Energy Research and Development Division
FINAL PROJECT REPORT

EVALUATION OF THE PERFORMANCE AND AIR POLLUTANT EMISSIONS OF HEAVY-DUTY VEHICLES OPERATING ON VARIOUS NATURAL GAS BLENDS

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Impact of Natural Gas Composition on the Performance & Emissions of Heavy-Duty Natural Gas Vehicles - Phase 2 is the final report for the Impact of Natural Gas Composition on the Performance & Emissions of Heavy-Duty Natural Gas Vehicles - Phase 2 project (contract number 500-12-009) conducted by CE-CERT, University of California, Riverside. The information from this project contributes to PIER's Energy-Related Environmentally Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

Natural gas composition can have an important impact on natural gas vehicle emissions and performance. With the expansion of natural gas production methods, a wider range of natural gas composition is available for use throughout California. This study's objective was to evaluate the natural gas composition impact on the performance and emissions of 2005 to 2013 heavy-duty vehicle models. A natural gas school bus, a natural gas waste hauler, a Class 8 natural gas refuse truck, and two Class 8 natural gas port trucks were selected and tested over application-specific duty cycles for 22 vehicle test days. The researchers conducted tests using a heavy-duty chassis dynamometer—a device used for measuring emissions and performance—with a range of three to seven different test fuels. Each fuel test compared exhaust emissions, fuel economy, particulate matter mass, particle number and particle size distributions, ammonia emissions, carbonyl compound emissions, and nitrous oxide emissions. The researchers found that the lean-burn school bus engine produced more pollutants compared to the stoichiometric waste hauler and port trucks. The stoichiometric engines also showed considerably lower emissions compared to previous studies of lean-burn technology. Using the low methane fuels, the lean-burn school bus and the local-haul tested port truck showed increases in pollutant emissions. The waste hauler and near-dock port truck showed mixed results with the low methane fuels. The evaluation of the performance and air pollutant emissions of heavy-duty vehicles operating on various natural gas blends ultimately benefits the understanding of gas interchangeability to ensure optimal vehicle performance and reduction of greenhouse gasses.

Keywords: Natural Gas, Vehicle Emissions, Transportation, Alternative Fuels

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EXECUTIVE SUMMARY

Introduction

The recent demand for natural gas (NG) in the State of California has increased, predominantly due to its use in commercial and residential power applications. The availability of natural gas from a wider range of sources is also expanding within the state, with the rapid development of natural gas production via horizontal drilling, hydraulic fracturing, and extracting liquefied natural gas from the Costa Azul gas terminal in Baja California, Mexico. The expansion of these new sources, in addition to changes in processing natural gas to meet markets, could contribute to a larger variety of natural gas compositions used throughout California. Since California has implemented the use of natural gas vehicles (NGVs) to improve urban air quality, the increase in variety of these natural gasses could influence the emissions and performance of NGVs.

The California Air Resources Board is currently revisiting the compressed natural gas fuel standards for motor vehicles. Previous studies of interchangeability (the impact of changing natural gas composition) were conducted on small stationary source engines, such as compressors, heavy-duty engines, and light-duty natural gas vehicles. Some of these studies have shown that natural gas composition can have an impact on emissions, including increases in oxides of nitrogen emissions that affect the Wobbe number. The Wobbe number, otherwise known as the Wobbe Index, is the result of the higher heating value of a gas divided by the square root of the specific gravity of the gas with respect to air. The higher the Wobbe number, the greater the heating value per volume of gas that will flow through a hole of a given size within a given amount of time. The Wobbe number not only measures the energy content within the fuel, but it is also an indicator of the fuels interchangeability. Two fuels with the same Wobbe numbers are ideally interchangeable. This interchangeability typically occurs with gases containing hydrocarbon amounts with higher carbon numbers than methane.

Project Purpose and Process

The objective of this study was to evaluate the impact of natural gas composition on the emissions of heavy-duty vehicles weighing above 10,001 pounds. To determine impact values, researchers tested several different models of heavy-duty vehicles using a chassis dynamometer. The chassis dynamometer is a device that tests different cycles to measure the emissions and fuel economy output of vehicles; the test cycles simulate a range of driving conditions, such as highway or urban driving speeds.

The tests were performed on several heavy-duty vehicles: a school bus with a 2005 8.1L lean-burn combustion, spark ignited John Deere 6081H engine; a 2011 waste hauler with a 8.9L stoichiometric, spark ignited Cummins Westport ISL-G engine; a truck with a 2012 stoichiometric spark ignited Cummins Westport ISL-G 8.9L engine with EGR and a TWC; and a truck with a 2013 Cummins Westport ISX12G 11.9L stoichiometric spark ignited engine. The school bus was equipped with an oxidation catalyst – a device that remediates pollutants such as carbon monoxide and hydrocarbons in the exhaust. The waste hauler and both trucks used exhaust gas recirculation (EGR) – a technique used to reduce oxides of nitrogen emissions. The newer vehicles were also equipped with a three-way catalyst (TWC) – a device that remediates carbon monoxide and unburned hydrocarbons while simultaneously reducing oxides of nitrogen emissions. The NG school bus was tested using the Central Business District cycle, the NG waste hauler was tested with the Refuse Truck cycle, and two NG class 8 trucks were tested on the Near Dock duty cycle and the Local Haul duty cycle.

The researchers tested seven fuels total—three historical baseline fuels available in Southern California (labeled H1, H2, and H7) and four low methane fuels (labeled LM3, LM4, LM5, and LM6). The first two historical test fuels were representative of Texas Pipeline gas (H1) and Rocky Mountain Pipeline gas (H2) between 2000 and 2010. The third historical fuel (H7) was a liquefied-compressed natural gas (L-CNG) fuel, which is a compressed natural gas blend produced from liquefied natural gas (LNG). The four low methane fuels included a Peruvian LNG with nitrogen added to achieve a Wobbe number of 1385 (LM3); a Middle East LNG with a Wobbe number above 1400 (LM4); a fuel with a high ethane content (LM5); and a fuel with a high propane content (LM6). Both LM5 and LM6 had the same high Wobbe number. The design and selection of the test fuels determined whether there were differences due to composition. The researchers compared the test fuels by measuring exhaust emissions, fuel economy, particulate matter mass, particle number and particle size distributions, ammonia emissions, carbonyl compound emissions, and oxides of nitrogen emissions.

Project Results

Some of the vehicles had similar pollutant and emissions outcomes according to the applied fuel compounds and dynamometer cycles; this verified fuel interchangeability. Please refer to more detailed emission results and corresponding p-values for the statistical analyses in Appendix B. Since some emissions components have very low values, the resulting emissions differences on a percentage basis can be quite large in some cases, even when the absolute differences between different fuels is small. The results below summarize key points in the researchers' findings for each vehicle and the assessed impact values.

- The researchers evaluated the 2005 John Deere School Bus emissions over the Central Business District (CBD) cycle with seven test fuels. The lean-burn John Deere engine showed the most variance in emission levels between fuels for most of the pollutants compared to the stoichiometric Cummins trucks.
- The researchers evaluated the 2011 Cummins Westport ISL G waste hauler on the Refuse Truck cycle using test fuels H1, H7, LM3, LM5, and LM6. Total hydrocarbons, non-methane hydrocarbons, methane, nitrogen oxides, formaldehyde, and acetaldehyde emissions for the Westport ISL-G waste hauler were considerably lower than the emissions from previous studies of lean burn technology engines.
- The researchers evaluated the 2012 Cummins Westport ISL G truck on the Near Dock duty cycle. The researchers conducted tests for three of the main test fuels: H1, LM5, and LM6. Low methane fuels showed lower total hydrocarbon, and methane emissions. Non-methane hydrocarbon emissions showed inconsistent increases with low methane fuels over the entire cycle.

- The researchers evaluated the 2013 Cummins Westport ISX12 G Truck using the Local Haul duty cycle. This engine was the newest technology tested during this program. Results from the 2013 Cummins Westport ISX12G Truck showed that most of the gaseous emissions for this engine were at higher concentrations compared to the emissions from the 2012 Cummins ISL G engine. .

The researchers concluded that the new stoichiometric natural gas engines show less significant fuel effects compared to the older lean burn engine. Total hydrocarbons (THC), non-methane hydrocarbons (NMHC), methane (CH_4), oxides of nitrogen (NOx), formaldehyde, and acetaldehyde emissions for the newer stoichiometric technology engines are considerably lower than the emissions from previous lean burn engine studies; however, the newer stoichiometric engines do show higher carbon monoxide (CO) and ammonia (NH_3) emissions compared to older lean burn engines. The lean burn school bus showed trends similar to those seen previously in older technology, with higher emissions of THC, CH_4, and NOx, and lower emissions of NMHC for the low methane fuels. Overall, CO_2 emissions do not show strong trends for any of the test vehicles. Fuel economy and consumption on a volumetric basis for each vehicle increased when using the low-methane, high-energy fuels. Particulate matter (PM) mass emissions are generally found at very low levels for all test vehicles and do not show consistent trends with the different test fuels. Similar to PM mass, particle number emissions do not show consistent fuel trends for the low methane fuels. Every test vehicle showed particle sizes at two specific size ranges over the Central Business District cycle.

Project Benefits

With the potential expansion of NG compositions available in California, it is important to understand how variations in composition can affect vehicle emissions and fuel economy. This study has shown how exhaust emissions of older engines and newer stoichiometric engines differ when run over a variety of duty cycles and under different operating conditions. Natural gas fuel composition can have an impact on older, heavy-duty vehicle emissions, even for fuels within pipeline specification; consequently, certain pipelines can also have extreme ranges of fuel compositions. Due to these influences, it is necessary to control natural gas specifications for older heavy-duty NGVs; however, newer heavy-duty natural gas engines can run on a wider range of NG fuels with varying composition. This condition holds true for a wider range of applications, such as waste haulers and port trucks. These results will be useful in understanding interchangeability and smoothing California’s transition into using a larger variety of NG fuel compositions for NGVs. This research will benefit California ratepayers through optimized heavy-duty NGV performance and greater market adoption by allowing natural gas engines to use a larger variety of NG fuel compositions. This performance optimization will ultimately reduce harmful pollutants and greenhouse gas emissions that are detrimental to the environment.

CHAPTER 1: Introduction

Natural gas (NG) is a potential alternative to conventional liquid fuels for use in internal combustion engines in motor vehicles. Implementing natural gas vehicles (NGVs) in a variety of applications aided in improving 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 are generally believed to produce lower emissions of nonmethane hydrocarbons (NMHC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM) compared to diesel vehicles without aftertreatment (Ma, F. et al. 2007, Hesterberg, T. et al. 2008, Zarante, P. and Sodre, J. 2009), although this belief is less of an issue with diesel particle filters (DPFs) and selective catalytic reduction (SCR) systems on diesel vehicles (Thiruvengadem, A. et al. 2011, Kado, N. et al. 2008, Okomoto, R. et al. 2006, Fontaras, G. et al. 2012, Holmen, B and Ayala, A. 2002, Jayaratne, E. et al. 2012, Wang, W. et al. 1997, Walkowicz, K. et al. 2003).

For NGVs, one issue that is important with respect to emissions is the effect of variations in the NG fuel composition. This fuel composition variation is part of a broader range of interchangeability issues. Interchangeability is the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, and performance, or materially increasing air pollutant emissions. Effects of NG composition studies have been conducted for small stationary source engines, such as compressors, and in heavy-duty engines and vehicles (Gutierrez, J. et al. 2003; Gutierrez, J. et al. 2006; Feist, M. 2006; Feist, M. 2009; Lee, Y. and Kim, G. 2000; Elder, S. et al. 1985; Matthews, R. et al. 1996; Malenshek, M. and Olsen, D. 2009; Bach, C. 2008; Naber, J. et al. 1994; McTaggart, G. et al. 2010; Durbin, T. et al. 2014). These studies show that NG composition can have an impact on emissions. NOx emissions, for example, were found to increase with increasing Wobbe number (WN) and/or decreasing methane number (MN) in several of these studies (Gutierrez, J. et al. 2003, Gutierrez, J. et al. 2006, Feist, M. 2006, Feist, M. 2009, Lee, Y. and Kim, G. 2000, Elder, S. et al. 1985, Matthews, R. et al. 1996, Malenshek, M. and Olsen, D. 2009, Bach, C. 2008, Naber, J. et al. 1994, McTaggart, G. et al. 2010, Durbin, T. et al. 2014). 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 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. WN is both an indicator of a fuel's energy content and its interchangeability. Two fuels with identical WN under identical conditions will be ideally interchangeable.

Dramatic changes in the NG market in recent years due to the rapid development of horizontal drilling and hydraulic fracturing underscore the importance of changing NG composition. Advanced drilling and fracturing techniques 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 British thermal units (Btu) in 2011 to a projected 33.9 quadrillion Btu in 2040, representing a sizable 44 percent increase (Energy Information Administration 2013). Shale gas production, which already accounted for 23 percent of total U.S. natural gas production in 2010, is expected to be the primary expansion driver, with shale gas production going from 6.8 trillion cubic feet (tcf) in 2011 to 13.6 tcf in 2035 (Energy Information Administration 2012). In California, the use of natural gas has also been increasing for a number of years, primarily due to expanded power and home heating needs. Currently, California supplies 85-90 percent of its needs with NG imported domestically from the Rockies, from southwestern states, such as Texas, and from Canada. As new production fields are developed in the United States, 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 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 used in California.

Natural gas quality depends on both its source as well as the degree to which it is processed. Natural gas is produced from oil fields (termed associated gas) or from gas fields (termed nonassociated 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 (NGC+ Interchangeability Work Group 2005, NGC+ Liquid Hydrocarbon Drop Out Task Group 2005). 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 present study's objective 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 (CARB 2015). 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 three to seven different test fuels. This included one NG school bus, one NG waste hauler, and two NG class 8 trucks tested over the central business district cycle (CBD), the Refuse Truck cycle, and segments of the drayage truck port cycle, respectively. The test fuels included fuels 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 fuels 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, of nitrous oxide (N_2O), 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 and other heavy-duty NGVs on a chassis dynamometer, which is discussed in a previous report (Durbin, T. et al. 2014).

CHAPTER 2: Experimental Procedures

2.1 Test Fuels

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

- Fuels H1 and H2 are representative of Texas and Rocky Mountain Pipeline gases. These fuels are based on actual pipeline data. H1 serves as the baseline fuel.
- Fuel LM3 is representative of Peruvian LNG that has been modified to meet a WN of 1385 and a MN of 75.
- Fuel LM4 is representative of Middle East LNG-Untreated with a high WN (above 1400).
- Fuel LM5 is a high ethane fuel with a WN of 1385 and a MN of 75.
- Fuel LM6 is a high propane, high butane fuel with a WN of 1385 and a MN of 75.
- Fuel H7 is representative of an L-CNG fuel sold in the South Coast Air Basin in 2014.

Test fuels H1 and H2 represent historical baseline gases for Southern California. Fuel H1, "Baseline, Texas Pipeline," refers to natural 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 natural gas entering the Southern California Gas territory through the Kern/Mojave Pipeline at Wheeler Ridge and Kramer Station. The actual test fuel compositions for H1 and H2 were derived by Air Resources Board staff from fuel quality data submitted by the Southern California Gas Company for the period from January 2000 to October 2010.

