%	-45.0%	-1.7%	-62.3%	2.2%	5.9%	-	-	-
		LM4	-7.1%	-17.4%	57.1%	17.8%	11.3%	53.8%	1.1%	-35.5%	0.2%	9.1%	-	-	-
Post-repair testing	H1.	LM5	-17.0%	-31.6%	87.7%	-23.2%	23.9%	101.3%	-2.7%	57.1%	5.0%	15.1%	-	-27%	-60%
		LM6	-13.0%	-24.8%	71.6%	-10.9%	49.9%	-1.9%	3.1%	-16.1%	-0.8%	8.7%	-	-41%	49%
		P-value													
Initial testing	H1	H2	0.492	0.079	0.001	0.902	0.070	0.632	0.004	0.511	0.007	0.327	0.011	0.024	0.074
		LM3	0.000	0.000	0.000	0.761	0.157	0.155	0.047	0.027	0.168	0.001	0.000	0.000	0.000
		LM4	0.002	0.000	0.000	0.592	0.003	0.789	0.004	0.087	0.026	0.001	0.000	0.016	0.000
Post-repair testing	H1	LM5	0.000	0.000	0.000	0.354	0.241	0.525	0.230	0.500	0.065	0.001	-	0.013	0.182
		LM6	0.001	0.000	0.000	0.441	0.000	0.988	0.079	0.813	0.574	0.001	-	0.002	0.189

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1); Note the units in the header pertain only to the average values. The units for the percent values and the p values are unitless.

2009 Cummins Westport ISL-G 8.9 L transit bus

	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	PM g/mile	miles/GGE	Miles/ft^3	PN #/miles	Formaldehyde mg/mile	Acetaldehyde mg/mile
Average													
H1	0.42	0.44	-0.14	8.06	0.254	1442.7	1710.0	0.0048	3.99	0.0308	4.1E+12	-2.02	1.25
H2	0.46	0.53	-0.22	8.32	0.292	1285.5	1715.9	0.0040	3.83	0.0316	5.6E+12	-1.14	0.66
LM3	0.61	0.72	-0.33	8.97	0.256	1432.7	1664.1	0.0047	3.95	0.0338	3.2E+12	-0.90	0.73
LM4	0.88	0.74	-0.07	8.82	0.238	1544.9	1680.5	0.0040	3.95	0.0355	1.9E+12	-1.37	0.40
LM5	0.47	0.62	-0.32	8.32	0.244	1651.5	1658.4	0.0039	4.01	0.0354	3.3E+12	-2.08	1.24
LM6	0.51	0.60	-0.26	8.37	0.217	1725.7	1687.4	0.0043	3.95	0.0349	3.7E+12	-1.87	0.00
Percentage difference													
H2	9.6%	20.1%	-49.7%	3.3%	14.8%	-10.9%	0.3%	-16.1%	-4.1%	2.5%	38%	43.4%	-47.1%
LM3	43.4%	65.0%	-126.5%	11.3%	0.8%	-0.7%	-2.7%	-1.0%	-1.0%	9.7%	-20%	55.3%	-41.7%
LM4	107.4%	68.7%	51.2%	9.5%	-6.5%	7.1%	-1.7%	-16.3%	-1.1%	15.1%	-52%	32.0%	-67.6%
LM5	11.7%	41.5%	-124.0%	3.3%	-3.8%	14.5%	-3.0%	-17.1%	0.5%	14.9%	-18%	-3.2%	-0.2%
LM6	21.6%	37.9%	-80.5%	3.9%	-14.4%	19.6%	-1.3%	-9.7%	-1.2%	13.1%	-10%	7.3%	-100.0%
p-value													
H2	0.669	0.168	0.259	0.766	0.428	0.115	0.849	0.574	0.359	0.196	0.083	0.722	0.490
LM3	0.157	0.007	0.000	0.210	0.952	0.928	0.134	0.972	0.813	0.000	0.183	0.651	0.547
LM4	0.012	0.001	0.601	0.318	0.528	0.134	0.179	0.565	0.797	0.000	0.015	0.794	0.321
LM5	0.572	0.019	0.000	0.678	0.723	0.008	0.055	0.576	0.901	0.000	0.104	0.979	0.998
LM6	0.373	0.026	0.051	0.691	0.118	0.001	0.255	0.751	0.782	0.000	0.315	0.951	0.148

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1); Note the units in the header pertain only to the average values. The units for the percent values and the p values are unitless.

2003 Cummins Westport 8.3L C-Gas Plus engine transit bus

	THC g/mil	CH4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	PM g/mile	miles/GGE	Miles/ft^3	PN #/miles	Formaldehyde mg/mile	Acetaldehyde mg/mile
Average													
H1	21.11	16.71	1.98	0.67	12.6	25.8	1753.2	0.0034	3.652	0.0294	6.64E+12	126.35	1.85
H2	20.73	16.00	2.42	1.06	12.4	36.2	1731.1	0.0034	3.710	0.0306	9.78E+12	120.59	3.04
LM3	17.88	12.84	3.20	1.19	17.3	35.8	1751.1	0.0026	3.691	0.0316	8.52E+12	96.35	1.53
LM5	16.07	11.28	3.22	1.90	19.3	26.9	1767.2	0.0023	3.718	0.0328	6.66E+12	108.69	2.95
LM6	16.75	12.23	2.76	1.35	16.7	28.6	1775.2	0.0015	3.692	0.0326	7.05E+12	95.69	2.67
Percentage difference													
H2	-1.8%	-4.3%	22.1%	58.9%	-1.7%	40.4%	-1.3%	-1.7%	1.6%	4.1%	47%	-4.6%	64.1%
LM3	-15.3%	-23.2%	62%	78%	38%	39.0%	-0.1%	-25.0%	1.1%	7.4%	28%	-23.7%	-17.7%
LM5	-23.9%	-33%	62.3%	185.0%	53.4%	4.2%	0.8%	-32.4%	1.8%	11.6%	0.4%	-14.0%	59.0%
LM6	-20.7%	-26.8%	39.2%	102.9%	32.4%	10.9%	1.3%	-55.5%	1.1%	10.8%	6%	-24.3%	44.1%
P-value													
H2	0.359	0.029	0.004	0.195	0.847	0.282	0.246	0.964	0.166	0.003	0.157	-	-
LM3	0.000	0.000	0.000	0.017	0.002	0.293	0.926	0.680	0.438	0.000	0.322	-	-
LM5	0.000	0.000	0.000	0.000	0.004	0.869	0.570	0.439	0.177	0.000	0.851	0.035	0.535
LM6	0.000	0.000	0.001	0.016	0.022	0.754	0.207	0.295	0.253	0.000	0.868	0.001	0.643

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1); Note the units in the header pertain only to the average values. The units for the percent values and the p values are unitless.

2002 Cummins Westport 8.3L C-Gas Plus Waste Hauler

Transport	THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
Average										
H1	17.8	13.0	2.73	1.15	19.0	36.1	1729.7	3.719	0.030	5.07E+12
H2	17.3	12.3	2.66	1.40	22.3	28.2	1723.2	3.745	0.031	3.10E+12
LM3	11.5	8.0	2.16	1.61	35.0	31.1	1642.7	3.962	0.034	1.96E+12
LM4	9.3	6.6	1.79	1.94	42.1	26.4	1660.7	3.971	0.036	1.87E+12
LM5	8.3	6.2	1.72	1.74	43.7	37.1	1690.5	3.914	0.035	5.33E+12
LM6	9.7	6.8	1.80	1.59	39.0	26.7	1655.1	3.994	0.035	5.09E+12
H7	16.5	12.5	1.77	0.99	17.4	32.2	1684.3	3.780	0.031	5.80E+12
Average										
Curbside pick up	THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
H1	60.4	47.6	8.85	0.49	102.2	111.2	6333.2	1.020	0.008	3.20E+13
H2	55.8	42.9	7.05	0.54	115.9	101.9	6413.5	1.010	0.008	2.09E+13
LM3	48.6	34.2	9.67	0.44	155.4	90.7	6299.6	1.034	0.009	1.50E+13
LM4	49.7	35.1	10.19	0.91	175.4	81.1	6667.8	0.986	0.009	1.71E+13
LM5	43.4	31.2	10.53	0.91	175.2	102.8	6438.4	1.090	0.010	3.20E+13
LM6	51.1	35.7	10.55	0.83	171.6	89.2	6664.0	0.990	0.009	3.35E+13
H7	67.3	53.8	7.43	0.43	95.5	115.9	6504.9	0.977	0.008	3.69E+13
Average										
Compaction	THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft$^{3/}$bhp.hr	PN #/'bhp.hr
H1	2.3	1.8	0.02	0.042	4.9	7.7	410.4	0.063	7.822	6.48E+11
H2	2.0	1.5	0.04	0.041	7.3	5.3	435.5	0.066	8.050	3.92E+11
LM3	1.4	1.0	0.13	0.028	14.3	9.6	458.0	0.070	8.127	2.62E+11
LM4	1.3	0.9	0.13	0.022	18.6	6.5	475.6	0.071	7.950	1.85E+11
LM5	1.2	0.8	0.17	0.024	18.9	4.9	479.3	0.070	7.897	6.35E+11
LM6	1.3	0.9	0.16	0.026	17.1	3.7	472.0	0.071	8.012	6.17E+11
H7	2.6	2.1	0.00	0.038	4.1	6.2	401.3	0.062	7.691	6.22E+11

Compaction	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/ whp.hr
H1	3.2	2.5	0.030	0.057	6.7	10.4	559.3	0.0859	10.661	8.87E+11
H2	2.5	1.9	0.052	0.053	9.4	6.7	559.1	0.0852	10.336	5.05E+11
LM3	1.7	1.2	0.163	0.034	17.4	11.8	558.7	0.0849	9.914	3.18E+11
LM4	1.5	1.1	0.157	0.026	21.9	7.6	560.6	0.0842	9.371	2.18E+11
LM5	1.5	1.0	0.209	0.029	22.7	5.8	575.1	0.0869	9.849	7.62E+11
LM6	1.6	1.1	0.187	0.031	20.5	4.4	566.6	0.0849	9.616	7.54E+11
H7	3.6	2.9	0.003	0.053	5.6	8.6	556.8	0.0867	10.671	8.62E+11

		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
Percentage difference	vs. H1										
Transport	H2	-2.8%	-5.3%	-2.6%	21.1%	17.3%	-22.0%	-0.4%	0.7%	3.2%	-39.0%
	LM3	-36%	-38.5%	-20.7%	39.7%	84.1%	-13.8%	-5.0%	6.5%	13.2%	-61.5%
	LM4	-48%	-49.2%	-34.4%	68.5%	121.2%	-26.9%	-4.0%	6.8%	19.1%	-63.1%
	LM5	-54%	-52.0%	-36.8%	51.0%	129.6%	2.8%	-2.3%	5.2%	15.3%	5.1%
	LM6	-45%	-47.4%	-33.9%	37.4%	104.8%	-26.2%	-4.3%	7.4%	17.7%	0.3%
	H7	-7.3%	-3.5%	-35.0%	-13.8%	-8.7%	-10.8%	-2.6%	1.6%	2.4%	14.4%
Percentage difference											
Curbside pick up	vs. H1	THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/m ile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
	H2	-7.5%	-9.7%	-20.3%	11.0%	13.4%	-8.4%	1.3%	-1.0%	1.5%	-34.7%
	LM3	-19.6%	-28.1%	9.2%	-10.1%	52%	-18.5%	-0.5%	1.4%	7.7%	-53.1%
	LM4	-17.7%	-26.3%	15.1%	86.2%	72%	-27.1%	5.3%	-3.3%	7.9%	-46.7%
	LM5	-28.1%	-34.4%	18.9%	87.7%	71%	-7.6%	1.7%	6.9%	17.1%	-0.2%
	LM6	-15.3%	-25.1%	19.2%	70.7%	68%	-19.8%	5.2%	-2.9%	6.4%	4.7%
	H7	11.5%	13.0%	-16.1%	-12.2%	-6.6%	4.2%	2.7%	-4.2%	-3.4%	15.3%
Percentage difference	vs. H1										
Compaction		THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft^3/bhp.hr	PN #/bhp.hr
	H2	-16.5%	-18.3%	79.2%	-2.7%	49.0%	-30.9%	6.1%	5.5%	2.9%	-39.6%
	LM3	-40%	-45%	511.5%	-33.3%	191%	25.4%	11.6%	10.4%	3.9%	-59.7%
	LM4	-45%	-51%	508.6%	-48.1%	278%	-15.1%	15.9%	13.4%	1.6%	-71.4%
	LM5	-48%	-54%	666.1%	-43.4%	286%	-35.8%	16.8%	10.6%	1.0%	-2.1%
	LM6	-43%	-49%	611.9%	-38.3%	248%	-51.9%	15.0%	12.3%	2.4%	-4.9%
	H7	11%	12.0%	-91.4%	-9.3%	-17.0%	-18.6%	-2.2%	-0.9%	-1.7%	-4.1%
Compaction	vs. H1	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	H2	-21%	-23%	75%	-7.9%	40%	-35%	0.0%	-0.8%	-3.1%	-43.1%

Compaction	vs. H1	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM3	-46%	-51%	451%	-40.0%	160%	13%	-0.1%	-1.2%	-7.0%	-64.1%
	LM4	-53%	-57%	430%	-55.0%	228%	-27%	0.2%	-1.9%	-12.1%	-75.4%
	LM5	-52%	-60%	605%	-49.8%	240%	-44%	2.8%	1.2%	-7.6%	-14.1%
	LM6	-50%	-55%	529%	-45.5%	207%	-58%	1.3%	-1.1%	-9.8%	-15.1%
	H7	13%	14.0%	-91%	-7.4%	-16%	-17%	-0.4%	0.9%	0.1%	-2.9%

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		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
Percentage difference	vs. H2										
Transport	LM3	-33.8%	-35.0%	-18.6%	15.4%	56.9%	10.6%	-4.7%	5.8%	9.7%	-36.9%
	LM4	-46.2%	-46.4%	-32.7%	39.2%	88.6%	-6.3%	-3.6%	6.0%	15.4%	-39.6%
	LM5	-52.4%	-49.4%	-35.1%	24.7%	95.7%	31.9%	-1.9%	4.5%	11.7%	72.1%
	LM6	-43.8%	-44.5%	-32.1%	13.5%	74.6%	-5.3%	-3.9%	6.7%	14.1%	64.3%
	H7	-4.6%	1.9%	-33.3%	-28.8%	-22.2%	14.4%	-2.3%	0.9%	-0.8%	87.4%
Percentage difference	vs. H2										
Curbside pick up		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
	LM3	-13.0%	-20.3%	37.1%	-19.0%	34%	-11.0%	-1.8%	2.4%	6.1%	-28.1%
	LM4	-11.0%	-18.4%	44.5%	67.7%	51%	-20.4%	4.0%	-2.4%	6.2%	-18.3%
	LM5	-22.2%	-27.3%	49.2%	69.1%	51%	1.0%	0.4%	8.0%	15.4%	53.0%
	LM6	-8.4%	-17.0%	49.6%	53.8%	48%	-12.4%	3.9%	-2.0%	4.8%	60.4%
	H7	20.6%	25.2%	5.3%	-20.9%	-17.6%	13.8%	1.4%	-3.2%	-4.8%	76.6%
Percentage difference	vs. H2										
Compaction		THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft^3/bhp.hr	PN #/bhp.hr
	LM3	-28%	-33%	241.3%	-31.4%	95%	81.6%	5.2%	4.6%	1.0%	-33.3%
	LM4	-34%	-40%	239.6%	-46.7%	154%	23.0%	9.2%	7.5%	-1.2%	-52.7%
	LM5	-38%	-44%	327.5%	-41.8%	159%	-7.1%	10.1%	4.9%	-1.9%	62.0%
	LM6	-31%	-37%	297.3%	-36.6%	134%	-30.3%	8.4%	6.4%	-0.5%	57.4%
	H7	32%	37.2%	-95.2%	-6.8%	-44.3%	17.9%	-7.8%	-6.1%	-4.5%	58.6%
Compaction	vs. H2	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM3	-32%	-37%	215%	-35%	86%	75%	-0.1%	-0.4%	-4.1%	-36.9%
	LM4	-40%	-45%	203%	-51%	134%	13%	0.3%	-1.2%	-9.3%	-56.7%
	LM5	-40%	-48%	303%	-45%	143%	-13%	2.9%	2.0%	-4.7%	50.9%

Compaction	vs. H2	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM6	-36%	-42%	260%	-41%	119%	-35%	1.3%	-0.3%	-7.0%	49.3%
	H7	43%	48%	-95%	0%	-40%	28%	-0.4%	1.7%	3.3%	70.7%

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		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
Percentage difference	vs. H7										
Transport	LM3	-30.6%	-36.2%	22.1%	62.1%	101.7%	-3.3%	-2.5%	4.8%	10.5%	-66.3%
	LM4	-43.6%	-47.4%	1.0%	95.5%	142.4%	-18.1%	-1.4%	5.1%	16.3%	-67.8%
	LM5	-50.1%	-50.3%	-2.7%	75.2%	151.5%	15.3%	0.4%	3.5%	12.6%	-8.2%
	LM6	-41.1%	-45.5%	1.8%	59.4%	124.4%	-17.2%	-1.7%	5.7%	14.9%	-12.4%
Percentage difference	vs. H7										
Curbside pick up		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
	LM3	-28%	-36.4%	30.3%	2.4%	63%	-21.7%	-3.2%	5.8%	11.5%	-59.3%
	LM4	-26%	-34.8%	37.3%	112.2%	84%	-30.0%	2.5%	0.9%	11.6%	-53.8%
	LM5	-35%	-41.9%	41.7%	113.9%	83%	-11.3%	-1.0%	11.5%	21.3%	-13.4%
	LM6	-24%	-33.7%	42.1%	94.5%	80%	-23.0%	2.4%	1.3%	10.1%	-9.2%
Percentage difference	vs. H7										
Compaction		THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft^3/bhp.hr	PN #/bhp.hr
	LM3	-46%	-51%	7036.3%	-26.4%	250%	54.0%	14.1%	11.4%	5.7%	-57.9%
	LM4	-50%	-56%	7002.2%	-42.8%	356%	4.3%	18.5%	14.4%	3.4%	-70.2%
	LM5	-53%	-59%	8840.2%	-37.6%	365%	-21.2%	19.4%	11.6%	2.7%	2.1%
	LM6	-48%	-54%	8207.8%	-32.0%	320%	-40.9%	17.6%	13.3%	4.2%	-0.8%
Compaction	vs. H7	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM3	-52%	-57%	5914%	-35%	209%	37%	0.3%	-2.1%	-7.1%	-63.1%
	LM4	-58%	-63%	5683%	-51%	288%	-12%	0.7%	-2.8%	-12.2%	-74.7%
	LM5	-58%	-65%	7593%	-46%	303%	-32%	3.3%	0.3%	-7.7%	-11.6%
	LM6	-55%	-61%	6768%	-41%	264%	-50%	1.8%	-2.0%	-9.9%	-12.6%