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

In addition, the CNG fueled John Deere school bus, waste hauler, and ISX12 G engines were run on an L-CNG, identified as H7. Test fuel H7 is a historical fuel representing an L-CNG fuel sold in the South Coast Air Basin in 2014. Test fuel H7 was included to capture the base line for these engines that fuel on LNG. L-CNG is LNG that has been vaporized to a gas at the fueling station. Although L-CNG was included as a test fuel to represent a waste hauler operating on LNG, a LNG waste hauler would never see LM3, LM5, LM6 because these fuels have inert components.

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 refrigerated to minus 260 degrees for liquefaction, conversion to LNG. For this study, the research team obtained L-CNG from a local fueling station for the school bus, the waste hauler, and ISX12 G truck. The compositions for H7 for each of these vehicles are listed separately based samples pulled from each vehicle.

Table 1: Test Fuel Specifications

Fuels #	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 (waste hauler)**	98.42	1.26	0.05	0.02	0.25	0	104.5	1339	1004	3.97
H7	**L-CNG fuel (school bus)**	95.24	4.39	0.11	0.01	0.25	0	97	1352	1029	3.91
H7	**L-CNG fuel (ISX12 G truck)**	94.63	4.61	0.14	0.02	0.55	0	96	1347	1027	3.91

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; 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)

Source: CE-CERT

2.1.1 Fuel Composition and Rich and Lean Combustion

Older lean burn engines have been observed to operate at slightly richer air-fuel (A/F) ratios during combustion when running on low methane fuels (Feist, M. 2006, 2009). Rich operation or rich combustion, as used throughout this report, means that the combustion is taking place at an A/F ratio that is lower than that for stoichiometric combustion. The A/F ratio for stoichiometric combustion represents the ratio where there is exactly enough air to completely burn all of the fuel during combustion. For rich combustion, the A/F ratio is lower than that for stoichiometric combustion, meaning that the amount of air is not fully sufficient to burn all of the fuel during combustion. Regardless of whether the actual combustion is rich, lean, or stoichiometric, as the A/F ratio for combustion decreases between any two points in time, the combustion is richer than the initial condition.

2.2 Test Vehicles

Four vehicles were selected to represent different vehicle types: a school bus, waste hauler, and two class 8 trucks, and different types of engines. The inclusion of the three vehicle types provides some information on the differences between school bus, waste hauler, and port-related service vehicles.

The school bus used a 2005 lean-burn combustion John Deere 8.1 L 6081H engine, with an oxidation catalyst (OC). The waste hauler was fitted with a 2011 8.9L stoichiometric spark ignited Cummins Westport ISL-G engine with cooled exhaust gas recirculation (EGR) and a three-way catalyst (TWC). This vehicle was selected to represent the latest engine technology available for natural gas engines. The third vehicle was equipped with a 2012 Cummins Westport ISL G 8.9 L stoichiometric engine, with a three-way catalyst (TWC) and a cooled exhaust gas recirculation (EGR) system. The fourth vehicle was a 2013 Cummins Westport ISX12 G stoichiometric engine, with a TWC device and a cooled EGR system. Table 2 provides the engine specifications. The certification Executive Orders for each of the engines tested are provided in Appendix A. The Colton Unified School District provided the school bus on loan. Waste Management provided the waste hauler. The Cummins trucks were leased from Ryder Truck Leasing, local to Riverside, California.

Table 2: Engine Specifications

Manufacturer	John Deere	Cummins Westport	Cummins Westport	Cummins Westport
Engine Model	6081HF	ISL-G	ISL G	ISX12 G
Model Year	2005	2011	2012	2013
Vehicle Type	Bus	Waste Hauler	Truck	Truck
Engine Family	5JDXH08.1067	BCEXH0540LBH	CCEXH0540LBH	DCEXH0729XBA
Engine Type	Lean burn Spark-ignited Turbocharged	Stoichiometric Spark-ignited Turbocharged, EGR	Stoichiometric Spark-ignited Turbocharged, EGR	Stoichiometric Spark-ignited Turbocharged, EGR
Horsepower	250 HP	320 HP	320 HP	400 HP
Number of Cylinders	6	6	6	6
Bore and Stroke	116 mmx 129 mm	114 mm x 145 mm	114 mm x 145 mm	130 mm x 150 mm
Displacement	8.1 L	8.9 L	8.9 L	11.9 L
Compression Ratio	11:1	12:1	12:1	
Peak Torque	735 ft-lbs. @ 1300 rpm	1000 ft-lbs. @ 1300 rpm	1000 ft-lbs. @ 2200 rpm	1450 ft-lbs. @ 1200 rpm
Aftertreatment	OC	TWC	TWC	TWC
Certification Level (g/bhp-hr)	NMHC+NO_x:1.2 CO:0.1 PM:0.01	NMHC: 0.08 NO_x:0.13 CO:14.2 PM:0.002	NMHC: 0.08 NO_x:0.13 CO:14.2 PM:0.002	NMHC: 0.03 NO_x:0.15 CO:8.7 PM:0.003

Source: CE-CERT

2.3 Test Cycles

For the John Deere school bus, testing was performed over the CBD test cycle. For the Cummins Westport ISL G truck, testing was performed on the Near Dock cycle, while for the Cummins Westport ISX12 G truck testing was performed over the Local Haul duty cycle. The test matrix was randomized to allow some measure of 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 3. For the John Deere school bus, all 7 test fuels were used, so the matrix was for 7 days ending with testing of gas H7. For the waste hauler, H1, H7, LM3, LM5, and LM6 were tested. For the Cummins Westport ISL

G truck, only H1, LM5, and LM6 were tested. For the Cummins Westport ISX12 G truck, H1, LM4, LM5, and H7 were tested.

Table 3: Chassis Dynamometer Test Matrix for Each Test Vehicle

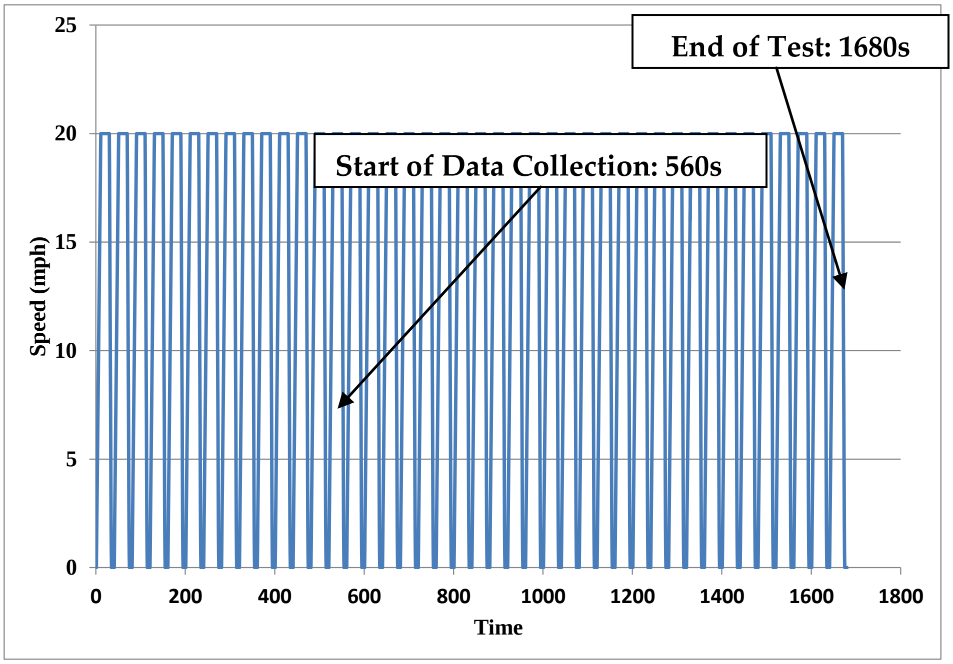
Test Day	Morning Schedule (assumes 3 replicates)	Afternoon Schedule (assumes 3 replicates)
ISL G – Near Dock		
Day 1	H1,H1,H1	LM5,LM5,LM5
Day 2	LM5,LM5,LM5	LM6,LM6,LM6
Day 3	LM6,LM6,LM6	H1,H1,H1
ISL G – Waste Hauler		
Day 1	H7,H7,H7	H1,H1,H1
Day 2	H1,H1,H1	LM3,LM3,LM3
Day 3	LM3,LM3,LM3	LM5,LM5,LM5
Day 4	LM5,LM5,LM5	LM6,LM6,LM6
Day 5	LM6,LM6,LM6	H7,H7,H7
John Deere - CBD		
Day 1	H7,H7,H7	H1,H1,H1
Day 2	H1,H1,H1	H2,H2,H2
Day 3	H2,H2,H2	LM3,LM3,LM3
Day 4	LM3,LM3,LM3	LM4,LM4,LM4
Day 5	LM4,LM4,LM4	LM5,LM5,LM5
Day 6	LM5,LM5,LM5	LM6,LM6,LM6
Day 7	LM6,LM6,LM6	H7,H7,H7
ISX12 G – Local Hauler		
Day 1	H7,H7,H7	H1,H1,H1
Day 2	H1,H1,H1	LM4,LM4,LM4
Day 3	LM4,LM4,LM4	LM5,LM5,LM5
Day 4	LM5,LM5,LM5	H7,H7,H7

CBD = Central Business District; WHM = William H. Martin;

Source: CE-CERT

A specially developed cycle was used for the CBD testing. This cycle consisted of a single CBD cycle as a warm-up, followed by a double (i.e., two iterations) CBD cycle. The CBD cycle was repeated twice to provide a sufficient particle sample for analysis. The CBD cycle is characterized by an average speed of 20.23 kilometers per hour (km/h), a maximum speed of 32.18 km/h [20 miles per hour (mph)], an average acceleration of 0.89 meters per second squared (m/s²), a maximum acceleration of 1.79 m/s². The driving distance for a single CBD cycle is 3.22 km, or 9.66 km for the full cycle, including the warm-up. Emission analyses for gaseous emissions were collected as an integrated sample over the double CBD cycle. West Virginia University (WVU) used a similar cycle in earlier testing on CNG buses (Walkowicz, K. et al. 2003). A speed-time trace for the extended CBD is provided in Figure 1.

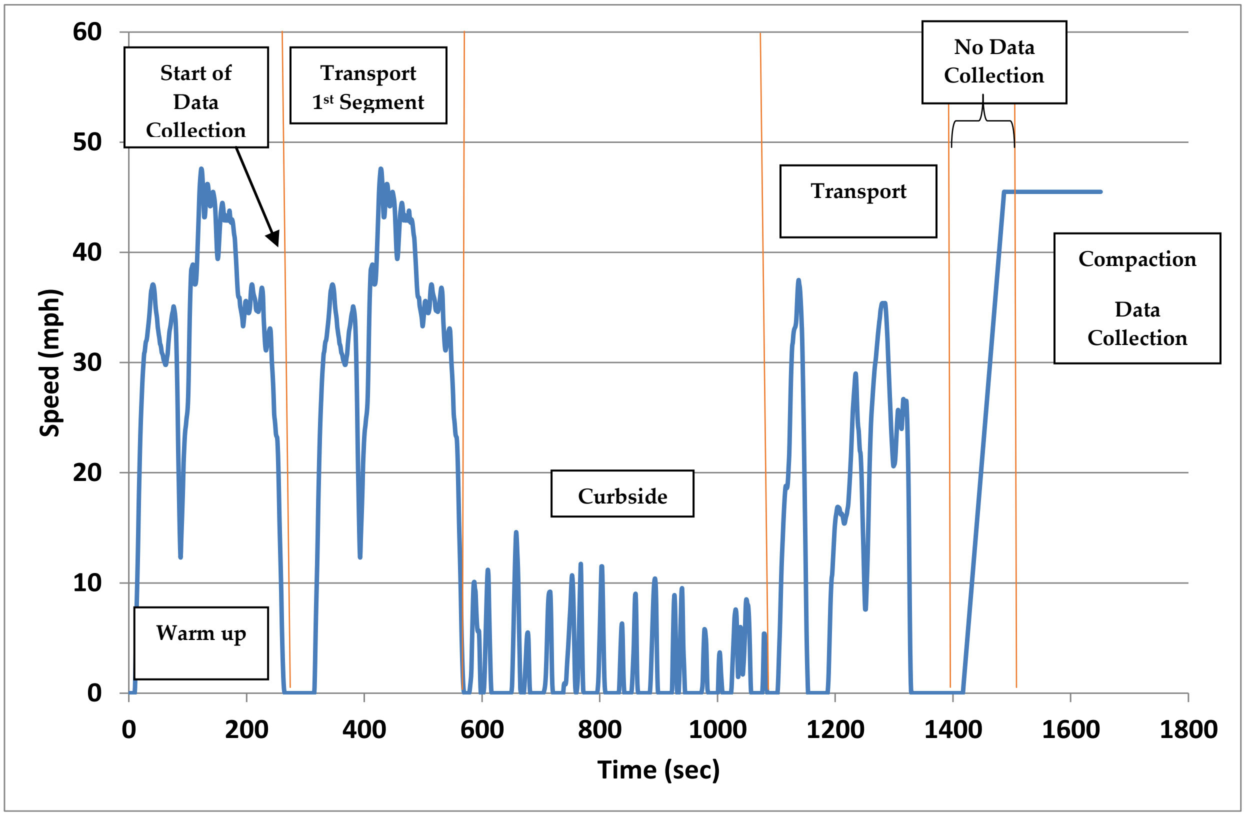
Figure 1: Double CBD Cycle with Warm-up



Source: CE-CERT

The waste hauler was tested over the William H. Martin (WHM) Refuse Truck Cycle. WVU developed this cycle 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 first 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. The first and second part of the transport cycle represents 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 emission data is 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 (Walkowicz, K. et al. 2003). The Refuse Truck Cycle is shown in Figure 2.

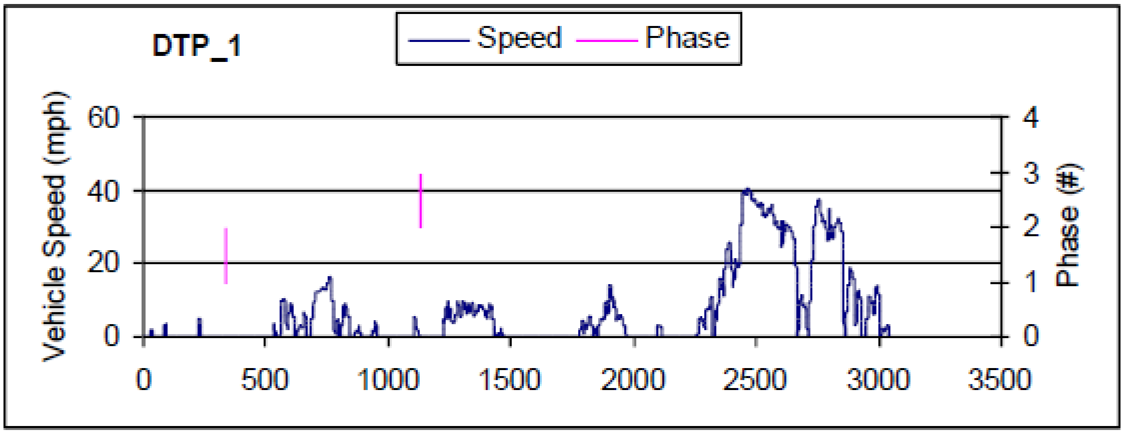
Figure 2: Refuse Truck Cycle



Source: CE-CERT

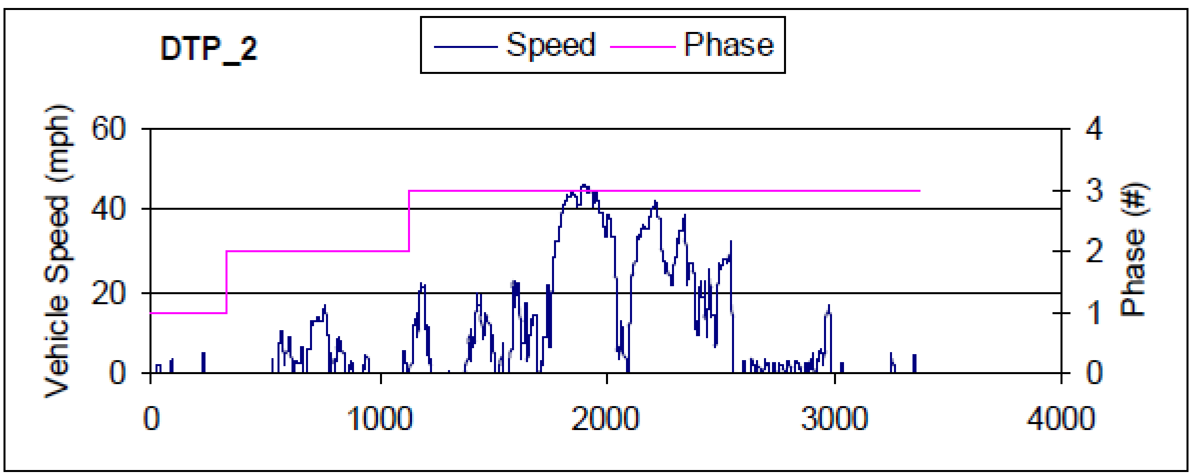
The Near Dock duty cycle and the Local Haul duty cycle are segments of the drayage truck port cycle developed by TIAX in conjunction with the Ports of Long Beach and Los Angeles. These cycles were developed based on data logging of over 1,000 Class 8 drayage trucks at these ports for trips over a four-week period in 2010. The Near Dock duty cycle consists of three different phases: a creep phase, a low speed transient phase, and a short high-speed transient phase. The cycle covers a total distance of 5.61 miles with an average speed of 6.6 mph and a maximum speed of 40.6 mph. Similar to the Near Dock duty cycle, the Local Haul duty cycle also consists of three different phases, with the creep phase and the low speed transient phase being the same as the Near Dock cycle. The Local Haul duty cycle; however, consists of a long high-speed transient phase. The cycle covers a total distance of 8.71 miles with an average speed of 9.3 mph and a maximum speed of 46.4 mph. The Near Dock Cycle and the Local Haul duty cycle are shown in Figure 3 and Figure 4.

Figure 3: Near Dock Duty Cycle



Source: CE-CERT

Figure 4: Local Haul Duty Cycle



Source: CE-CERT

The vehicles were warmed up in the morning over a single iteration of the test cycle the vehicle was being tested on and the test fuel that was being tested first on that particular day. Between tests, there was a hot soak, where the engine is turned off for about 20 minutes. As discussed above, the CBD tests for the school bus were conducted as hot running tests, with a single CBD used as the warm-up. For the waste hauler, all tests were conducted as hot running tests, with the 277-second warm-up. For the Near Dock duty cycle and the Local Haul duty cycle, the vehicles were warmed up in the morning and after each fuel change prior to testing over the final phase of the test cycles on the first test fuel for that particular day. The Near Dock duty cycles and the Local Haul duty cycles were run as hot start tests, meaning the cycles were run/started after the vehicle sat for a short period of time with the engine shut off. In this case, the creep portion of the cycle was started right after the 20 minute soak period where the engine was shut off after completing the warm up cycle. The vehicles were monitored throughout the course of testing for differences in the operability of the engine on the different blends, such as knock. No significant differences in operability of the engine on the different test blends were observed during the course of normal testing.

The road load coefficients were calculated based on the frontal area of the vehicle and a factor accounting for its general shape for the school bus and the two class 8 trucks. The road load coefficients for the waste hauler were the same as that used in the first round testing of the waste hauler testing, determined by coasting down the vehicle from approximately 60 mph to approximately 10 mph (Durbin, T. et al. 2014). The test weight used for the school bus was 30,560 lbs. based on procedures similar to those used in a recent study (Durbin, T. et al. 2014). The test vehicle for the waste hauler was the same as that used in the first round testing of the waste hauler testing (i.e., 33,520 lbs.). The test weight used for the two class 8 trucks was 56,000 lbs., which is a typical weight for trucks hauling goods in the local port areas.

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. UCR's chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb. to 80,000 lb. This covers a broad range of in-use medium and heavy-duty vehicles. The design incorporates 48" rolls, axial loading to prevent tire slippage, 45,000 lb base inertial plus two large AC drives for achieving a range of inertias. The dynamometer has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600-horse power at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common.

The chassis dynamometer was designed to accurately perform the new CARB 4-mode cycle, the urban dynamometer driving schedule (UDDS), refuse drive schedules (WHM), bus cycles (like the central business district [CBD] cycle), as well as a range of other speed vs time traces. The load measurement uses state of the art sensing and is accurate to 0.05 percent of full scale and has a response time of less than 100 ms, which is necessary for repeatable and accurate transient testing. The speed accuracy of the rolls is ± 0.01 mph and has acceleration accuracy of ± 0.02 mph/sec, both measured digitally and thus easy to maintain their accuracy. The torque transducer is calibrated as per Code of Federal Regulations (CFR) 1065, which is a standard method used for determining accurate and reliable wheel loads. A typical vehicle set up on the chassis dynamometer is shown in Figure 5.

Figure 5: Typical Setup of Test Vehicles on the Chassis Dynamometer

Photo Credit: CE-CERT

The CE-CERT team obtained the emission measurements using its Mobile Emissions Laboratory (MEL). For all tests, standard emissions measurements of total hydrocarbons (THC), NMHC, methane (CH_4), CO, NOx, carbon dioxide (CO_2), and PM, were measured. The 602P nondispersive infrared (NDIR) analyzer from California Analytical Instruments (CAI) measured the CO and CO_2 emissions. THC, NMHC, and CH_4 emissions were measured with 600HFID flame ionization detector (FID) from CAI. NOx 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 that is incorporated in the MEL. Measurements of nitrous oxide (N_2O) were made using a Fourier Transform Infrared (FTIR).

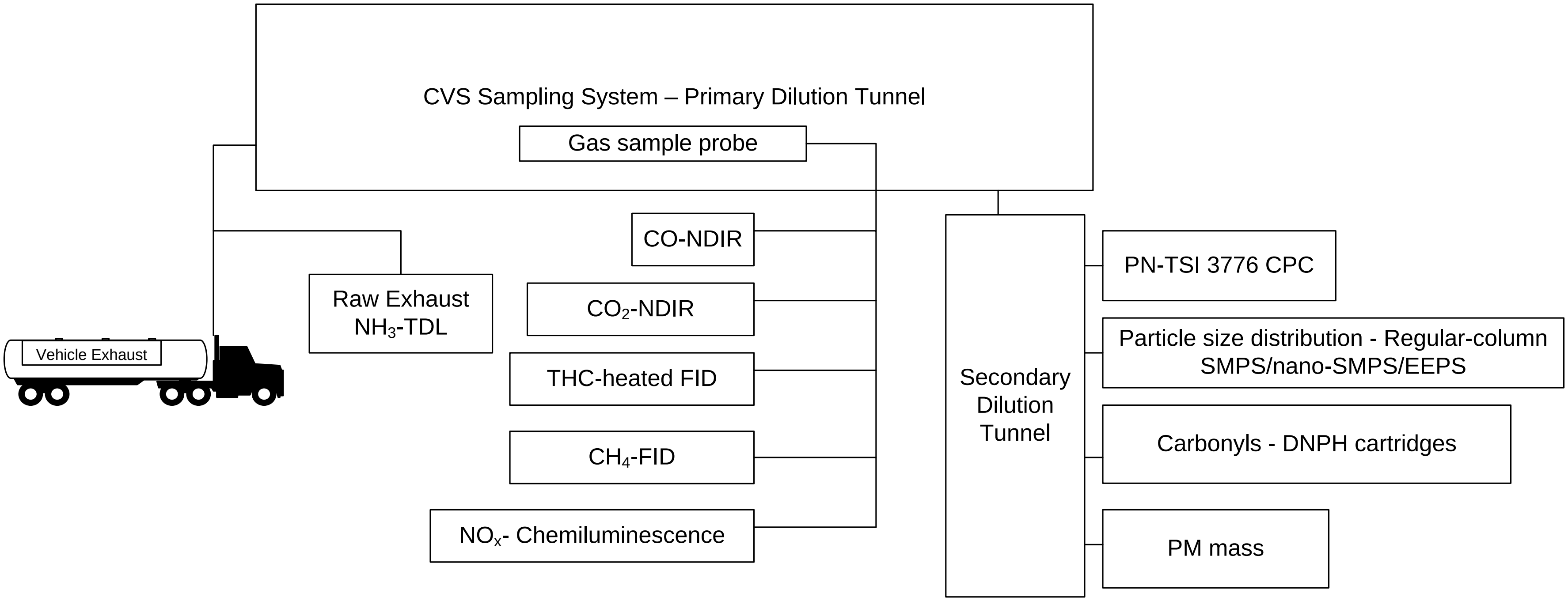
The mass concentrations of $PM_{2.5}$ were obtained by analysis of particulates collected on 47mm diameter 2μm pore Teflo filters (Whatman brand). The filters were measured for net gains using a UMX2 ultra precision microbalance with buoyancy correction following the CFR weighing procedure guidelines.

The sampling of carbonyls was done for 3-4 tests per test fuel/vehicle combination. Samples for carbonyl analysis were collected onto 2, 4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA). A critical flow orifice controls the flow to 1.0 liter per minute through the cartridge. Sampled cartridges were extracted using 5 mL of acetonitrile and injected into an Agilent 1200 series high performance liquid chromatograph (HPLC) equipped with a variable wavelength detector. The column used was a 5 µm Deltabond AK resolution (200cm x 4.6mm ID) with upstream guard column. The HPLC sample injection and operating conditions were set up according to the specifications of the SAE 930142HP protocol (Siegl, W. et al. 1993). Samples from the dilution air were collected for background correction.

Sampling for carbonyl compounds and the PM mass was done cumulatively over the entire duration of each test cycle due to the low mass levels expected for these pollutants and the corresponding need to collect a sufficient sample for analysis. As such, results for the individual modes of the Refuse Truck cycle, Near Dock duty cycle, and the Local Hauler duty cycle are not available for these pollutants. The FTIR N_2O measurements were also made from bag samples that collected cumulatively over the duration of each cycle. A schematic of the experimental setup is provided in Figure 6.

Particle number counts were measured with a TSI 3776 ultrafine-Condensation Particle Counter (CPC) with a 2.5 nm cut point. An Engine Exhaust Particle Sizer (EEPS) spectrometer (TSI 3090, firmware version 8.0.0) measured real-time second-by-second particle size distributions between 5.6 to 560 nm. The EEPS has a scan time of one second and provides a size range from 6 to 423 nm in electrical mobility. Particles were sampled at a flow rate of 10 L/min for the EEPS, which is considered high enough to minimize diffusional losses. A corona charger then charged the particles and determined the size based on their electrical mobility in an electrical field. Concentrations were determined using multiple electrometers.

Figure 6: Schematic of the Sampling Systems and Instruments



Source: CE-CERT

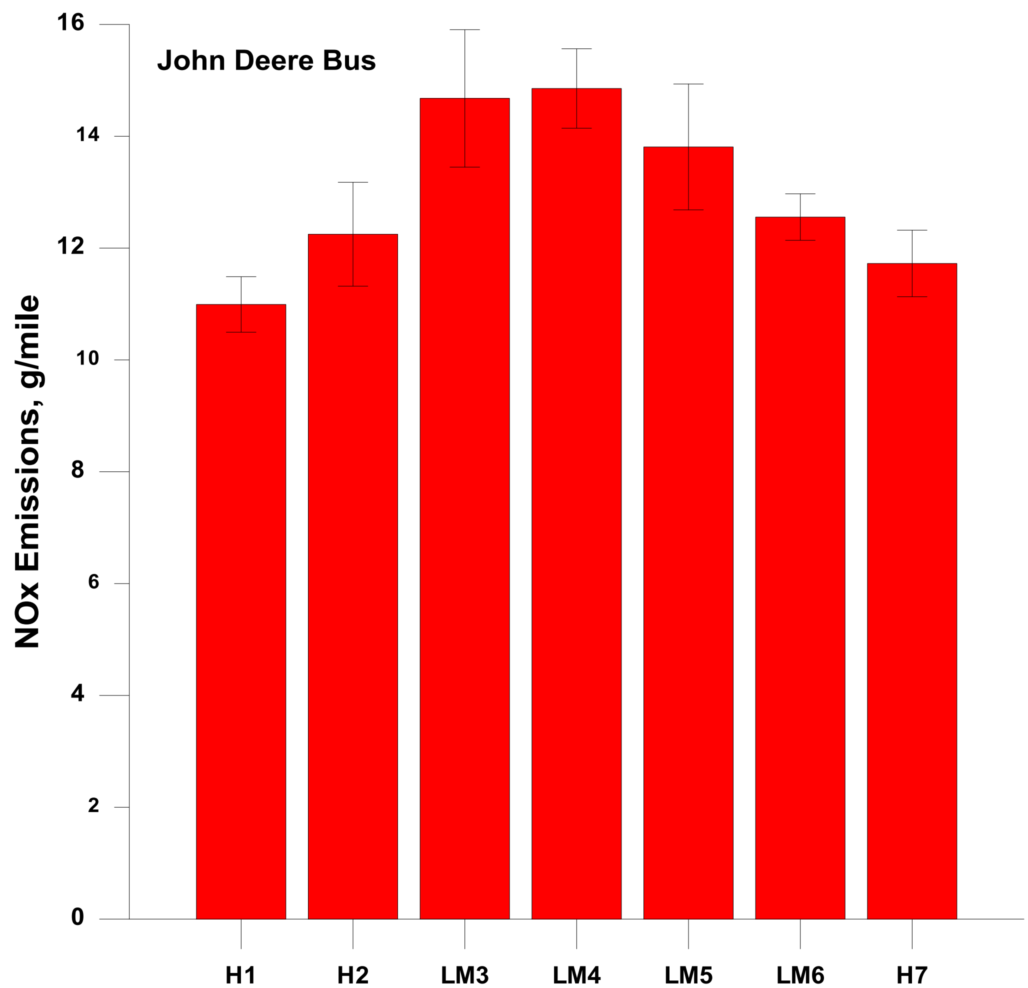
CHAPTER 3: Heavy-Duty Vehicle Chassis Dynamometer Testing Results

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. To provide a better representation of the results, the emission pollutants for the class 8 trucks over the Near Dock and Local Haul duty cycles are shown for each of the individual phases of the cycle, i.e., the creep phase, the low speed transient phase, and the short high-speed transient phase.