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		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
P-value											
Transport	Vs. H1										
	H2	0.813	0.569	0.904	0.410	0.000	0.193	0.842	0.730	0.131	0.009
	LM3	0.003	0.000	0.227	0.110	0.000	0.541	0.008	0.003	0.000	0.001
	LM4	0.000	0.000	0.050	0.008	0.000	0.154	0.041	0.004	0.000	0.000
	LM5		0.000		0.014	0.000	0.862	0.209			0.698
	LM6	0.000	0.000	0.055	0.057	0.000	0.195	0.027	0.002	0.000	0.988
	H7	0.400	0.591	0.054	0.434	0.002	0.573	0.185	0.389	0.245	0.310
P-value	Vs. H1										
Curbside		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
	H2	0.113	0.037	0.096	0.785	0.006	0.709	0.666	0.730	0.602	0.006
	LM3	0.001	0.000	0.241	0.818	0.000	0.435	0.876	0.678	0.042	0.000
	LM4	0.003	0.000	0.029	0.356	0.000	0.265	0.097	0.264	0.020	0.001
	LM5		0.000		0.332	0.000	0.716	0.597			0.987
	LM6	0.011	0.000	0.055	0.260	0.000	0.424	0.149	0.381	0.080	0.754
	H7	0.026	0.012	0.113	0.775	0.124	0.847	0.410	0.204	0.294	0.191
P-value	Vs. H1										
Compaction		THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft^3/bhp.hr	PN #/bhp.hr
	H2	0.000	0.000	0.340	0.792	0.000	0.040	0.001	0.001	0.040	0.006
	LM3	0.000	0.000	0.000	0.016	0.000	0.214	0.000	0.000	0.000	0.000
	LM4	0.000	0.000	0.000	0.002	0.000	0.509	0.000	0.000	0.027	0.000
	LM5		0.000		0.006	0.000	0.164	0.000			0.854
	LM6	0.000	0.000	0.000	0.001	0.000	0.017	0.000	0.000	0.026	0.772
	H7	0.001	0.000	0.022	0.341	0.028	0.304	0.010	0.221	0.033	0.720
Compaction	Vs. H1	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	H2	0.000	0.000	0.363	0.438	0.000	0.016	0.966	0.377	0.005	0.006

Compaction	Vs. H1	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM3	0.000	0.000	0.000	0.004	0.000	0.500	0.904	0.202	0.000	0.000
	LM4	0.000	0.000	0.000	0.000	0.000	0.196	0.802	0.052	0.000	0.000
	LM5		0.000		0.002	0.000	0.063	0.002			0.265
	LM6	0.000	0.000	0.000	0.000	0.000	0.005	0.245	0.310	0.000	0.414
	H7	0.006	0.003	0.022	0.428	0.020	0.337	0.644	0.635	0.752	0.813

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1) whp-hr = wheel horsepower-hour basis; bhp-hr = brake horsepower-hour basis from engine control module (ECM); Note the units in the header pertain only to the average values. The p-values are unitless.

		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
P-value											
Transport	Vs. H2										
	LM3	0.004	0.001	0.202	0.496	0.000	0.681	0.002	0.001	0.000	0.000
	LM4	0.000	0.000	0.028	0.085	0.000	0.717	0.023	0.001	0.000	0.000
	LM5		0.000		0.178	0.000	0.040	0.178			0.000
	LM6	0.000	0.000	0.032	0.453	0.000	0.792	0.012	0.001	0.000	0.000
	H7	0.551	0.772	0.035	0.122	0.000	0.469	0.177	0.516	0.629	0.000
P-value											
Curbside	Vs. H2	THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
	LM3	0.000	0.000	0.020	0.565	0.000	0.671	0.389	0.255	0.014	0.000
	LM4	0.006	0.000	0.005	0.401	0.000	0.439	0.005	0.059	0.000	0.001
	LM5		0.000		0.376	0.000	0.967	0.797			0.000
	LM6	0.051	0.000	0.007	0.297	0.000	0.645	0.079	0.327	0.038	0.000
	H7	0.000	0.000	0.737	0.510	0.000	0.568	0.417	0.080	0.014	0.000
P-value											
Compaction	Vs. H2	THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft^3/bhp.hr	PN #/bhp.hr
	LM3	0.000	0.000	0.000	0.011	0.000	0.021	0.002	0.004	0.453	0.001
	LM4	0.000	0.000	0.000	0.001	0.000	0.510	0.000	0.000	0.327	0.000
	LM5		0.000		0.004	0.000	0.849	0.000			0.000
	LM6	0.000	0.000	0.000	0.000	0.000	0.311	0.000	0.001	0.738	0.000
	H7	0.000	0.000	0.049	0.383	0.000	0.523	0.000	0.001	0.004	0.000
Compaction	Vs. H2	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM3	0.000	0.000	0.001	0.007	0.000	0.035	0.949	0.724	0.004	0.001
	LM4	0.000	0.000	0.001	0.000	0.000	0.682	0.814	0.320	0.000	0.000
	LM5		0.000		0.003	0.000	0.706	0.013			0.000
	LM6	0.000	0.000	0.000	0.000	0.000	0.218	0.304	0.805	0.000	0.001
	H7	0.000	0.000	0.054	0.954	0.000	0.339	0.726	0.319	0.047	0.000

Yellow highlight: Statistically significant (p-value $\leq$ 0.05) or Marginally statistically significant (0.05<p-value$\leq$0.1) whp-hr = wheel horsepower-hour basis; bhp-hr = brake horsepower-hour basis from engine control module (ECM); Note the units in the header pertain only to the average values. The p-values are unitless.

		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
P-value											
Transport	Vs. H7										
	LM3	0.000	0.000	0.056	0.019	0.000	0.892	0.080	0.004	0.000	0.000
	LM4	0.000	0.000	0.900	0.001	0.000	0.362	0.365	0.007	0.000	0.000
	LM5		0.000		0.000	0.000	0.391	0.805			0.267
	LM6	0.000	0.000	0.832	0.002	0.000	0.421	0.252	0.003	0.000	0.185
P-value											
Curbside	Vs. H7	THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NO_x g/mile	NH_3 mg/mile	CO_2 g/mile	miles/GGE	miles/ft^3	PN #/mile
	LM3	0.000	0.000	0.017	0.957	0.000	0.331	0.208	0.038	0.001	0.000
	LM4	0.000	0.000	0.002	0.283	0.000	0.193	0.173	0.627	0.000	0.000
	LM5		0.000		0.261	0.000	0.562	0.613			0.028
	LM6	0.000	0.000	0.006	0.168	0.000	0.326	0.326	0.602	0.002	0.190
P-value											
Compaction	Vs. H7	THC g/bhp.hr	CH_4 g/bhp.hr	NMHC g/bhp.hr	CO g/bhp.hr	NO_x g/bhp.hr	NH_3 mg/bhp.hr	CO_2 g/bhp.hr	GGE/bhp.hr	ft^3/bhp.hr	PN #/bhp.hr
	LM3	0.000	0.000	0.000	0.026	0.000	0.089	0.000	0.000	0.000	0.000
	LM4	0.000	0.000	0.000	0.002	0.000	0.894	0.000	0.000	0.001	0.000
	LM5		0.000		0.009	0.000	0.542	0.000			0.399
	LM6	0.000	0.000	0.000	0.000	0.000	0.170	0.000	0.000	0.002	0.794
Compaction	Vs. H7	THC g/whp.hr	CH_4 g/whp.hr	NMHC g/whp.hr	CO g/whp.hr	NO_x g/whp.hr	NH_3 mg/whp.hr	CO_2 g/whp.hr	GGE/whp.hr	ft^3/whp.hr	PN #/whp.hr
	LM3	0.000	0.000	0.000	0.004	0.000	0.219	0.775	0.204	0.000	0.000
	LM4	0.000	0.000	0.000	0.000	0.000	0.691	0.577	0.079	0.000	0.000
	LM5		0.000		0.002	0.000	0.309	0.010			0.000
	LM6	0.000	0.000	0.000	0.000	0.000	0.079	0.210	0.275	0.000	0.000

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1) whp-hr = wheel horsepower-hour basis; bhp-hr = brake horsepower-hour basis from engine control module (ECM); Note the units in the header pertain only to the average values. The p-values are unitless.

	PM g/cycle	Formaldehyde (mg/cycle)	Acetaldehyde (mg/cycle)
	Average		
H1	0.061	1275.29	56.02
H2	0.069	1178.94	57.76
LM3	0.040	578.43	22.03
LM4	0.028	676.99	20.76
LM5	0.025	667.73	26.54
LM6	0.030	619.26	21.30
H7	0.046	1436.96	42.48
Vs. H1	**Percentage difference**		
H2	12.3%	-7.6%	3.1%
LM3	-36%	-54.6%	-60.7%
LM4	-54%	-46.9%	-62.9%
LM5	-60%	-47.6%	-52.6%
LM6	-51%	-51.4%	-62.0%
H7	-26%	12.7%	-24.2%
Vs. H1	**P-value**		
H2	0.608	0.362	0.823
LM3	0.129	0.001	0.003
LM4	0.020	0.006	0.002
LM5	0.014	0.004	0.012
LM6	0.029	0.002	0.049
H7	0.230	0.141	0.054
Vs. H2	**Percentage difference**		
LM3	-43%	-51%	-62%
LM4	-59%	-43%	-64%
LM5	-64%	-43%	-54%
LM6	-57%	-47%	-63%

	PM g/cycle	Formaldehyde (mg/cycle)	Acetaldehyde (mg/cycle)
H7	-34%	22%	-26%
Vs. H2	**P-value**		
LM3	0.013	0.000	0.009
LM4	0.001	0.005	0.007
LM5	0.001	0.003	0.021
LM6	0.002	0.001	0.054
H7	0.031	0.011	0.102
Vs. H7	**Percentage difference**		
LM3	-14%	-60%	-48%
LM4	-38%	-53%	-51%
LM5	-46%	-54%	-38%
LM6	-34%	-57%	-50%
Vs. H7	**P-value**		
LM3	0.281	0.000	0.019
LM4	0.006	0.001	0.010
LM5	0.004	0.000	0.073
LM6	0.024	0.000	0.162

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1); Note the units in the header pertain only to the average values. The units for the percent values and the p values are unitless.