3.1 Nitrogen Oxides Emissions

Figure 7 shows the NOx emissions for the John Deere school bus. Fuel composition influences NOx emission levels for the school bus, with the low methane fuels resulting in higher NOx emissions compared to the high methane fuels. The school bus showed statistically significant increases of 33.5 percent, 35.1 percent, 25.6 percent, and 14.2 percent, respectively for LM3, LM4, LM5, and LM6 compared to H1. Statistically significant increases in NOx emissions were also seen for H2 (11.4 percent) and H7 (6.6 percent) relative to H1. Compared to H2, NOx emissions showed statistically significant increases of 19.8 percent, 21.2 percent, and 12.7 percent, respectively, for LM3, LM4, and LM5, whereas H1 showed a statistically significant reduction in NOx emissions of 10.2 percent. Similar to H1 and H2 fuels, NOx emissions showed statistically significant increases of 25.1 percent, 26.7 percent, 17.7 percent, and 7.1 percent, respectively, for LM3, LM4, LM5, and LM6 compared to H7, whereas H1 showed a NOx reduction of 6.2 percent at a statistically significant level.

Figure 7: Average NOx Emissions for the John Deere Bus



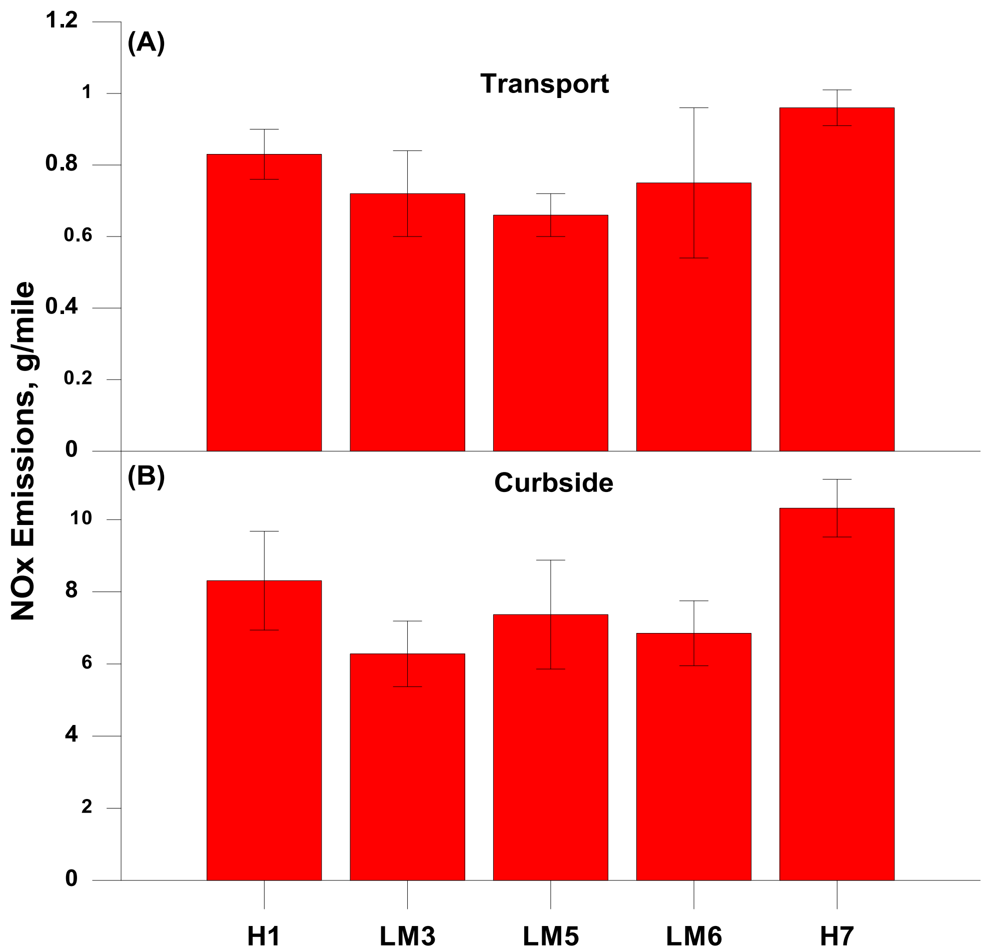
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

The increases in NOx emissions with LM3, LM4, LM5, and LM6 fuels for the lean-burn engine fitted with the oxidation catalyst can be attributed to the presence of high molecular-weight hydrocarbons in these fuels. 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 higher temperatures result. Peak combustion temperatures are higher due to the advanced location of peak pressure and higher adiabatic flame temperature (Fiest, M. et al. 2010), which would result in higher NOx emissions, as NOx is generated predominantly through the strongly temperature-dependent thermal NO mechanism (McTaggart, G. et al. 2010, Naber, J. et al. 1994). Previous studies have also shown that lean-burn engines run richer as MN is decreased (Fiest, 2009). This reaction 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 NOx. The results reported here are also in agreement with previous studies conducted at UCR CE-CERT utilizing lean-burn engines on low methane fuels (Karavalakis, G. et al. 2013; Hajbabaei, M. et al. 2013), where higher NOx emissions are seen with low methane fuels are seen for transit buses and a waste hauler equipped with lean-burn engines and operated over the CBD cycle and the Refuse Truck cycle (RTC), respectively.

Error! Reference source not found. (a-b) shows the emissions of NOx in grams (g) per mile for the waste hauler for the transport and curbside segments of the Refuse Truck Cycle. **Error! Reference source not found.** shows the emissions of NOx for the waste hauler for the compaction segment of the Refuse Truck Cycle. For the compaction segment, the emissions are presented on a brake horsepower-hour (bhp-hr) basis based on readings from the engine's control module (ECM). Bhp-hr is an important emission measurement metric, since the compaction segment is not designed to represent a driving cycle and since heavy-duty natural gas engines are certified on a bhp-hr basis.

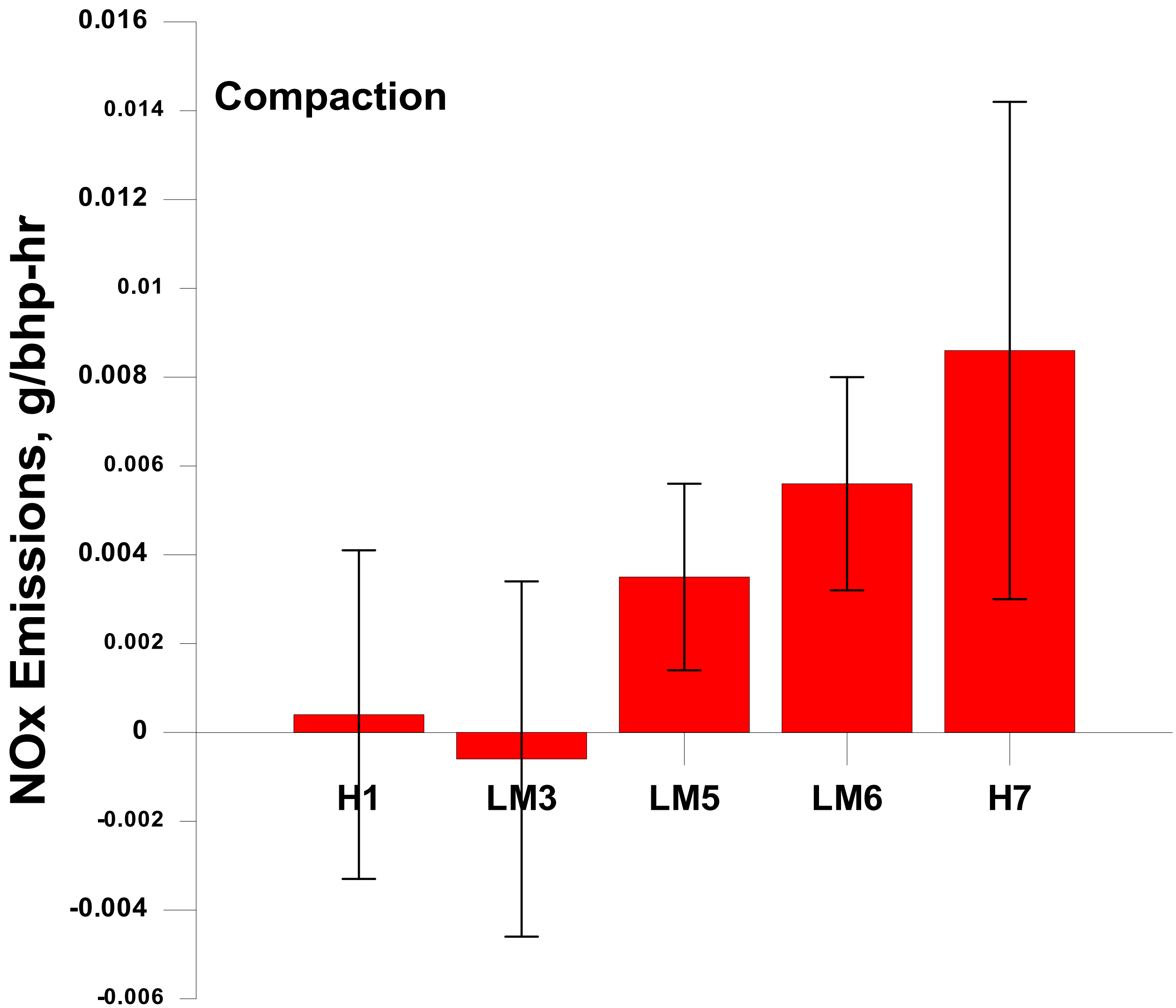
Figure 8 (a-b): Average NOx Emissions for the Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 9: Average NO_x Emissions for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

NOx emission levels for the Cummins Westport ISL-G waste hauler ranging from 0.66-0.96 g/mile for the transport phase, from 6.28-10.32 g/mile for the curbside phase, and from -0.0006-0.0086 g/bhp-hr for the compaction phase. The significantly higher NOx emissions for the curbside phase compared to the transport phase of the RTC are due to the curbside segment's composition of short, low speed accelerations between idle periods that cover a very short distance (0.36 miles). Stop and go driving tends to create high emissions when evaluated on a per mile basis. For the transport cycle, the LM3 and LM5 show marginally statistically significant and statistically significant reductions in NOx emissions compared to H1 of 13 percent and 20.9 percent, respectively, while NOx emissions for H7 shows a statistically significant increase of 15.1 percent compared to H1. For the curbside cycle, LM3 and LM6 demonstrated a 24.3 percent and 17.4 percent reduction in NOx emissions compared to H1, respectively, while NOx emissions for H7 shows a statistically significant increase of 24.2 percent compared to H1. NOx emissions for the compaction cycle are at very low levels and considerably below the 0.2 g/bhp-hr standard. Statistically significant increases in NOx emissions are seen for LM6 and H7 compared to H1 on the order of 1,323 percent and 2,086 percent, respectively, while LM5 shows a marginally statistically significant increase in NOx emissions of 779 percent compared to H1. The high percentage increases for the compaction cycle can be attributed to the very low emission levels, and that these differences are relatively small on an absolute basis.

The results reported here show substantially lower NOx emission levels than those found in the Phase 1 part of this study (Durbin, T. e al. 2014) for a legacy waste hauler equipped with a 2002 Cummins 8.3L C Gas Plus, lean burn, spark ignited engine using the same gas blends and operated over the RTC. Several studies have shown that the majority of NOx reductions can be attributed to the TWC (Einewall, P. et al. 2005, Chiu, J. 2007). The newer stoichiometric engine tested in this study also has EGR that introduces inert exhaust gases into the combustion cylinder, which reduces cylinder combustion temperature and results in lower NOx emissions.

The slight decrease in NOx emissions for the low methane fuels may be due to slightly richer air/fuel (A/F) ratios for combustion. The resultant decrease in oxygen may also lead to increased effectiveness in the TWC's ability to further reduce NOx emissions. Previously, lean burn engines have also been observed to operate with a slightly richer A/F ratio when running on low methane fuels (Feist, M. 2006). In this case, the engines experienced increased NOx emissions, which had been attributed to higher flame speeds and adiabatic flame temperatures (Feist, M. 2006, Durbin, T. 2014). Stoichiometric engines generally exhibit tighter A/F ratio control, so any change in the A/F ratio should be slight with minimal engine effects; however, along with decreases in NOx emissions from operation on low methane fuels, the refuse hauler exhibited increased CO emissions as discussed in Section 3.5, which is consistent with slightly richer combustion.

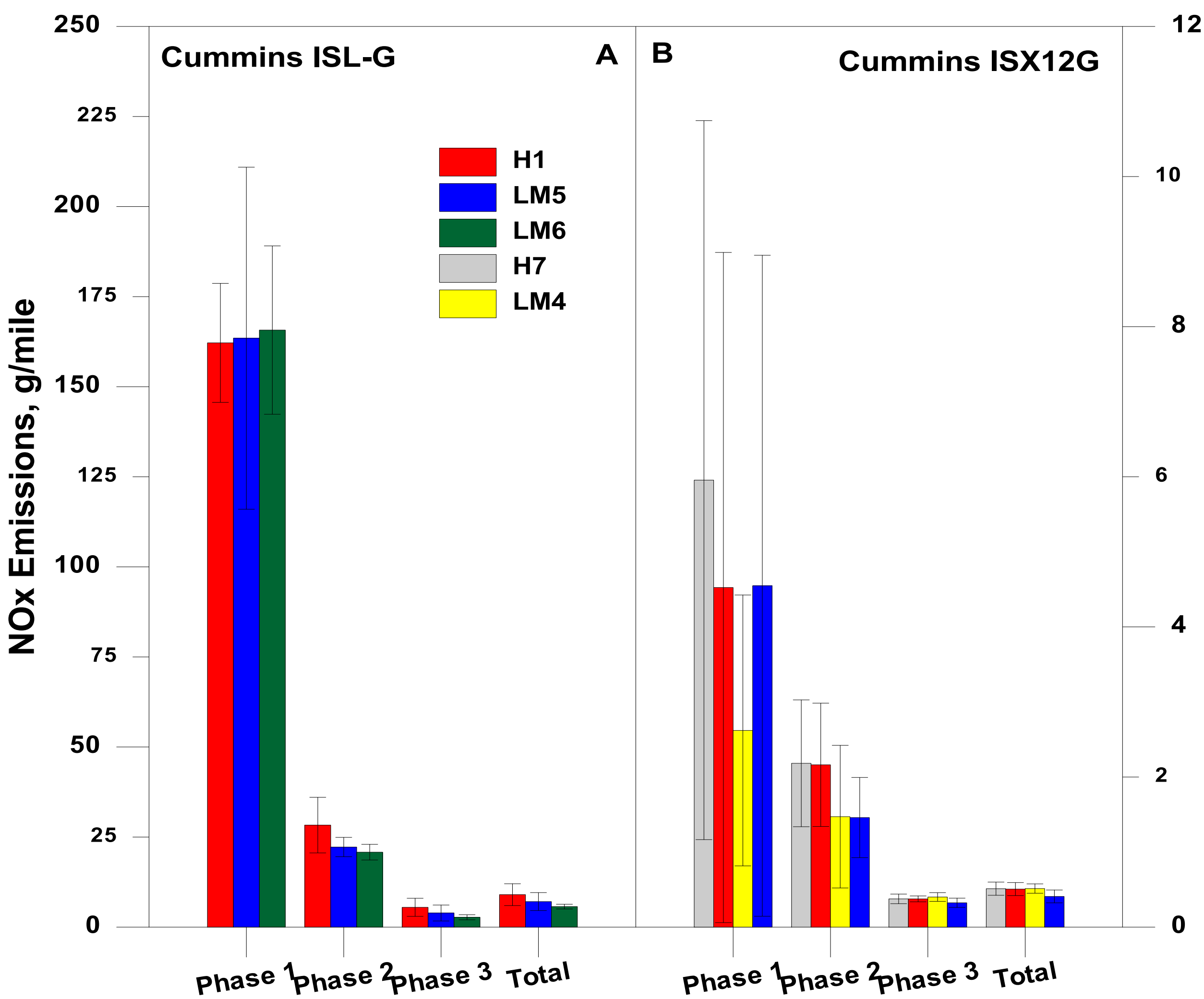
Figure 10 shows the NOx emissions for the Cummins Westport ISL G (A) and Cummins Westport ISX12 G (B) Class 8 trucks. NOx emissions for both trucks are presented for the three individual phases of the Near Dock cycle and the Local Haul Duty cycle as well as for the accumulated cycle. The Cummins ISX12 G truck produces substantially lower NOx emission levels than the Cummins ISL G truck. Both vehicles showed the highest emissions for the creep phase of the test cycle. Both Cummins trucks and the low MN/high Wobbe number fuels generally show lower NOx levels than the high methane fuels. This reduction in NOx levels is opposite to the trends for the lean-burn John Deere engine, where the low methane fuels clearly produce higher NOx emissions than the baseline fuels.