b) Test results on each bus

2004 John Deere 8.1L 6081H transit bus

Date	File Name	Fuel	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	NH_3 mg/mile	CO2 g/mile	PM g/mile	miles/GGE	miles/ft3	Formaldehyde mg/mile	Acetaldehyde mg/mile	Particle #/mile
7/6/2011	201107060910	H1	15.94	12.17	2.02	0.109	66.09	13.22	1895.15	0.004	3.409	0.0275	202.103	3.732	7.24E+12
7/6/2011	201107060956	H1	16.52	12.97	1.67	0.080	66.97	31.41	1905.94	0.003	3.388	0.0273	210.251	3.919	7.08E+12
7/6/2011	201107061054	H1	16.83	13.24	1.68	0.147	68.78	23.77	1930.26	0.003	3.345	0.0269	189.102	3.412	7.25E+12
7/6/2011	201107061137	H1	16.21	12.77	1.60	0.087	66.91	14.50	1852.02	0.003	3.486	0.0281	177.850	2.430	7.66E+12
		H1		Due to engine mechanical failure only four replicates were tested. The remainder of the tests were completed when the vehicle returned.											
		H1													
7/6/2011	201107061242	H2	16.35	12.30	2.28	0.190	74.67	37.90	2003.93	0.004	3.235	0.0267	174.991	0.713	7.19E+12
7/6/2011	201107061322	H2	17.01	12.79	2.37	0.112	74.63	32.87	1987.90	0.002	3.258	0.0269	160.220	3.239	6.70E+12
7/6/2011	201107061403	H2	16.78	12.63	2.33	0.101	74.98	15.66	1989.93	0.003	3.256	0.0269	150.549	0.000	6.52E+12
7/7/2011	201107070737	H2	15.10	11.37	2.09	0.085	64.33	12.88	1934.61	0.002	3.354	0.0277			5.95E+12
7/7/2011	201107070824	H2	15.38	11.57	2.15	0.074	70.23	4.62	1956.12	0.000	3.317	0.0274			6.02E+12
7/7/2011	201107070911	H2	15.79	11.91	2.17	0.051	71.25	-7.47	1957.89	0.003	3.312	0.0274			5.85E+12
7/7/2011	201107071018	LM3	14.16	9.80	2.96	0.021	78.45	10.82	1958.02	0.003	3.326	0.0285	122.349	0.000	5.85E+12
7/7/2011	201107071058	LM3	14.77	10.22	3.09	0.166	79.94	11.80	1968.24	0.000	3.306	0.0283	114.880	0.000	5.64E+12
7/7/2011	201107071138	LM3	14.20	9.83	2.97	0.105	79.70	30.94	1933.08	*	3.367	0.0288	105.369	0.000	5.82E+12
7/8/2011	201107080728	LM3	14.65	9.99	3.23	0.150	56.38	9.19	1907.68	0.002	3.409	0.0292			4.84E+12
7/8/2011	201107080811	LM3	14.18	9.68	3.13	0.142	74.14	-3.76	1914.72	0.000	3.399	0.0291			5.14E+12
7/8/2011	201107080857	LM3	14.67	10.05	3.19	0.106	78.22	-5.97	1941.92	0.000	3.350	0.0287			5.19E+12
7/8/2011	201107081007	LM4	14.95	10.00	3.52	0.081	82.40	6.43	1999.63	0.001	3.287	0.0295	71.332	0.000	5.49E+12
7/8/2011	201107081048	LM4	14.98	10.04	3.51	0.123	82.44	11.54	1994.47	0.003	3.295	0.0296	88.248	0.000	5.40E+12
7/8/2011	201107081133	LM4	14.84	9.93	3.49	0.158	74.59	56.20	1986.94	0.001	3.308	0.0297	160.800	0.000	5.42E+12
		LM4													
		LM4		These three tests were eliminated because it was determined that the engine had failed and was not operating correctly during these tests.											
		LM4													

*Outlier tests that were eliminated from the averages
201107071138: The PM mass collected was below the background level.

Date	File Name	Fuel	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	NH_3 mg/mile	CO2 g/mile	PM g/mile	miles/GGE	miles/ft3	Formaldehyde mg/mile	Acetaldehyde mg/mile	Particle #/mile
5/29/2012	201205291256	LM6	15.89	10.53	3.87	0.112	66.18	25.06	1833.88	0.003	3.582	0.0316	130.430	2.955	
5/29/2012	201205291344	LM6	14.87	9.82	3.66	0.152	64.25	3.01	1737.59	0.002	3.782	0.0334	132.100	2.834	
5/29/2012	201205291431	LM6	15.47	10.18	3.84	0.112	59.60	1.42	1781.25	0.002	3.688	0.0326	144.876	3.107	
5/31/2012	201205311026	LM6	16.45	10.91	3.99	0.103	56.69	13.07	1748.63	0.004	3.750	0.0331			
5/31/2012	201205311112	LM6	16.11	10.66	3.93	0.109	59.97	-4.71	1773.37	0.001	3.701	0.0327			
5/31/2012	201205311157	LM6	16.79	11.18	4.03	0.066	62.59	-3.55	1836.81	0.000	3.572	0.0316			
5/30/2012	201205300842	H1	17.94	13.77	2.19	0.121	36.60	11.98	1717.98	0.000	3.742	0.0301	205.963	0.897	
5/30/2012	201205300928	H1	18.82	14.39	2.35	0.121	38.55	8.77	1750.25	0.005	3.670	0.0296	237.981	3.020	
5/30/2012	201205301014	H1	18.14	13.89	2.25	0.125	48.07	-3.27	1728.13	0.002	3.719	0.0300	247.184	2.042	
5/30/2012	201205301218	LM5	15.43	9.64	4.44	0.098	62.26	-11.08	1749.87	0.004	3.749	0.0331	164.040	0.929	
5/30/2012	201205301302	LM5	15.07	9.39	4.36	0.116	60.30	13.69	1697.16	0.007	3.865	0.0341	182.855	1.433	
5/30/2012	201205301346	LM5	14.69	9.17	4.22	0.164	60.91	12.84	1651.81	0.003	3.971	0.0351	160.801	0.000	
5/31/2012	201205310804	LM5	14.29	9.14	3.86	0.082	32.08	16.39	1587.08	0.000	4.132	0.0365			
5/31/2012	201205310850	LM5	15.94	10.16	4.35	0.084	45.96	7.02	1737.79	0.003	3.772	0.0333			
5/31/2012	201205310936	LM5	15.71	10.02	4.27	0.019	43.84	31.53	1683.42	0.003	3.893	0.0344			

2009 Cummins Westport ISL-G 8.9 L transit bus

Date	File Name	Fuel	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	NH_3 mg/mile	CO2 g/mile	PM g/mile	miles/GGE	miles/ft3	Formaldehyde mg/mile	Acetaldehyde mg/mile	Particle #/mile
5/4/2011	201105041117	H1	0.486	0.493	-0.147	7.61	0.281	1391.4	1745.3	0.006	3.751	0.0302			3.51E+12
5/4/2011	201105041202	H1	0.194	0.263	-0.149	6.60	0.302	1377.9	1706.2	0.003	3.841	0.0309			3.44E+12
5/4/2011	201105041242	H1	0.362	0.400	-0.156	6.73	0.265	1393.3	1679.2	0.003	3.901	0.0314			4.01E+12
4/27/2011	201104270821	H1	0.257	0.324	-0.171	8.63	0.176	1704.5	1656.7	0.010	3.947	0.0318	0.366	2.404	5.68E+12
4/27/2011	201104270904	H1	0.734	0.669	-0.127	10.31	0.259	1420.5	1745.5	0.002	3.740	0.0301	0.152	0.000	3.44E+12
4/27/2011	201104270944	H1	0.508	0.482	-0.115	8.46	0.241	1368.6	1727.0	0.004	4.780	0.0305	-6.568*	1.334	4.29E+12
4/28/2011	201104280809	H2	0.369	0.520	-0.305	7.46	0.204	1239.7	1684.5	0.004	3.898	0.0322			8.58E+12
4/28/2011	201104280853	H2	0.365	0.539	-0.333	6.93	0.237	1140.5	1686.8	0.006	3.895	0.0322			5.19E+12
4/28/2011	201104280940	H2	0.357	0.535	-0.336	6.37	0.268	1146.1	1638.4	0.004	4.012	0.0331			3.69E+12
4/27/2011	201104271134	H2	0.597	0.551	-0.111	10.25	0.241	1634.2	1810.0	0.003	3.620	0.0299	-0.932	0.000	6.76E+12
4/27/2011	201104271219	H2	0.567	0.511	-0.091	9.92	0.312	1300.4	1696.6	0.003	3.861	0.0319	-0.773	1.123	4.96E+12
4/27/2011	201104271301	H2	0.529	0.502	-0.118	9.02	0.488	1252.4	1779.3	0.003	3.686	0.0304	-1.719	0.853	4.50E+12
4/29/2011	201104290703	LM3	0.708	0.737	-0.242	8.71	0.166	1364.5	1633.1	0.003	4.023	0.0344			2.80E+12
4/29/2011	201104290746	LM3	0.735	0.790	-0.283	8.68	0.189	1165.8	1598.4	0.003	4.110	0.0352			2.19E+12
4/29/2011	201104290827	LM3	0.872	0.918	-0.310	10.12	0.277	1221.3	1608.6	0.005	4.077	0.0349			1.96E+12
4/28/2011	201104281142	LM3	0.253	0.487	-0.380	8.34	0.270	1788.7	1736.6	0.005	3.789	0.0324	-0.536	0.891	4.67E+12
4/28/2011	201104281228	LM3	0.461	0.649	-0.378	7.90	0.301	1546.2	1690.2	0.007	3.893	0.0333	-1.233	0.012	4.32E+12
4/28/2011	201104281317	LM3	0.616	0.760	-0.366	10.08	0.333	1509.7	1717.8	0.004	3.822	0.0327	-0.935	1.276	3.50E+12
5/2/2011	201105020806	LM4	0.575	0.641	-0.245	7.50	0.186	1488.6	1632.3	0.005	4.071	0.0366			3.77E+12
5/2/2011	201105020849	LM4	1.169	0.691	0.289	7.91	0.222	1495.4	1670.8	0.004	3.972	0.0357			2.85E+12
5/2/2011	201105020931	LM4	1.342	0.723	0.424	8.67	0.238	1547.5	1676.7	0.002	3.955	0.0355			3.37E+12
4/29/2011	201104291003	LM4	0.804	0.830	-0.265	10.54	0.202	1681.2	1704.7	0.003	3.888	0.0349	-0.725	0.027	5.35E+11
4/29/2011	201104291043	LM4	0.732	0.804	-0.304	9.65	0.299	1596.8	1732.1	0.006	3.830	0.0344	-1.415	0.267	4.85E+11
4/29/2011	201104291125	LM4	0.647	0.750	-0.322	8.66	0.279	1459.7	1666.3	0.005	3.984	0.0358	-1.976	0.917	5.86E+11
5/3/2011	201105021108	LM5	0.341	0.504	-0.308	8.67	0.276	1734.9	1718.6	0.004	3.872	0.0342			3.92E+12
5/3/2011	201105021155	LM5	0.502	0.647	-0.327	8.17	0.274	1741.5	1678.9	0.003	3.964	0.0350			3.25E+12