For the Cummins ISL G truck, the accumulated NOx emissions show some trends towards lower emissions with the low methane fuels, i.e., LM5 and LM6, compared to H1. NOx emissions show statistically significantly reductions of 36.7 percent for LM6 compared to H1. Emissions of NOx are considerably higher for the creep phase than the other two phases of the

Near Dock duty cycle. For the creep phase, there are no strong fuel effects in NOx emissions. For the low speed transient phase, NOx emissions show a marginally statistically significant decrease of 21.5 percent and a statistically significant decrease of 26.5 percent, respectively, for LM5 and LM6 compared to H1. For the short high-speed transient phase, NOx levels show a statistically significant decrease of 50.2 percent for LM6 compared to H1.

For the Cummins Westport ISX12 G truck, the accumulated NOx emissions generally show weak trends between fuels with the exception of LM5, which shows marginally statistically significant reductions of 19.3 percent and 20.2 percent, respectively, compared to H1 and H2. While some trends towards lower NOx emissions are observed for the low methane fuels for each individual phase of the Local Haul duty cycle, there are no statistically significant differences between fuels.

Figure 10: NO_x Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



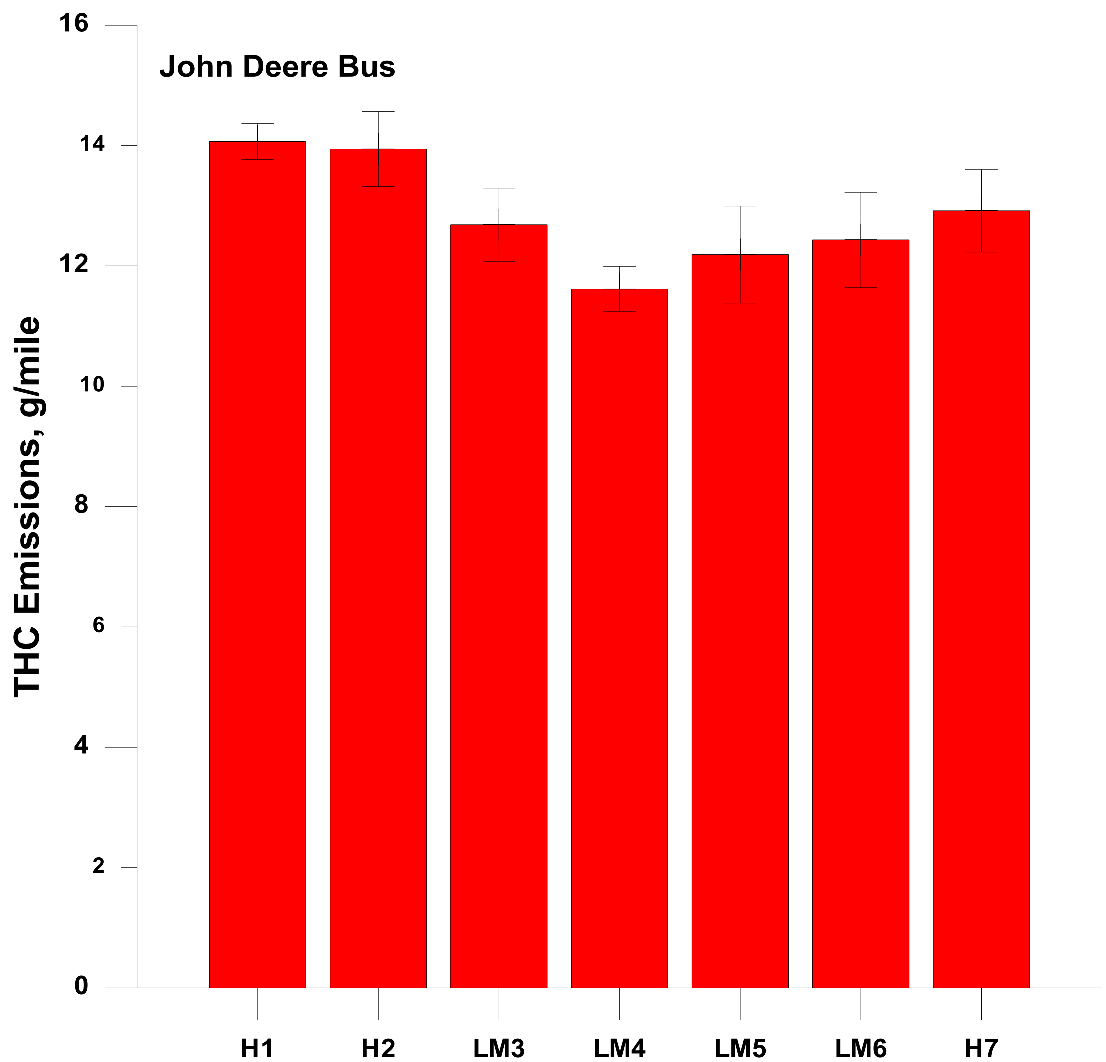
H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), L-CNG: (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

3.2 Total Hydrocarbon Emissions

Figure 11 shows the THC emissions for the John Deere school bus over the CBD cycle. THC emissions show a trend of reductions for the low methane fuels compared to the high methane fuels. THC emissions are lower at a statistically significant level by 9.8 percent, 17.4 percent, 13.4 percent, 11.6 percent, and 8.2 percent, respectively, for LM3, LM4, LM5, LM6, and H7 compared to H1. Compared to H2, THC emissions also show statistically significant decreases of 9 percent, 16.7 percent, 12.6 percent, 10.8 percent, and 7.4 percent, respectively, for LM3, LM4, LM5, LM6, and H7. Compared to H7, THC emissions show statistically significant increases of 8.9 percent and 7.9 percent, respectively, for H1 and H2, while LM4 shows a statistically significant decrease of 10.1 percent.

Figure 11: Average THC Emissions for the John Deere Bus



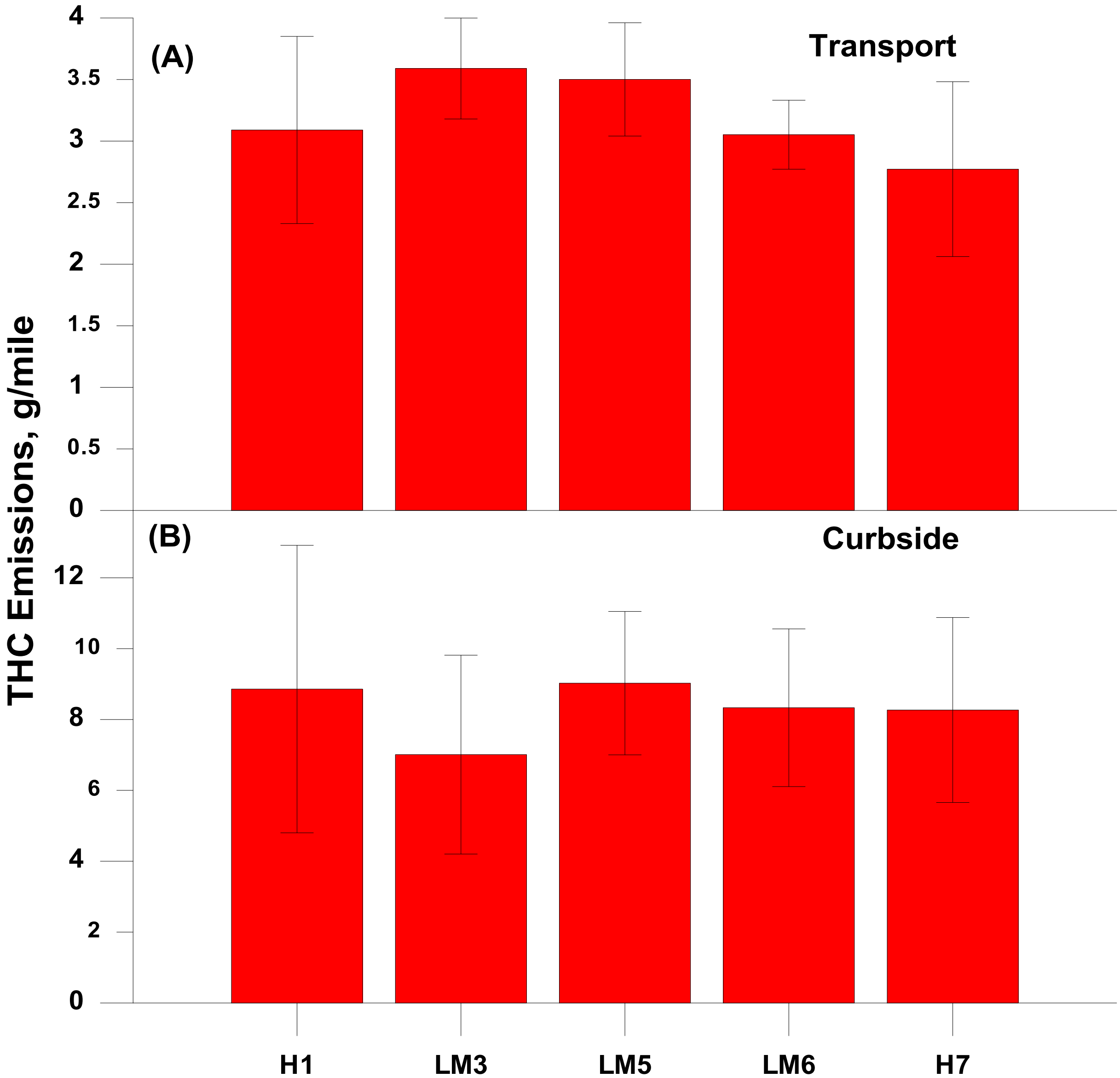
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 12 (a-b) shows the THC emissions for the waste hauler for the transport and curbside segments, while Figure 13 shows the THC emissions for the compaction segment on a bhp-hr basis. THC emissions are significantly lower than typically found for older lean burn NG engines equipped with oxidation catalysts (OCs). This reduction in THC emissions can be attributed to the differences in engine technology, since older engines are lean-burn engines with OCs designed to meet an earlier certification standard, and the ISL-G is a stoichiometric engine with a TWC that is designed to meet a more recent and stringent certification standard (The International Council on Clean Transportation, 2009). Overall, THC emissions do not show strong fuel trends. There are no statistically significant differences between fuels for the transport and curbside phases of the RTC. The only statistically significant differences are for

LM3 and LM5 compared to H7, which shows a statistically significant 29 percent increase in THC emissions and a marginally statistically significant increase of 26 percent, respectively. For the compaction cycle, LM3 is higher (22.2 percent) than H1 at a statistically significant level, while LM6 is higher (16.4 percent) than H1 at a marginally statistically significant level. Although the low methane fuels over the compaction cycle showed some trends toward higher THC emissions, there are no consistent fuel trends over the different RTC phases. The results show that the differences in the hydrocarbon composition of the test fuels do not influence the THC emission control systems effectiveness.