Date	File Name	Fuel	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	NH_3 mg/mile	CO2 g/mile	PM g/mile	miles/GGE	miles/ft3	Formaldehyde mg/mile	Acetaldehyde mg/mile	Particle #/mile
5/3/2011	201105021238	LM5	0.447	0.572	-0.286	7.84	0.268	1671.3	1696.4	0.002	3.925	0.0346			2.93E+12
5/2/2011	201105030755	LM5	0.531	0.631	-0.279	7.42	0.170	1508.9	1624.6	0.002	4.098	0.0362	-1.986	1.761	3.96E+12
5/2/2011	201105030840	LM5	0.527	0.692	-0.361	9.12	0.198	1651.7	1609.8	0.007	4.129	0.0364	-2.154	0.204	2.99E+12
5/2/2011	201105030920	LM5	0.491	0.676	-0.376	8.73	0.280	1600.8	1621.9	0.005	4.100	0.0362	-2.106	1.769	3.00E+12
5/4/2011	201105040811	LM6	0.641	0.613	-0.145	7.18	0.189	1677.1	1680.3	0.005	3.967	0.0350			4.17E+12
5/4/2011	201105040858	LM6	0.663	0.639	-0.154	10.77	0.191	1695.9	1674.9	0.001	3.966	0.0350			3.64E+12
5/4/2011	201105040943	LM6	0.577	0.558	-0.136	8.65	0.217	1733.0	1666.5	0.004	3.994	0.0353			4.04E+12
5/3/2011	201105031128	LM6	0.309	0.512	-0.350	7.73	0.206	1677.3	1689.3	0.005	3.946	0.0348	-2.246	0.000	3.48E+12
5/3/2011	201105031217	LM6	0.491	0.685	-0.387	8.26	0.268	1784.8	1671.2	0.006	3.985	0.0352	-1.893	0.000	3.23E+12
5/3/2011	201105031303	LM6	0.407	0.619	-0.388	7.64	0.233	1786.2	1742.2	0.004	3.827	0.0338	-1.467	0.000	3.37E+12

* This number is very close to the background levels and was not eliminated, as it's partly just an artifact of having greater variability in measuring very low values.

2003 Cummins Westport 8.3L C-Gas Plus engine transit bus

Date	File Name	Fuel	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	NH3 mg/mile	CO2 g/mile	PM g/mile	miles/GGE	miles/ft3	Formaldehyde mg/mile	Acetaldehyde mg/mile	Particle #/mile
9/12/2012	201209121054	H1	21.56	17.26	1.81	0.555	10.31	45.6	1764.8	0.003	3.627	0.0292			1.14E+13
9/12/2012	201209121141	H1	21.97	17.12	2.38	0.358	10.41	21.6	1728.1	0.007	3.699	0.0298			1.20E+13
9/18/2012	201209181031	H1	20.95	16.53	2.02	0.587	12.29	33.9	1774.8	0.003	3.609	0.0291	125.967	2.945	4.24E+12
9/18/2012	201209181114	H1	20.79	16.46	1.95	0.717	12.99	7.8	1746.3	0.003	3.667	0.0295	128.751	1.231	5.51E+12
9/18/2012	201209181155	H1	20.93	16.71	1.81	0.622	13.87	11.2	1724.5	0.004	3.712	0.0299	124.345	1.386	5.37E+12
9/18/2012	201209181327	H1	20.48	16.20	1.93	1.164	15.68	34.6	1780.5	0.000	3.599	0.0290			1.28E+12
9/12/2012	201209121315	H2	21.41	16.50	2.53	1.339	13.64	20.1	1756.5	0.007	3.652	0.0302			1.12E+13
9/12/2012	201209121358	H2	20.77	15.97	2.50	1.940	13.86	46.3	1777.3	0.003	3.612	0.0298			1.08E+13
9/12/2012	201209121444	H2	21.85	16.76	2.67	1.536	13.65	53.5	1754.4	0.002	3.653	0.0302	120.588	3.043	1.33E+13
9/13/2012	201209130820	H2	20.08	15.47	2.39	0.378	10.23	48.9	1694.7	0.003	3.791	0.0313			9.97E+12
9/13/2012	201209130904	H2	20.58	15.95	2.33	0.437	10.95	11.7	1687.4	0.002	3.804	0.0314			5.37E+12
9/13/2012	201209130948	H2	19.69	15.36	2.11	0.731	11.96	36.6	1716.2	0.002	3.746	0.0309			8.12E+12
9/13/2012	201209131031	LM3	18.05	12.99	3.20	1.463	16.56	54.2	1766.7	0.000	3.655	0.0313			9.08E+12
9/13/2012	201209131117	LM3	19.20	13.75	3.47	1.184	16.41	49.5	1767.5	0.000	3.648	0.0312			9.54E+12
9/13/2012	201209131209	LM3	19.26	13.93	3.33	1.652	19.08	29.8	1798.8	0.000	3.585	0.0307			9.98E+12
9/14/2012	201209140823	LM3	16.61	11.85	3.06	0.633	14.19	*	1662.7	0.000	3.888	0.0333			7.95E+12
9/14/2012	201209140911	LM3	16.99	12.22	3.02	1.194	19.31	22.9	1777.8	0.011	3.639	0.0311			8.20E+12
9/14/2012	201209140954	LM3	17.16	12.27	3.13	1.016	18.35	22.7	1733.0	0.004	3.730	0.0319			6.37E+12
9/19/2012	201209190907	LM3	This test was only performed to collect carbonyl sample**										96.350	1.526	
9/14/2012	201209141044	LM5	16.38	11.31	3.45	2.115	22.86	21.8	1803.3	0.002	3.631	0.0321			6.98E+12
9/14/2012	201209141128	LM5	15.99	11.10	3.30	1.740	22.70	22.5	1816.4	0.001	3.609	0.0319			3.82E+12
9/14/2012	201209141210	LM5	*	11.46	*	1.842	22.86	28.1	1822.5	0.000	3.653	0.0322			8.67E+12
9/17/2012	201209170825	LM5	15.61	10.88	3.17	1.549	14.38	22.4	1703.6	0.000	3.844	0.0339			7.88E+12
9/17/2012	201209170913	LM5	16.47	11.68	3.13	2.040	15.30	32.6	1714.1	0.005	3.815	0.0337			6.54E+12
9/17/2012	201209170959	LM5	15.91	11.25	3.05	2.119	17.82	33.7	1743.1	0.005	3.756	0.0332			8.09E+12
9/19/2012	201209190940	LM5	These tests were only performed to collect carbonyl samples**										102.585	1.073	
9/19/2012	201209191014	LM5											114.786	4.824	
9/17/2012	201209171102	LM6	17.09	12.71	2.55	1.862	17.70	36.9	1802.1	*	3.635	0.0321			7.78E+12

Date	File Name	Fuel	THC g/mile	CH4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	NH3 mg/mile	CO2 g/mile	PM g/mile	miles/GGE	miles/ft3	Formaldehyde mg/mile	Acetaldehyde mg/mile	Particle #/mile
9/17/2012	201209171146	LM6	16.01	11.76	2.57	1.307	17.74	32.7	1787.2	0.005	3.671	0.0324			9.13E+12
9/17/2012	201209171234	LM6	16.40	11.90	2.79	1.473	18.27	31.8	1770.8	0.000	3.701	0.0327			7.93E+12
9/18/2012	201209180830	LM6	17.48	12.54	3.14	0.772	12.95	12.8	1740.6	0.000	3.760	0.0332	98.287	4.589	3.35E+12
		LM6 LM6		These tests could not be completed due to an insufficient amount of fuel.											
9/18/2012	201209180919	LM6	This test was only performed only a single CBD to collect a carbonyl sample. The fuel volume was insufficient to complete the standard cycle										93.096	0.756	

*Outlier tests that were eliminated from the averages,
201209140823: Almost zero value for ammonia which was far below the average.
201209141210: Negative value for NMHC and very low value for THC.
201209171102: The PM mass collected was below the background level.
** There was some issue with the carbonyl sampling system that the samples were not being collected in some of the tests, therefore, these carbonyl tests were run separately.

2002 Cummins Westport 8.3L C-Gas Plus Waste Hauler *(File name-number: Transport (1), Curbside(2), Compaction bhp.hr(3))*

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	PM	Fuel E/C	Volumetric E/C	Formaldehyde mg/cycle	Acetaldehyde mg/cycle	Particle
5/16/2011	201105160950-1	H1	17.432	12.663	2.632	0.762	19.444	41.900	1784.691	0.096	3.607	0.0291	1112.83	53.47	3.94E+12
	201105160950-2	H1	50.975	40.637	6.721	0.495	93.121	105.305	5773.044		1.117	0.0090			2.40E+13
	201105160950-3	H1	2.360	1.856	0.017	0.047	4.488	7.279	411.526		0.063	7.8446			6.14E+11
5/16/2011	201105161032-1	H1	21.428	15.125	3.661	1.095	19.788	33.808	1751.315	0.088	3.653	0.0294	1364.67	51.42	4.03E+12
	201105161032-2	H1	66.661	52.805	9.934	0.930	119.905	106.368	7077.033		0.909	0.0073			2.82E+13
	201105161032-3	H1	2.341	1.829	0.033	0.043	4.846	7.166	411.433		0.063	7.8423			5.10E+11
5/16/2011	201105161114-1	H1	22.906	15.748	4.256	1.892	18.994	39.185	1791.449	0.040	3.564	0.0287	1348.38	63.17	4.08E+12
	201105161114-2	H1	57.714	44.927	9.381	0.826	100.767	106.284	6212.263		1.036	0.0083			2.39E+13
	201105161114-3	H1	2.223	1.728	0.041	0.053	5.767	9.369	418.055		0.064	7.9624			4.33E+11
5/17/2011	201105170704-1	H2	15.293	10.924	2.544	1.114	23.721	34.812	1747.795	0.070	3.702	0.0306	*	*	3.28E+12
	201105170704-2	H2	59.393	44.442	10.340	0.232	116.442	182.987	6474.924		0.998	0.0082	*	*	2.30E+13
	201105170704-3	H2	2.099	1.582	0.099	0.041	5.902	1.468	425.648		0.065	7.8773	*	*	4.65E+11
5/17/2011	201105170746-1	H2	*	*	*	*	*	*	*	0.055	*	*	1135.02	49.86	3.11E+12
	201105170746-2	H2	54.578	41.558	8.619	0.811	115.461	68.102	6476.955		1.000	0.0083			2.13E+13
	201105170746-3	H2	1.953	1.483	0.069	0.047	7.211	5.253	428.746		0.065	7.9276			3.76E+11
5/17/2011	201105170828-1	H2	21.408	14.668	3.826	1.420	20.919	25.449	1680.028	0.081	3.815	0.0315	1129.86	53.10	3.43E+12
	201105170828-2	H2	53.223	41.136	6.739	0.654	121.932	77.580	6442.121		1.006	0.0083			2.34E+13
	201105170828-3	H2	1.960	1.505	0.049	0.047	6.947	6.268	420.803		0.064	7.7823			4.11E+11
5/17/2011	201105170928-1	H2	15.657	11.377	2.059	1.796	22.598	29.622	1741.818	0.103	3.712	0.0307	1271.94	70.33	2.83E+12
	201105170928-2	H2	53.201	41.813	4.996	0.189	112.932	111.464	6212.028		1.043	0.0086			1.92E+13
	201105170928-3	H2	1.921	1.484	0.003	0.033	7.599	6.834	442.109		0.067	8.1683			3.81E+11
5/17/2011	201105171009-1	H2	14.412	10.636	1.791	1.970	22.242	25.049	1684.924	0.051	3.840	0.0317			2.56E+12
	201105171009-2	H2	56.057	43.764	5.155	0.727	116.114	95.245	6527.955		0.993	0.0082			1.91E+13
	201105171009-3	H2	1.937	1.499	0.010	0.043	7.702	6.720	442.950		0.068	8.1851			3.43E+11
5/17/2011	201105171050-1	H2	19.949	13.956	3.066	0.683	22.118	25.834	1761.190	0.054	3.655	0.0302			3.36E+12
	201105171050-2	H2	58.562	44.960	6.479	0.628	112.515	75.807	6346.723		1.019	0.0084			1.94E+13
	201105171050-3	H2	1.871	1.445	0.005	0.036	8.496	5.191	452.522		0.069	8.3571			3.76E+11
5/18/2011	201105180704-1	LM3	10.130	7.065	2.016	1.399	34.620	12.007	1626.738	0.037	4.008	0.0343			1.47E+12

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	PM	Fuel E/C	Volumetric E/C	Formaldehyde mg/cycle	Acetaldehyde mg/cycle	Particle
	201105180704-2	LM3	48.565	33.870	10.950	0.465	144.755	0.000	6036.495		1.076	0.0092			1.37E+13
	201105180704-3	LM3	1.424	1.007	0.146	0.030	12.803	15.105	447.407		0.068	7.9411			1.94E+11
5/18/2011	201105180745-1	LM3	10.258	7.253	1.985	1.779	35.750	57.726	1660.282	*	3.926	0.0336	564.55	27.88	1.63E+12
	201105180745-2	LM3	45.505	32.164	9.353	0.441	156.345	116.111	6289.696		1.035	0.0089			1.49E+13
	201105180745-3	LM3	1.339	0.956	0.124	0.025	16.092	5.210	456.921		0.069	8.1050			1.78E+11
5/18/2011	201105180829-1	LM3	10.622	7.457	2.067	1.148	33.737	33.900	1628.884	0.039	4.001	0.0342	642.75	14.08	1.98E+12
	201105180829-2	LM3	49.934	35.336	10.612	0.628	154.004	92.372	6174.883		1.052	0.0090			1.62E+13
	201105180829-3	LM3	1.405	1.002	0.125	0.037	13.919	11.024	460.560		0.070	8.1717			3.21E+11
5/18/2011	201105180920-1	LM3	10.029	7.050	1.835	1.402	34.634	23.639	1620.608	0.049	4.024	0.0344	527.98	24.12	1.89E+12
	201105180920-2	LM3	50.483	35.673	10.102	0.714	166.088	119.016	6684.514		0.973	0.0083			1.55E+13
	201105180920-3	LM3	1.418	1.007	0.135	0.034	13.622	9.190	456.969		0.069	8.1091			2.93E+11
5/18/2011	201105181001-1	LM3	13.509	9.356	2.406	2.512	35.496	30.391	1672.379	0.029	3.879	0.0332			2.31E+12
	201105181001-2	LM3	48.578	34.306	8.274	-0.206	163.537	112.962	6605.696		0.986	0.0084			1.61E+13
	201105181001-3	LM3	1.434	1.017	0.138	0.013	14.626	8.147	464.281		0.071	8.2381			2.77E+11
5/18/2011	201105181042-1	LM3	14.379	9.828	2.676	1.430	35.941	29.132	1647.180	0.043	3.937	0.0337			2.44E+12
	201105181042-2	LM3	48.319	34.035	8.740	0.581	147.813	103.784	6006.202		1.082	0.0093			1.37E+13
	201105181042-3	LM3	1.438	1.018	0.135	0.030	14.560	8.950	462.077		0.070	8.1996			3.06E+11
5/19/2011	201105190700-1	LM4	8.284	5.858	1.641	1.800	42.472	16.240	1682.367	0.028	3.926	0.0353	818.23	27.08	1.73E+12
	201105190700-2	LM4	44.387	31.041	10.466	0.540	173.791	0.000	6512.749		1.010	0.0091			1.67E+13
	201105190700-3	LM4	1.274	0.895	0.144	0.023	18.162	0.000	467.909		0.070	7.8222			1.83E+11
5/19/2011	201105190741-1	LM4	9.342	6.670	1.799	1.997	41.971	13.561	1624.835	0.025	4.055	0.0364	550.80	18.63	1.93E+12
	201105190741-2	LM4	49.231	35.115	9.644	2.609	173.267	67.364	6702.789		0.980	0.0088			1.80E+13
	201105190741-3	LM4	1.238	0.885	0.117	0.031	18.873	4.900	471.306		0.071	7.8771			1.90E+11
5/19/2011	201105190823-1	LM4	9.289	6.571	1.815	1.920	41.624	37.767	1629.693	0.024	4.044	0.0363	661.95	16.57	1.86E+12
	201105190823-2	LM4	47.443	33.432	9.691	0.492	170.649	83.639	6507.051		1.010	0.0091			1.72E+13
	201105190823-3	LM4	1.277	0.903	0.139	0.031	18.474	6.870	479.638		0.072	8.0174			1.94E+11
5/19/2011	201105190917-1	LM4	9.761	6.905	1.814	1.435	41.354	26.133	1661.271	0.030	3.968	0.0357			1.84E+12
	201105190917-2	LM4	52.417	36.965	10.121	-0.191	176.789	102.489	6832.201		0.962	0.0086			1.66E+13
	201105190917-3	LM4	1.307	0.931	0.115	0.011	18.138	6.965	481.413		0.072	8.0465			1.79E+11

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	PM	Fuel E/C	Volumetric E/C	Formaldehyde mg/cycle	Acetaldehyde mg/cycle	Particle
5/19/2011	201105190958-1	LM4	9.712	6.799	1.919	1.806	43.400	30.066	1723.229	0.041	3.826	0.0344			1.98E+12
	201105190958-2	LM4	51.036	35.721	10.493	1.468	176.425	139.557	6701.459		0.980	0.0088			1.73E+13
	201105190958-3	LM4	1.307	0.915	0.151	0.017	18.739	11.387	476.650		0.072	7.9686			1.89E+11
5/19/2011	201105191041-1	LM4	9.548	6.809	1.749	2.705	41.702	34.551	1642.845	0.023	4.008	0.0360			1.89E+12
	201105191041-2	LM4	53.711	38.040	10.747	0.518	181.322	93.531	6750.769		0.972	0.0087			1.66E+13
	201105191041-3	LM4	1.290	0.914	0.132	0.019	19.000	8.902	476.733		0.072	7.9690			1.78E+11
5/23/2011	201105230658-1	LM5	8.261	5.641	1.725	1.837	43.818	25.318	1690.994	0.037	3.914	0.0345	747.84	36.25	5.35E+12
	201105230658-2	LM5	43.447	29.230	10.525	2.209	163.033	95.718	6039.798		1.090	0.0096			3.41E+13
	201105230658-3	LM5	1.218	0.828	0.168	0.038	18.020	-0.211	464.924		0.070	7.8972			6.64E+11
5/23/2011	201105230746-1	LM5	*	6.355	*	1.781	42.244	39.456	1642.627	0.030	*	*	539.49	16.84	5.90E+12
	201105230746-2	LM5	*	30.538	*	0.545	175.325	53.895	6462.904		*	*			3.36E+13
	201105230746-3	LM5	*	0.829	*	0.021	18.979	3.909	469.422		*	*			6.40E+11
5/23/2011	201105230829-1	LM5	*	7.015	*	1.656	43.621	32.000	1741.663	0.010	*	*	715.85	26.54	5.93E+12
	201105230829-2	LM5	*	30.820	*	1.987	176.241	109.887	6521.058		*	*			3.37E+13
	201105230829-3	LM5	*	0.850	*	0.013	19.105	3.365	489.112		*	*			6.51E+11
5/23/2011	201105230934-1	LM5	*	6.109	*	1.325	43.299	37.538	1708.725	0.018	*	*			4.52E+12
	201105230934-2	LM5	*	31.324	*	-0.132	175.077	140.982	6498.587		*	*			2.68E+13
	201105230934-3	LM5	*	0.847	*	0.015	19.352	12.175	484.128		*	*			5.94E+11
5/23/2011	201105231016-1	LM5	*	6.501	*	2.062	44.515	45.229	1702.294	0.028	*	*			5.46E+12
	201105231016-2	LM5	*	33.028	*	0.410	180.797	142.458	6505.894		*	*			3.23E+13
	201105231016-3	LM5	*	0.852	*	0.024	19.127	7.039	486.982		*	*			6.29E+11
5/23/2011	201105231056-1	LM5	*	5.795	*	1.795	44.555	43.291	1656.563	0.027	*	*			4.81E+12
	201105231056-2	LM5	*	32.409	*	0.460	180.461	74.076	6602.403		*	*			3.14E+13
	201105231056-3	LM5	*	0.851	*	0.033	19.015	3.219	480.975		*	*			6.29E+11
5/24/2011	201105240657-1	LM6	9.062	6.447	1.585	1.321	40.342	25.169	1668.726	0.032	3.966	0.0350	573.20	44.27	4.89E+12
	201105240657-2	LM6	45.258	31.936	8.910	0.526	162.389	94.249	6336.840		1.041	0.0092			3.37E+13
	201105240657-3	LM6	1.334	0.944	0.141	0.029	15.688	0.000	461.429		0.069	7.8322			6.16E+11
5/24/2011	201105240746-1	LM6	9.554	6.781	1.725	1.642	37.869	9.968	1620.064	0.022	4.078	0.0360	601.44	4.55	5.08E+12
	201105240746-2	LM6	50.433	35.618	10.688	0.168	168.862	0.000	6406.193		1.027	0.0091			3.21E+13