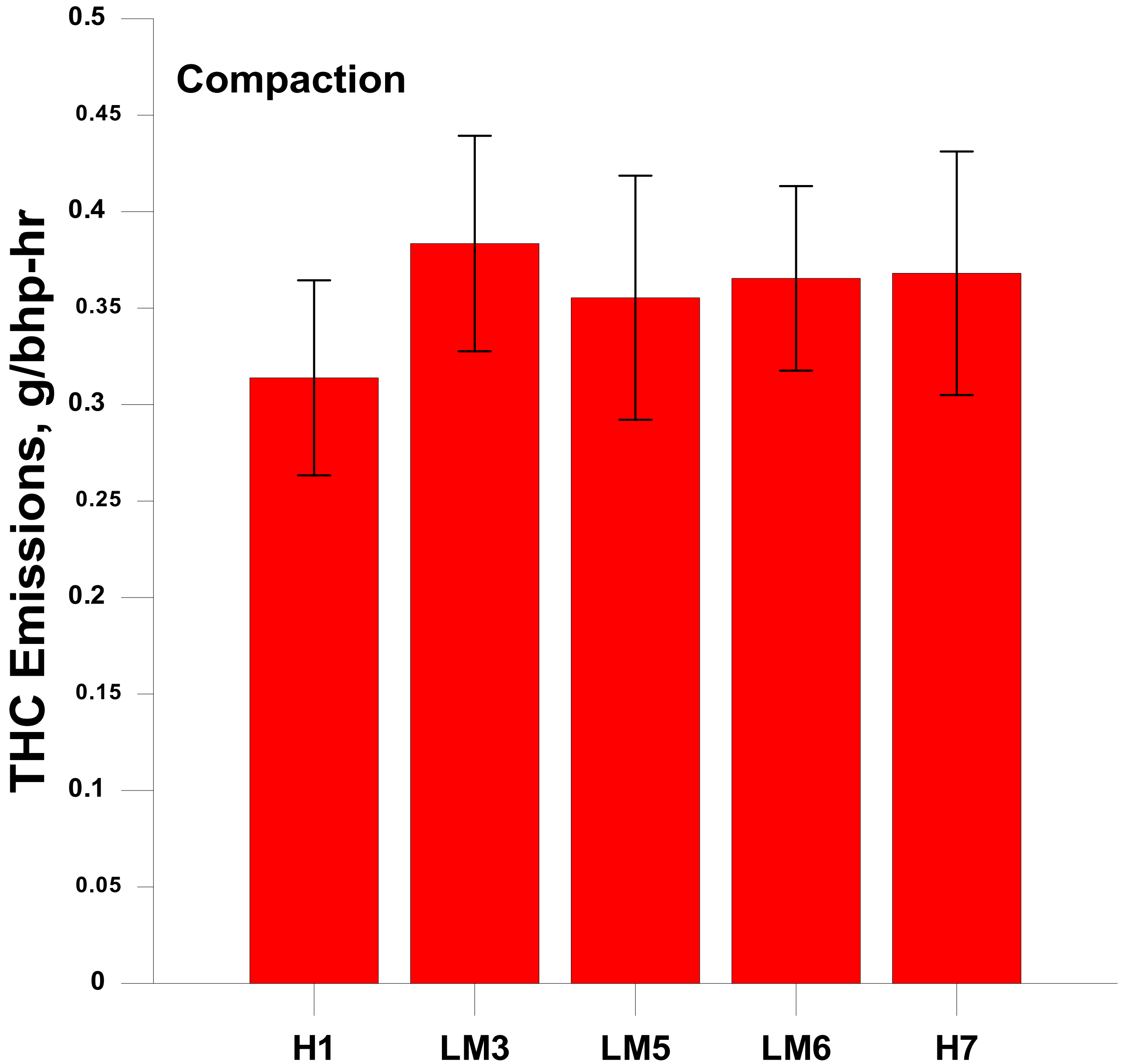
Figure 12 (a-b): Average THC Emissions for Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 13: Average THC Emissions for the Waste Hauler for the Compaction and on an Engine bhp-hr Basis



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

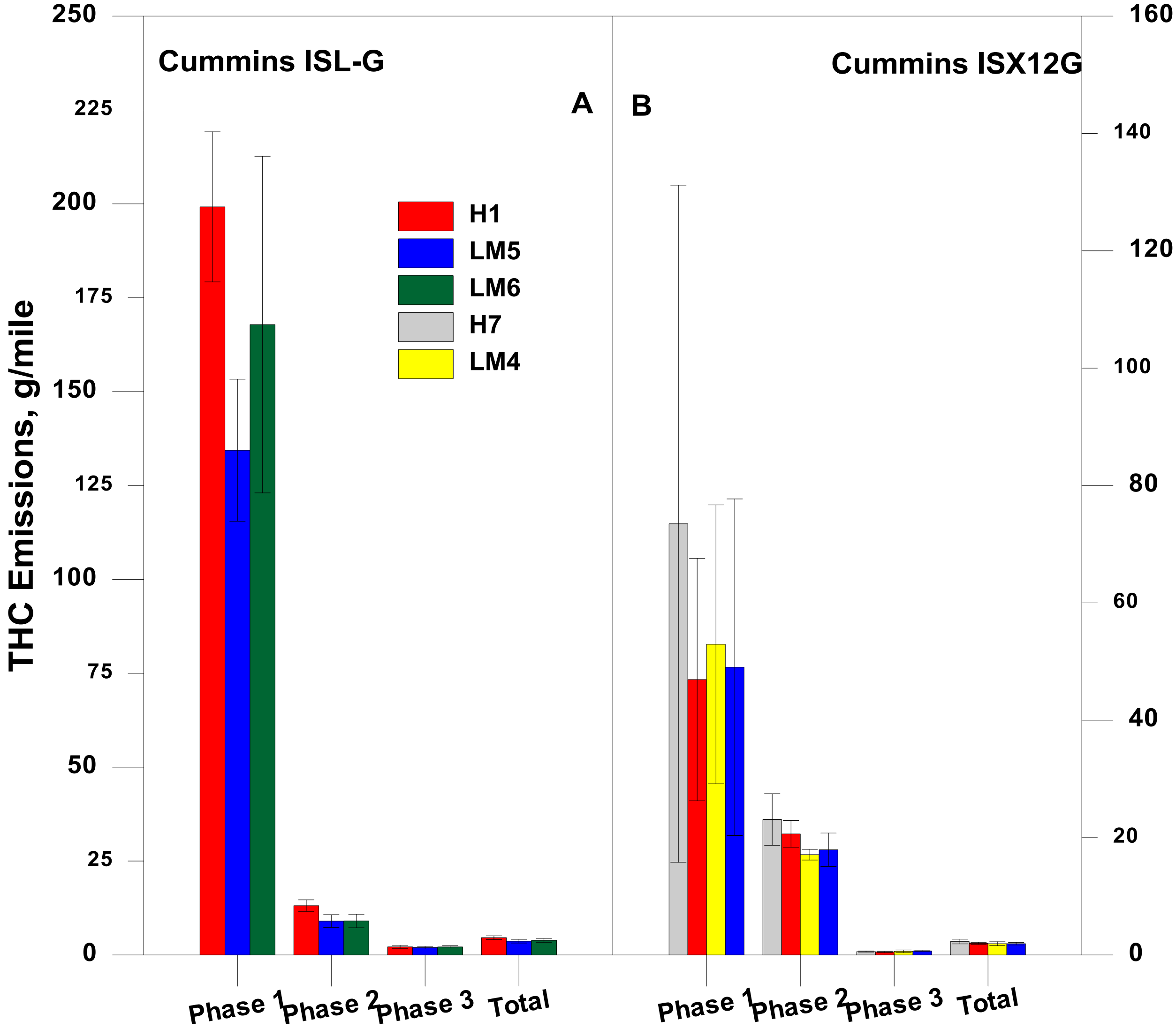
Figure 13 shows the THC emissions for the Cummins Westport ISL G (A) and the Cummins Westport ISX12 G (B) trucks over the Near Dock duty cycle and the Local Haul duty cycle, respectively. For both vehicles, the highest THC emissions were found for the creep phase and the lowest emissions were found for the high-speed transient phase. The Cummins Westport

ISL G truck showed higher THC emissions for the creep phase, but not for the low speed transient phase.

For the Cummins Westport ISL G truck, the accumulated THC emissions show statistically significant reductions of 20.5 percent and 15.7 percent, respectively, for LM5 and LM6 compared to H1. For the individual phases of the Near Dock cycle, THC emissions show a declining trend with the low methane fuels relative to H1. For the creep phase, THC emissions show a statistically significant decrease of 32.5 percent for LM5 compared to H1, while for the low speed transient phase both the LM5 and LM6 showed decreases of 31.4 percent and 31.2 percent, respectively, compared to H1 at a statistically significant level.

For the Cummins Westport ISX12 G truck, accumulated THC emissions do not show large differences between the test fuels, although some trends towards lower THC emissions for the low methane fuels are observed. A marginally statistically significant decrease in the accumulated THC emissions is also seen for LM5 (16 percent) compared to H7. For the low speed transient phase, THC emissions show statistically significant decreases of 17.2 percent for LM4 compared to H1, and 26 percent and 22.3 percent, respectively, for LM4 and LM5 compared to H7. For the long high-speed transient phase, THC emissions show statistically significant decreases of 32.4 percent and 18 percent, respectively, for LM5 compared to H1 and H7.

Figure 14: THC Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



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); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

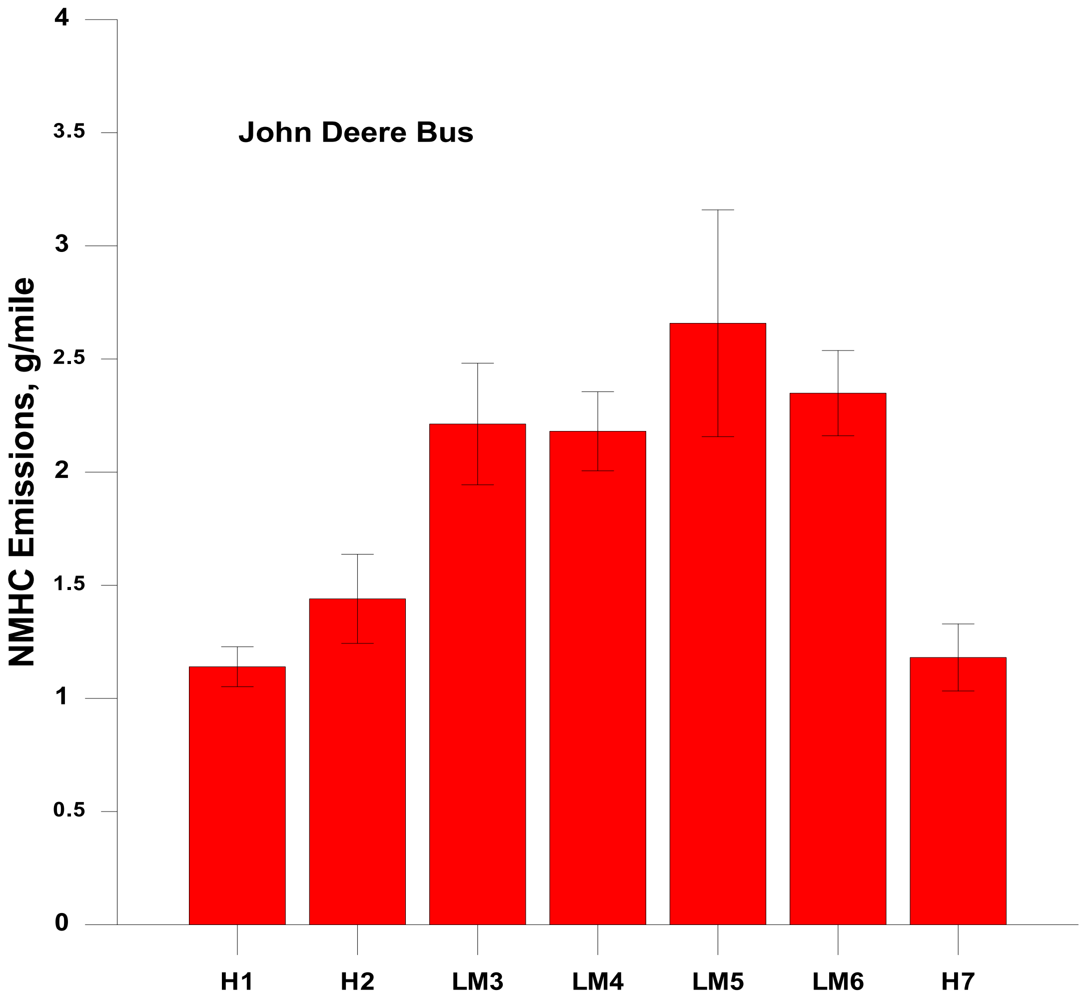
THC emissions are significantly lower for the stoichiometric Cummins Westport engines compared to the John Deere lean-burn engine. This reduction in THC emissions can be attributed to the differences in the engine technology, since the older technology lean-burn John Deere engine is fitted with an OC designed to meet an earlier certification standard, while the stoichiometric Cummins engines are fitted with TWC devices designed to meet a more recent, more stringent certification standard (Einewall, P. et al. 2005, The International Council on

Clean Transportation 2009). The John Deere school bus and the Cummins trucks show trends of higher THC emissions for the high methane fuels. This trend is consistent with results previously reported by other authors (Wang, W. et al. 1997), and also in agreement with previous studies conducted at CE-CERT (Karavalakis, G. et al. 2013, Hajbabaei et al. 2013). This result is probably due to the THC emissions from these engine/aftertreatment types, which are predominantly methane. The discussion below describes the trend, as the CH_4 emissions are roughly comparable to the THC emissions, while the NMHC emissions are very low. The reduction in THC emissions for the low methane fuels could also be due to more complete oxidation of the fuel as the combustion temperatures increase, as discussed under the NOx section. CH_4 is also less reactive from a combustion standpoint than higher hydrocarbons (Burcat, A. et al. 1971), so it is more likely to go through the combustion process unburned and pass unreacted across the catalyst.

3.3 Nonmethane Hydrocarbon Emissions

Figure 15 shows the NMHC emissions for the John Deere school bus over the CBD test cycle. Emissions of NMHC show strong fuel trends for the John Deere bus, with the low methane fuels producing higher NMHC emissions than the high methane fuels. The NMHC emissions show statistically significant increases of 26.3 percent, 94.1 percent, 91.3 percent, 133.2 percent, and 106.1 percent, respectively, for H2, LM3, LM4, LM5, and LM6 compared to H1. Compared to H2, all test fuels show statistically significant differences in NMHC emissions with the low methane fuels showing statistically significant increases and the high methane fuels showing statistically significant decreases. Similar to H2, all test fuels showed statistically significant increases in NMHC emissions compared to H7 ranging from 21.9 percent to 125.1 percent, with the exception of H1.

Figure 15: Average NMHC Emissions for the John Deere Bus



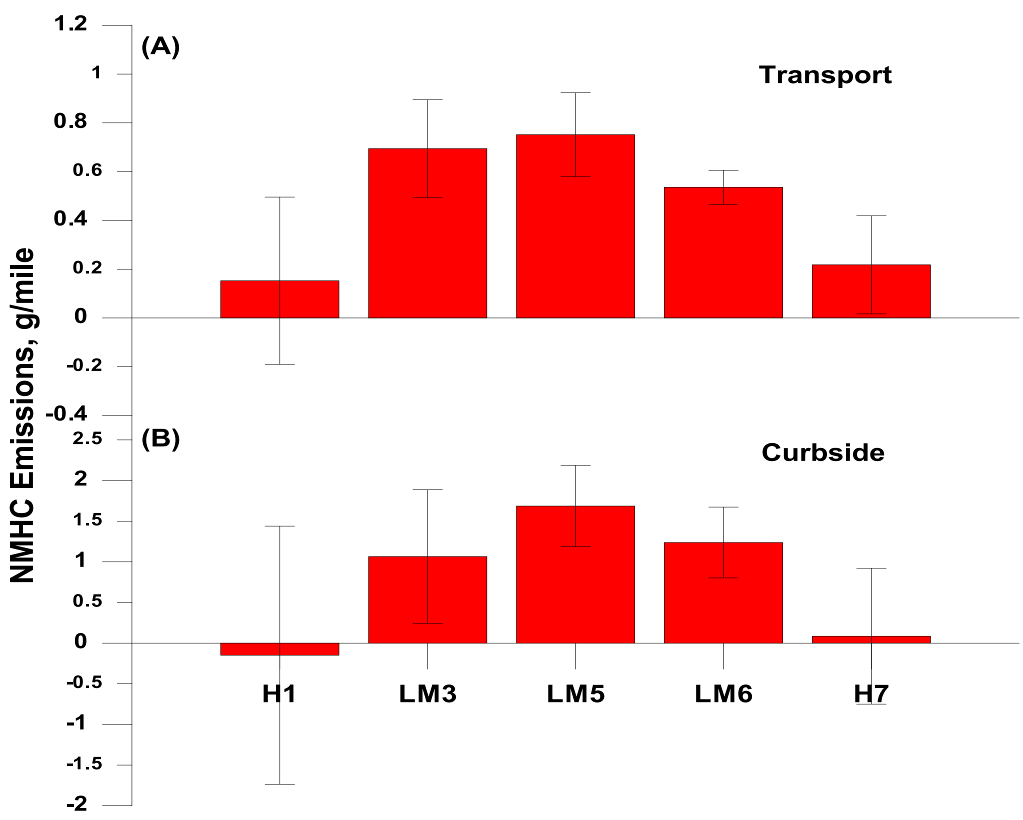
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 16 (a-b) shows the NMHC emissions for the waste hauler for the transport and curbside segments, while Figure 17

Figure 17shows the NMHC emissions for the compaction segment on a bhp-hr basis. NMHC emissions show a trend of higher emissions for the low methane fuels containing higher levels of NMHCs. This trend is for all three cycles. For both the transport and curbside cycles, NMHC emissions are higher for LM3, LM5, and LM6 at a statistically significant or marginally statistically significant level compared to H1 and H7, except for the comparison between LM3 and H1 for the curbside cycle. NMHC emissions for the compaction cycle are also higher at a statistically significant level for LM3, LM5, and LM6 compared to H1 and a marginally statistically significant level for LM3 compared to H7. Previous studies have also shown that NMHC emissions increase with low methane fuels (Burcat, A. et al. 1971, Min, B. et al. 2002). THC emissions from natural gas engines are predominantly unburned fuel; therefore, the nonmethane hydrocarbon fraction of THC exhaust emission typically trends with the percentage of nonmethane hydrocarbons in the test fuel. Previous studies conducted at CE-CERT for the stoichiometric Cummins ISL-G8.9 engine do not show any strong fuel trends for NMHC emissions; however, the results of this study somewhat agree with those obtained from older technology lean burn engines showing that NMHC emissions increased with decreasing methane number of the fuels (Karavalakis, G. et al. 2013).