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	PM	Fuel E/C	Volumetric E/C	Formaldehyde mg/cycle	Acetaldehyde mg/cycle	Particle
	201105240746-3	LM6	1.301	0.921	0.137	0.021	17.745	0.000	465.233		0.070	7.8948			5.96E+11
5/24/2011	201105240828-1	LM6	9.911	6.981	1.814	2.064	37.625	45.094	1623.656	0.013	4.066	0.0359	683.12	15.07	5.29E+12
	201105240828-2	LM6	50.257	35.246	9.813	1.042	168.282	133.505	6563.140		1.004	0.0089			3.48E+13
	201105240828-3	LM6	1.347	0.949	0.149	0.026	16.734	7.823	464.755		0.070	7.8888			6.39E+11
5/24/2011	201105240922-1	LM6	10.180	7.119	1.927	1.584	37.327	32.631	1675.540	0.038	3.942	0.0348			**
	201105240922-2	LM6	50.341	35.208	10.285	1.882	171.549	133.557	6835.302		0.964	0.0085			**
	201105240922-3	LM6	1.362	0.952	0.159	0.024	16.951	4.727	482.277		0.072	8.1849			**
5/24/2011	201105241003-1	LM6	10.625	7.309	2.065	1.483	40.489	23.138	1705.760	0.034	3.872	0.0342			**
	201105241003-2	LM6	51.626	35.409	10.301	0.601	174.018	76.593	6719.829		0.980	0.0087			**
	201105241003-3	LM6	1.330	0.917	0.171	0.027	17.925	4.662	480.302		0.072	8.1507			**
5/24/2011	201105241051-1	LM6	9.128	6.375	1.709	1.418	40.107	23.937	1636.939	0.041	4.041	0.0357			**
	201105241051-2	LM6	58.983	40.510	13.330	0.764	184.458	97.437	7122.711		0.923	0.0082			**
	201105241051-3	LM6	1.376	0.949	0.178	0.028	17.494	4.899	478.294		0.072	8.1186			**
5/26/2011	201105260825-1	H7	16.527	12.665	1.734	1.211	18.383	44.450	1751.616	0.059	3.634	0.0295	1389.49	45.06	6.17E+12
	201105260825-2	H7	64.397	51.089	7.791	0.532	95.203	150.512	6298.192		1.009	0.0082			3.73E+13
	201105260825-3	H7	2.721	2.151	0.004	0.041	3.276	7.104	394.169		0.061	7.5613			6.00E+11
5/26/2011	201105260906-1	H7	15.969	11.989	1.868	0.717	16.797	21.194	1609.165	0.038	3.953	0.0321	1417.18	35.65	4.88E+12
	201105260906-2	H7	71.366	56.487	9.137	0.358	94.329	87.999	6451.071		0.982	0.0080			3.99E+13
	201105260906-3	H7	2.668	2.119	-0.002	0.038	3.416	3.565	396.022		0.062	7.5943			5.87E+11
5/26/2011	201105260947-1	H7	17.649	13.140	2.299	1.207	16.946	30.732	1690.053	0.058	3.757	0.0305	1504.21	46.73	6.01E+12
	201105260947-2	H7	69.576	55.313	8.791	0.680	100.589	106.295	6792.115		0.935	0.0076			4.08E+13
	201105260947-3	H7	2.572	2.034	0.021	0.040	4.408	6.302	407.822		0.063	7.8142			6.06E+11
5/26/2011	201105261044-1	H7	16.388	12.514	1.760	1.201	16.714	44.846	1713.867	0.041	3.713	0.0301			5.35E+12
	201105261044-2	H7	66.833	53.582	7.910	0.558	96.593	176.533	6580.240		0.965	0.0078			3.28E+13
	201105261044-3	H7	2.526	2.012	-0.002	0.034	4.387	10.344	404.424		0.063	7.7474			6.39E+11
5/26/2011	201105261125-1	H7	16.875	12.771	1.622	0.749	17.068	33.931	1664.727	0.043	3.821	0.0310			5.28E+12
	201105261125-2	H7	63.697	51.442	5.292	0.598	89.262	102.543	6184.786		1.028	0.0083			3.17E+13
	201105261125-3	H7	2.538	2.018	-0.006	0.045	4.470	7.679	401.929		0.063	7.7006			6.51E+11
5/26/2011	201105261205-1	H7	15.847	12.184	1.351	0.880	18.284	18.061	1676.143	0.036	3.800	0.0309			7.12E+12

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	PM	Fuel E/C	Volumetric E/C	Formaldehyde mg/cycle	Acetaldehyde mg/cycle	Particle
	201105261205-2	H7	68.171	54.784	5.631	-0.165	96.834	71.590	6723.035		0.946	0.0077			3.91E+13
	201105261205-3	H7	2.515	2.007	-0.004	0.032	4.480	2.422	403.537		0.063	7.7302			6.48E+11
5/31/2011	201105310753-1	H1	14.147	10.962	1.597	1.267	18.031	54.188	1740.937	0.076	3.710	0.0299			7.77E+12
	201105310753-2	H1	61.762	48.822	8.536	-0.134	100.152	191.750	6443.410		0.999	0.0080			4.00E+13
	201105310753-3	H1	2.493	1.953	0.013	0.029	4.169	8.288	404.975		0.062	7.7256			9.33E+11
5/31/2011	201105310834-1	H1	14.957	11.396	2.053	0.768	19.063	28.197	1667.877	0.033	3.865	0.0311			5.41E+12
	201105310834-2	H1	59.209	47.055	8.621	0.261	100.553	86.799	6197.557		1.038	0.0084			3.57E+13
	201105310834-3	H1	2.299	1.817	0.000	0.036	5.194	8.565	410.321		0.063	7.8186			7.05E+11
5/31/2011	201105310917-1	H1	16.177	12.124	2.167	1.139	18.832	19.419	1641.771	0.036	3.918	0.0316			5.21E+12
	201105310917-2	H1	65.991	51.235	9.928	0.541	98.842	70.949	6295.799		1.020	0.0082			4.03E+13
	201105310917-3	H1	2.339	1.834	0.027	0.046	4.967	5.277	405.845		0.062	7.7371			6.96E+11

*Outlier tests that were eliminated from the averages,
** No data collected
201105170704: Almost zero values for carbonyls.
201105170746-1: Relatively very high CO_2 emissions for this test. Emission values for the whole segment were invalid.
201105180745-1: The PM mass collected was below the background level.
201105230746, 0829, 0934, 1016, and 1056: Negative values for THC and NMHC.

2002 Cummins Westport 8.3L C-Gas Plus Waste Hauler *(Filename-3 :Compaction (whp.hr))*

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	Fuel E/C	Volumetric E/C	Particle
5/16/2011	201105160950-3	H1	3.205	2.520	0.023	0.064	6.095	9.885	558.865	0.0858	10.653	8.34E+11
	201105161032-3	H1	3.167	2.474	0.045	0.058	6.555	9.693	556.522	0.0855	10.608	6.89E+11
	201105161114-3	H1	2.955	2.297	0.055	0.070	7.666	12.455	555.769	0.0853	10.585	5.76E+11
5/17/2011	201105170704-3	H2	2.853	2.151	0.134	0.056	8.022	1.995	578.603	0.0883	10.708	6.32E+11
	201105170746-3	H2	2.547	1.935	0.090	0.061	9.407	6.852	559.312	0.0852	10.342	4.90E+11
	201105170828-3	H2	2.563	1.967	0.064	0.062	9.084	8.196	550.256	0.0839	10.176	5.38E+11
5/17/2011	201105170928-3	H2	2.422	1.871	0.004	0.041	9.578	8.615	557.301	0.0849	10.297	4.80E+11
	201105171009-3	H2	2.410	1.865	0.013	0.054	9.580	8.358	550.935	0.0839	10.181	4.26E+11
	201105171050-3	H2	2.308	1.782	0.006	0.044	10.481	6.404	558.266	0.0850	10.310	4.64E+11
5/18/2011	201105180704-3	LM3	1.835	1.297	0.189	0.038	16.495	19.460	576.403	0.0876	10.231	2.50E+11
	201105180745-3	LM3	1.601	1.143	0.148	0.030	19.249	6.232	546.572	0.0830	9.695	2.13E+11
	201105180829-3	LM3	1.716	1.223	0.152	0.045	16.997	13.462	562.407	0.0854	9.979	3.92E+11
5/18/2011	201105180920-3	LM3	1.730	1.229	0.164	0.041	16.621	11.214	557.582	0.0847	9.895	3.57E+11
	201105181001-3	LM3	1.731	1.227	0.167	0.016	17.651	9.832	560.281	0.0851	9.941	3.35E+11
	201105181042-3	LM3	1.708	1.210	0.161	0.036	17.300	10.634	549.043	0.0834	9.743	3.64E+11
5/19/2011	201105190700-3	LM4	1.546	1.086	0.175	0.028	22.044	0.000	567.922	0.0853	9.494	2.22E+11
	201105190741-3	LM4	1.423	1.018	0.134	0.036	21.699	5.634	541.880	0.0814	9.057	2.19E+11
	201105190823-3	LM4	1.527	1.079	0.167	0.037	22.079	8.211	573.234	0.0861	9.582	2.32E+11
5/19/2011	201105190917-3	LM4	1.527	1.087	0.134	0.013	21.183	8.134	562.231	0.0845	9.397	2.09E+11
	201105190958-3	LM4	1.543	1.080	0.179	0.019	22.115	13.439	562.533	0.0845	9.404	2.23E+11
	201105191041-3	LM4	1.504	1.065	0.154	0.023	22.148	10.377	555.729	0.0835	9.290	2.08E+11
5/23/2011	201105230658-3	LM5	1.519	1.033	0.209	0.047	22.473	-0.264	579.814	0.0869	9.849	8.28E+11
	201105230746-3	LM5	*	0.990	*	0.026	22.674	4.670	560.824			7.65E+11
	201105230829-3	LM5	*	1.009	*	0.015	22.664	3.992	580.249			7.73E+11
5/23/2011	201105230934-3	LM5	*	1.004	*	0.017	22.943	14.434	573.978			7.05E+11
	201105231016-3	LM5	*	1.020	*	0.029	22.885	8.422	582.669			7.53E+11
	201105231056-3	LM5	*	1.014	*	0.039	22.650	3.834	572.911			7.50E+11

Date	File Name	Fuel	THC	CH4	NMHC	CO	NOx	NH3	CO2	Fuel E/C	Volumetric E/C	Particle
5/24/2011	201105240657-3	LM6	1.693	1.198	0.179	0.037	19.901	0.000	585.368	0.0878	9.936	7.81E+11
	201105240746-3	LM6	1.573	1.114	0.165	0.025	21.455	0.000	562.515	0.0843	9.546	7.20E+11
	201105240828-3	LM6	1.602	1.129	0.177	0.031	19.906	9.307	552.865	0.0829	9.384	7.60E+11
5/24/2011	201105240922-3	LM6	1.639	1.146	0.191	0.029	20.404	5.690	580.517	0.0870	9.852	**
	201105241003-3	LM6	1.560	1.076	0.201	0.032	21.024	5.468	563.361	0.0844	9.560	**
	201105241051-3	LM6	1.597	1.101	0.206	0.033	20.295	5.683	554.862	0.0832	9.418	**
5/26/2011	201105260825-3	H7	3.920	3.098	0.006	0.058	4.718	10.233	567.767	0.0884	10.891	8.64E+11
	201105260906-3	H7	3.803	3.020	-0.002	0.055	4.869	5.081	564.494	0.0879	10.825	8.37E+11
	201105260947-3	H7	3.581	2.833	0.029	0.056	6.139	8.777	567.990	0.0884	10.883	8.44E+11
5/26/2011	201105261044-3	H7	3.451	2.749	-0.002	0.047	5.994	14.132	552.564	0.0860	10.585	8.72E+11
	201105261125-3	H7	3.406	2.708	-0.009	0.060	5.999	10.304	539.339	0.0839	10.333	8.73E+11
	201105261205-3	H7	3.420	2.729	-0.005	0.043	6.092	3.293	548.698	0.0853	10.511	8.81E+11
5/31/2011	201105310753-3	H1	3.507	2.748	0.018	0.041	5.867	11.662	569.832	0.0876	10.871	1.31E+12
	201105310834-3	H1	3.124	2.469	-0.001	0.048	7.059	11.640	557.627	0.0856	10.626	9.58E+11
	201105310917-3	H1	3.212	2.519	0.037	0.063	6.820	7.246	557.291	0.0856	10.624	9.56E+11

*Outlier tests that were eliminated from the averages,
** No data collected

Appendix C. Fuel Economy/Consumption Calculation

Fuel Economy Calculated on a Gasoline Gallon Energy Equivalent Basis

$$mpg_e = \frac{CWF_{HC/NG} \times D_{NG} \times 112,194/LHV}{(0.749 \times CH_4) + (CWF_{NMHC} \times NMHC) + (0.429 \times CO) + (0.273 \times (CO_2 - CO_{2NG}))}$$

Note that the above equation is slightly modified from that given in the US EPA Code of Federal Regulations to account for the differences in the energy content and other properties of the test gases

Fuel Economy Calculated Based on Volume of Natural Gas Consumed

$$mpg_v = \frac{CWF_{NG} \times D_{NG}}{(0.749 \times CH_4) + (CWF_{NMHC} \times NMHC) + (0.429 \times CO) + (0.273 \times CO_2)}$$

mpg_e = miles per equivalent gallon of natural gas

mpg_v = miles per cubic feet of natural gas fuel consumed

$CWF_{HC/NG}$ = carbon weight fraction based on the hydrocarbon constituents in the natural gas fuel

CWF_{NG} = carbon weight fraction of the natural gas fuel

D_{NG} = density of the natural gas fuel [grams/ft^3 at 68°F (20°C) and 14.696 psi (760 mm Hg, or 101.325 kPa)]
= specific gravity of fuel x 28.316847 liters/ft^3 x density of air (1.2047 g/l) [1, 2]

112,194 BTU/gal is the energy equivalent of a gallon of gasoline [3]

LHV = the lower heating value of the test fuel in BTU/ft^3 [2]

CH_4, NMHC, CO, and CO_2 = weighted mass exhaust emissions [grams/mile] for methane, non-methane hydrocarbon, carbon monoxide, and carbon dioxide

CWF_{NMHC} = carbon weight fraction of the non-methane hydrocarbon constituents in the fuel

CO_{2NG}= grams of carbon dioxide in the natural gas fuel consumed per mile of travel

$$CO_{2NG} = FC_{NG} \times D_{NG} \times WF_{CO2}$$

Where

WF_{CO2} = weight fraction carbon dioxide of the natural gas fuel

Fuel Consumption

$$FC_{NG} = \frac{(0.749 \times CH_4) + (CWF_{NMHC} \times NMHC) + (0.429 \times CO) + (0.273 \times CO_2)}{CWF_{NG} \times D_{NG}}$$

FC_{NG}= cubic feet of natural gas fuel consumed per mile

CWF_{NG} = carbon weight fraction of the natural gas fuel

D_{NG} = density of the natural gas fuel [grams/ft^3 at 68°F (20°C) and 14.696 psi (760 mm Hg, or 101.325 kPa)]

CH_4 , NMHC, CO, and CO_2 = weighted mass exhaust emissions [grams/mile] for methane, non-methane hydrocarbon, carbon monoxide, and carbon dioxide

CWF_{NMHC} = carbon weight fraction of the non-methane hydrocarbon constituents in the fuel

Gas	Methane	Ethane	Propane	i-Butane	n-Butane	i-Pentane	n-Pentane	C6+	CO_2	O_2	N_2	**$CWF_{HC/NG}$**	**CWF_{NG}**	**CWF_{NMHC}**	**D_{NG}**	**LHV**
H1	96.00	1.80	0.40	0.15	0.00	0.00	0.00	0.00	0.95	0.00	0.70	0.724	0.731	0.806	19.844	903.8
H2	94.50	3.50	0.60	0.30	0.00	0.00	0.00	0.00	0.75	0.00	0.35	0.735	0.740	0.805	20.151	926.6
LM3	88.30	10.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.743	0.743	0.799	20.840	960.3
LM4	89.30	6.80	2.60	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.762	0.762	0.809	21.570	1008.3
LM5	83.65	10.75	2.70	0.2	0.00	0.00	0.00	0.00	0.00	0.00	2.70	0.732	0.732	0.804	22.092	990.4
LM6	87.20	4.50	4.40	1.20	0.00	0.00	0.00	0.00	0.00	0.00	2.70	0.732	0.732	0.813	22.116	990.9
H7	98.44	1.23	0.25	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.750	0.750	0.805	19.25	911.0

* D_{NG} = density of the natural gas fuel [grams/ft^3 at 68°F (20°C) and 14.696 psi (760 mm Hg, or 101.325 kPa)]

** LHV = the lower heating value of the test fuel in BTU/ft^3 at 68°F (20°C) and 14.696 psi (760 mm Hg, or 101.325 kPa)

Note: that the calculations in this appendix are based on a temperature of 68°F and a pressure of 14.696, as opposed to the 60°F and 14.73 psi used for the characterization of the gases in Table 2-1. This was to ensure that all the constants and values, such as WI, density and heating value, used in these formulas were calculated based on the same temperature and pressure basis used in the Code of Federal Regulations.

References

1. Environmental Protection Agency, National Vehicle and Fuel Emissions Laboratory (NVFEL) Emissions Analysis, http://www.epa.gov/nvfel/testing/methods.htm
2. American Gas Association Report No.5, "Natural Gas Energy Measurement", AGA 5 Calculation Spreadsheet – Imperial Units of Measure, version 1.1, Feb 26, 2008
3. US Dept. of Energy, Argonne National Laboratory, GREET 1 2013, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, http://greet.es.anl.gov/, 2013
4. Code of Federal Regulations, Part 600, Subpart B- Fuel Economy and Carbon-Related Exhaust Emission Test Procedures, 2012.