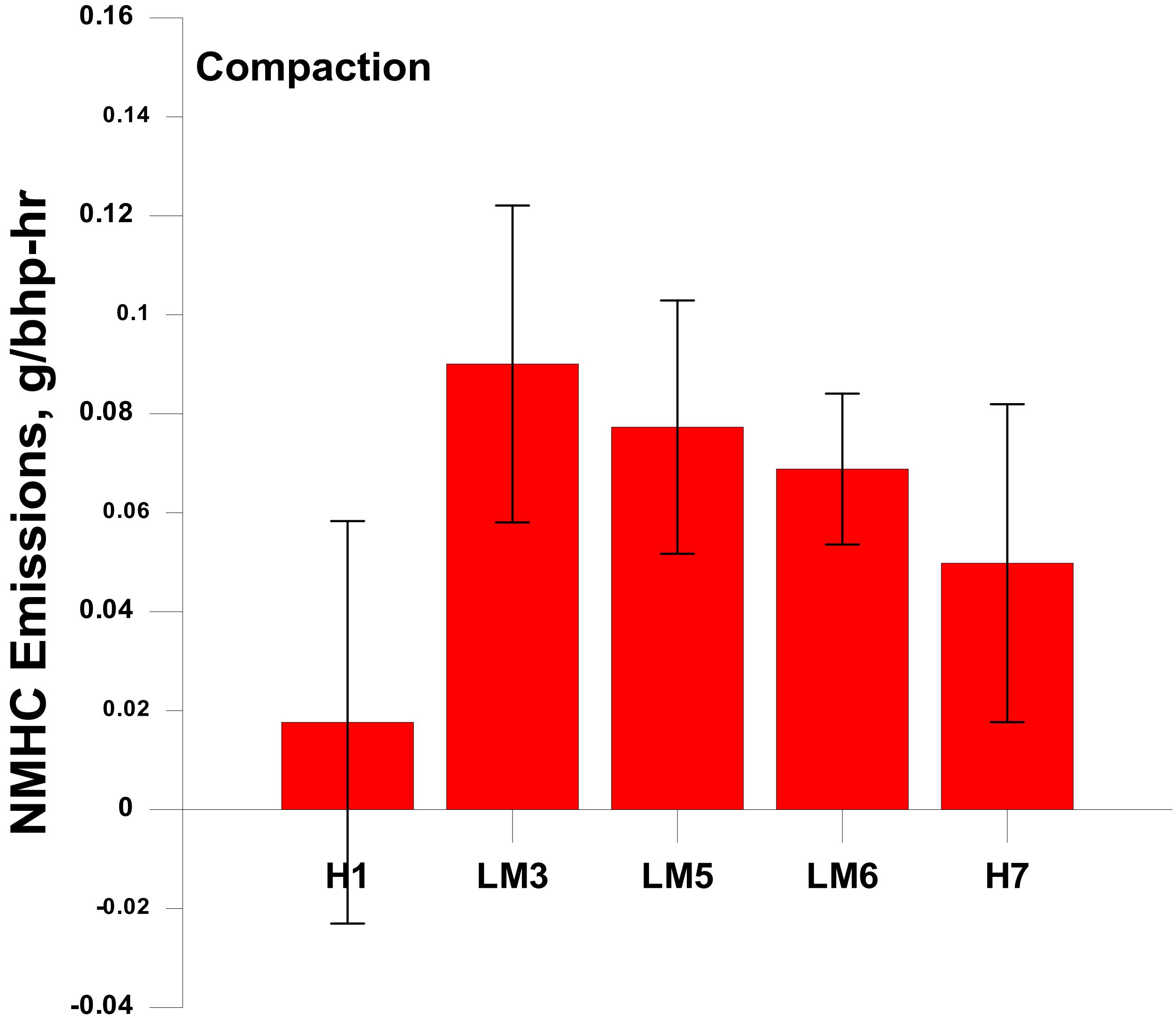
Figure 16 (a-b): Average NMHC Emissions for Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 17: Average NMHC Emissions for Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

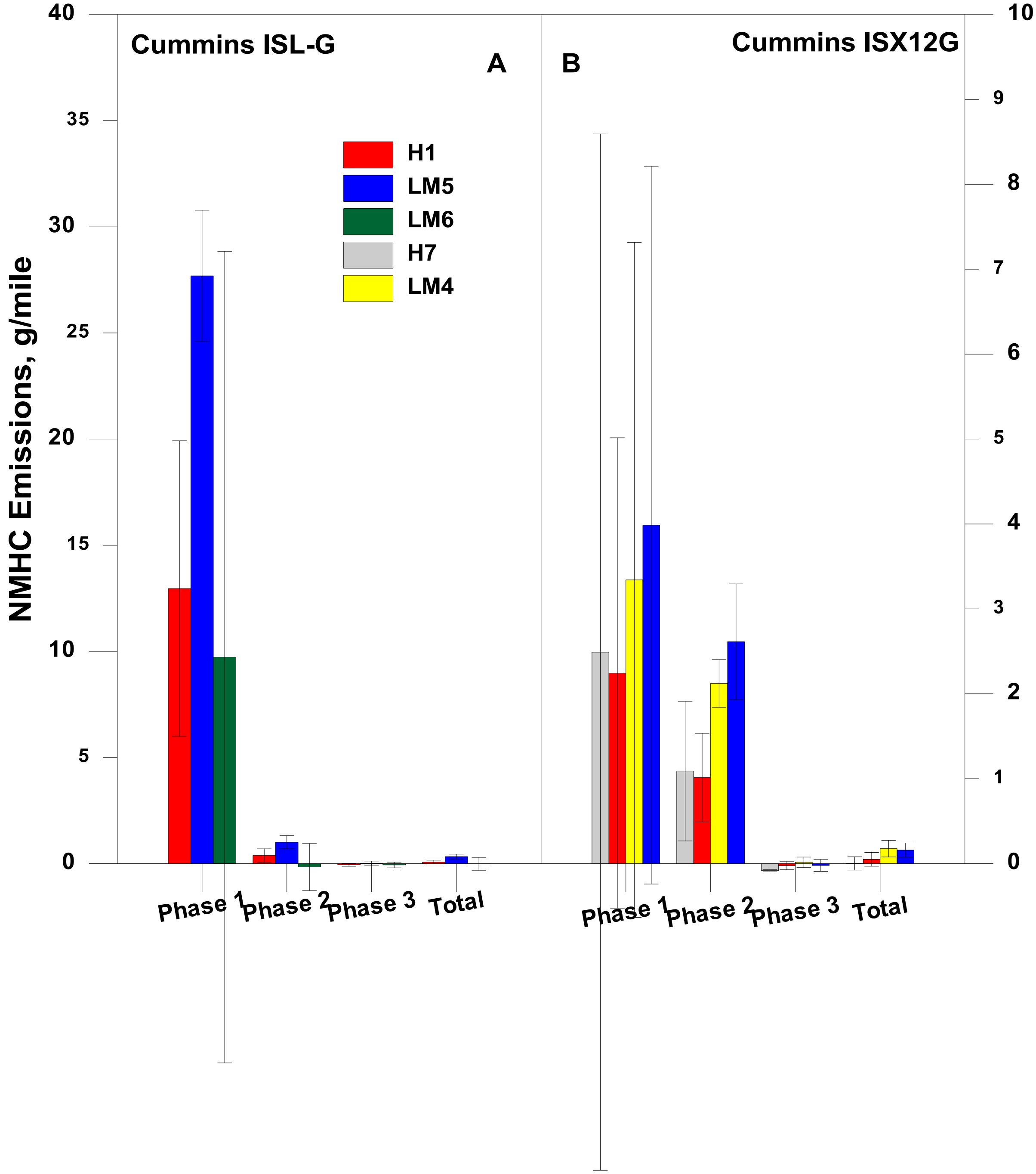
Source: CE-CERT

Figure 18 shows the NMHC emissions for the Cummins Westport ISL G (A) and Cummins Westport ISX12 G (B) trucks over the Near Dock duty cycle and the Local Haul duty cycle, respectively. The Cummins Westport ISL G truck showed higher NMHC emissions than the Cummins Westport ISX12 truck for the creep cycle. For both trucks NMHC emissions were below 5 g/mi for both the low speed and high speed transient cycles.

For the Cummins Westport ISL G truck, accumulated NMHC emissions show a statistically significant increase of 347 percent for LM5 compared to H1. Similar patterns are observed for the creep and low speed transient phases for NMHC emissions, with LM5 showing statistically significant increases of 113.7 percent and 165.7 percent, respectively, compared to H1. For the Cummins Westport ISX12 G truck, accumulated NMHC emissions show stronger trends for the low methane fuels, with LM4 and LM5 showing marginally statistically significant and statistically significant increases of 253.0 percent and 219.8 percent, respectively, compared to H1. Both LM4 and LM5 fuels show statistically significant increases in accumulated NMHC emissions compared to H7. For the low speed transient phase, NMHC emissions show statistically significant decreases of 22.9 percent and 21.5 percent, respectively, and 31.4 percent and 30.1 percent, respectively, for LM4 and LM5 compared to H1 and H7. For the long high-speed transient phase, NMHC emissions are found at very low concentrations, and close to background tunnel levels.

Overall, all test vehicles emit very low levels of NMHC emissions compared to THC emissions, with the NMHC emissions for the newer technology stoichiometric Cummins Westport trucks close to background levels. This observation is consistent with expectations and indicates that the THC emissions from these vehicles are predominantly methane with little NMHC. The lean-burn John Deere school bus shows trends of higher NMHC emissions for the fuels containing higher levels of NMHCs. Previous studies have also shown that NMHC emissions increase with decreasing methane number of the fuels (Fiest, M. et al. 2010, Min, B. et al. 2002). THC emissions from natural gas engines are predominantly unburned fuel; therefore, the nonmethane hydrocarbon fraction of THC exhaust emission typically trends with the percentage of nonmethane hydrocarbons in the test fuel.

Figure 18: NMHC Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



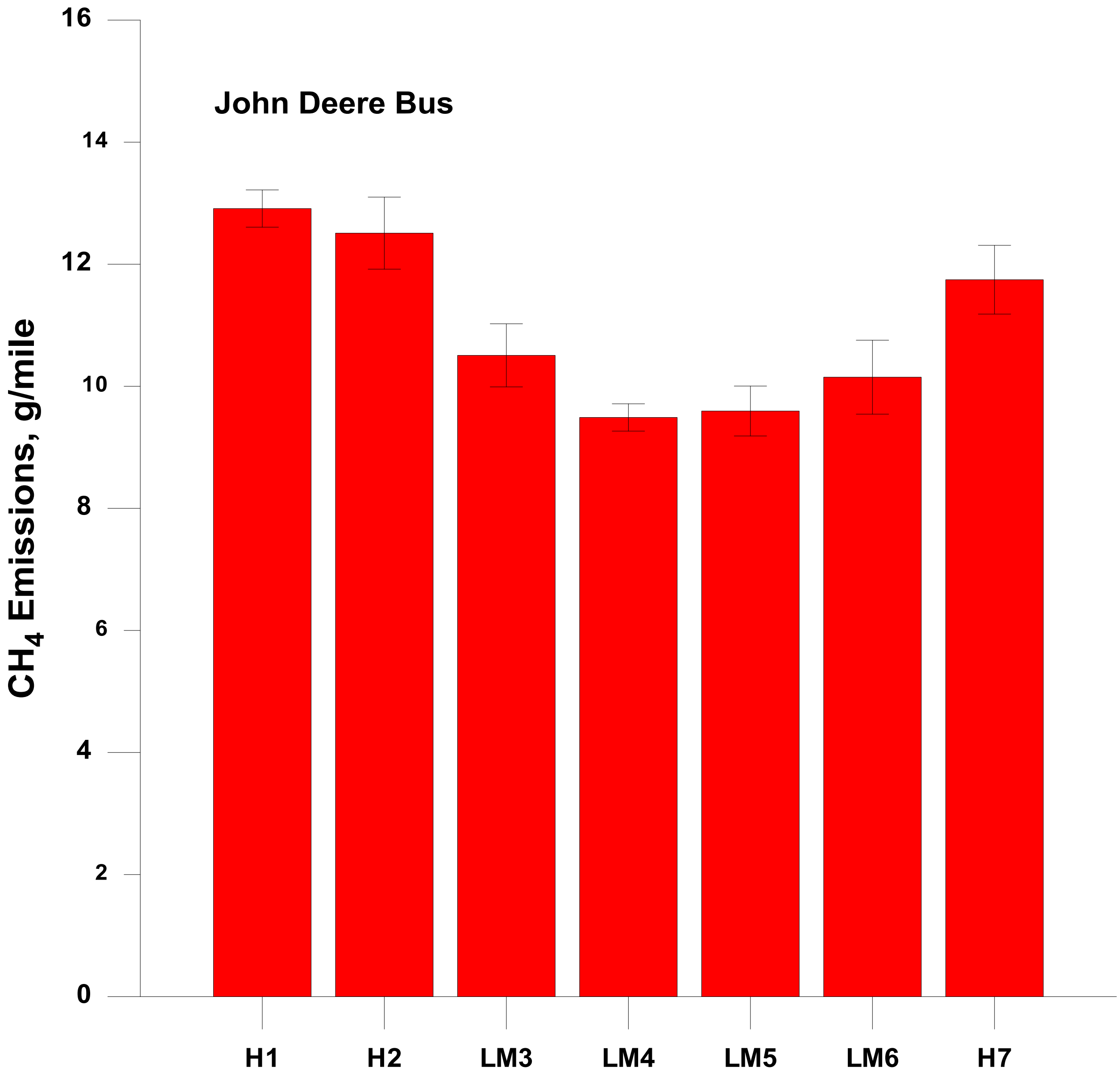
H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

3.4 Methane Emissions

Methane (CH_4) is a greenhouse gas with a global warming potential 25 times higher than carbon dioxide (CO_2) that is emitted directly from vehicles at the tailpipe as a result of combusting fuel. Figure 19 shows the CH_4 emissions for the John Deere school bus over the CBD test cycle. Analogous to THC emissions, CH_4 emissions show clear reductions for the fuels with higher Wobbe numbers and higher hydrocarbon contents. Emissions of CH_4 show statistically significant decreases of 18.6 percent, 26.5 percent, 25.7 percent, 21.4 percent, and 9.1 percent for LM3, LM4, LM5, LM6, and H7, respectively, compared to H1. Similar statistically significant reductions in CH_4 emissions are also seen when compared to H2, ranging from 6.1 percent to 24.1 percent, with the exception of H1. When compared to H7, statistically significant increases in CH_4 emissions are seen for H1 and H2, while statistically significant decreases are seen for the low methane fuels.

Figure 19: Average CH_4 Emissions for the John Deere Bus

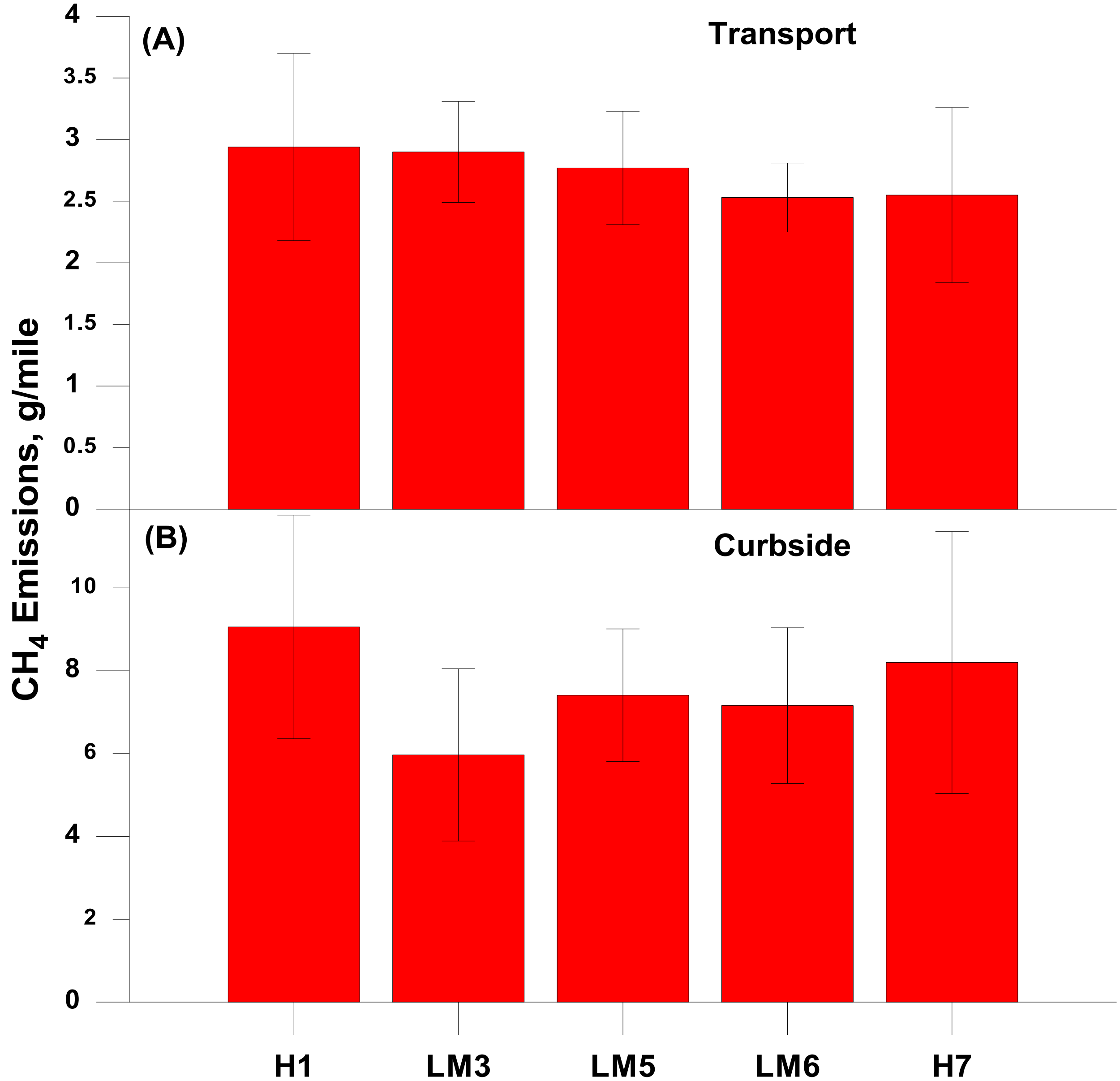


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 20 (a-b) shows the CH_4 emissions for the waste hauler for the transport and curbside segments, while Figure 21 shows the CH_4 emissions for the compaction segment on a bhp-hr basis. The CH_4 emissions are roughly comparable to the THC emissions, indicating that the THC emissions are predominantly CH_4. CH_4 emissions for the stoichiometric NG engines are significantly lower than typically found for older lean burn NG engines (Durbin, T. et al. 2014). Similar to THC emissions, there are no strong fuel trends for CH_4 emissions. CH_4 emissions do not show any statistically significant differences between fuels for the transport cycle. For the curbside cycle, the only statistically significant decrease is seen for LM3 (34 percent) compared to H1. Although there are no large fuel differences, there is a trend showing higher CH_4 emissions for the curbside cycle for H1 and H7, which are the two fuels with the higher levels of CH_4 in the test fuels. The compaction cycle did not show any statistically significant differences for CH_4 emissions.

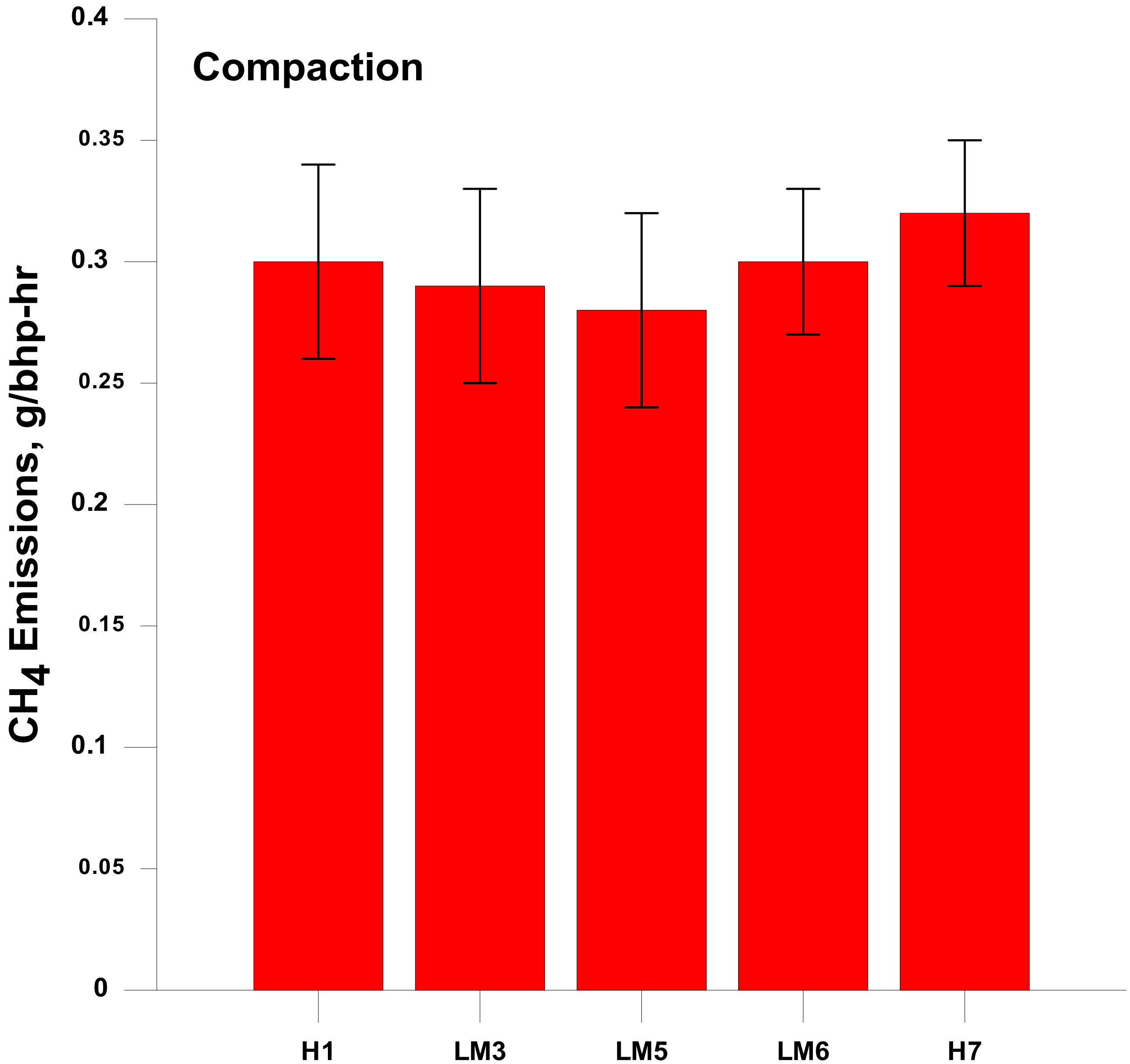
Figure 20 (a-b): Average CH_4 Emissions for Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 21: Average CH_4 Emissions for Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

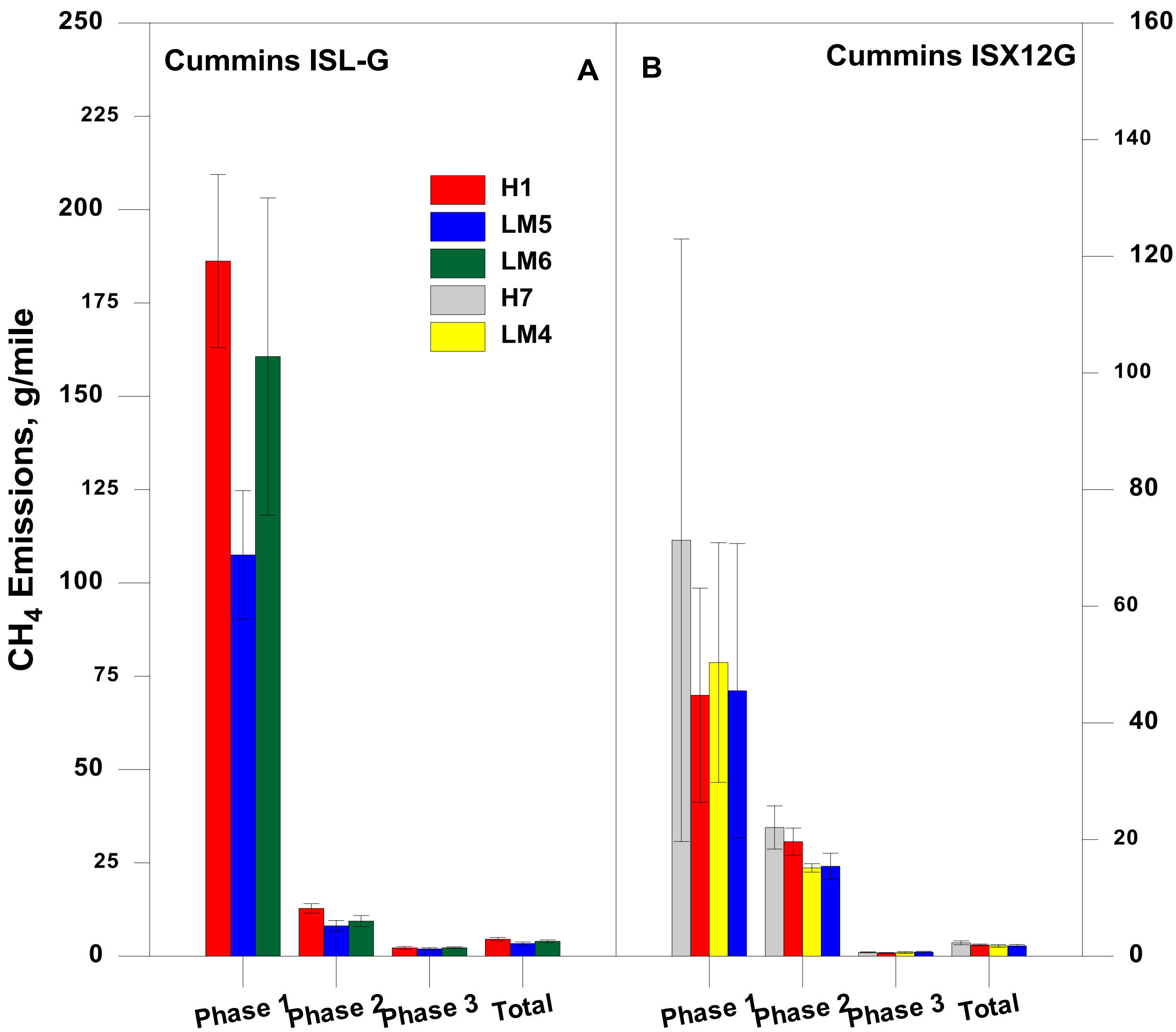
Source: CE-CERT

Figure 22 presents the CH_4 emissions for the Cummins Westport ISL G (A) truck and Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and the Local Haul duty cycle, respectively. The results show that the Cummins Westport ISL G truck CH_4 emissions were about two times higher than those for the Cummins Westport ISX12 G truck. For both trucks the highest CH_4 emissions were seen for the creep phase and the lowest CH_4 emissions were seen for the high speed phase.

For the Cummins Westport ISL G truck, the accumulated CH_4 emissions show statistically significant decreases of 25.6 percent and 12.4 percent for LM5 and LM6, respectively, compared to H1. For the creep phase, LM5 shows a statistically significant decrease in CH_4 emissions of 42.3 percent relative to H1, while for the low speed transient phase both LM5 and LM6 show statistically significant decreases of 36.5 percent and 26.5 percent, respectively, compared to H1.

For the Cummins Westport ISX12 G truck, the accumulated CH_4 emissions show a statistically significant increase of 19.2 percent for H7 compared to H1, while statistically significant reductions in accumulated CH_4 emissions of 16.1 percent, 23.1 percent, and 22.6 percent for H1, LM4, and LM5, respectively, compared to H7 were also observed. For the low speed transient phase, CH_4 emissions show statistically significant decreases of 22.9 percent and 21.5 percent, respectively, for LM4 and LM5 compared to H1 and of 31.4 percent and 30.1 percent, respectively, compared to H7. For the long high-speed transient phase, CH_4 emissions show a statistically significant increase of 31.5 percent for LM5 and a marginally statistically significant increase of 23.3 percent compared to H1.

Figure 22: CH_4 Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



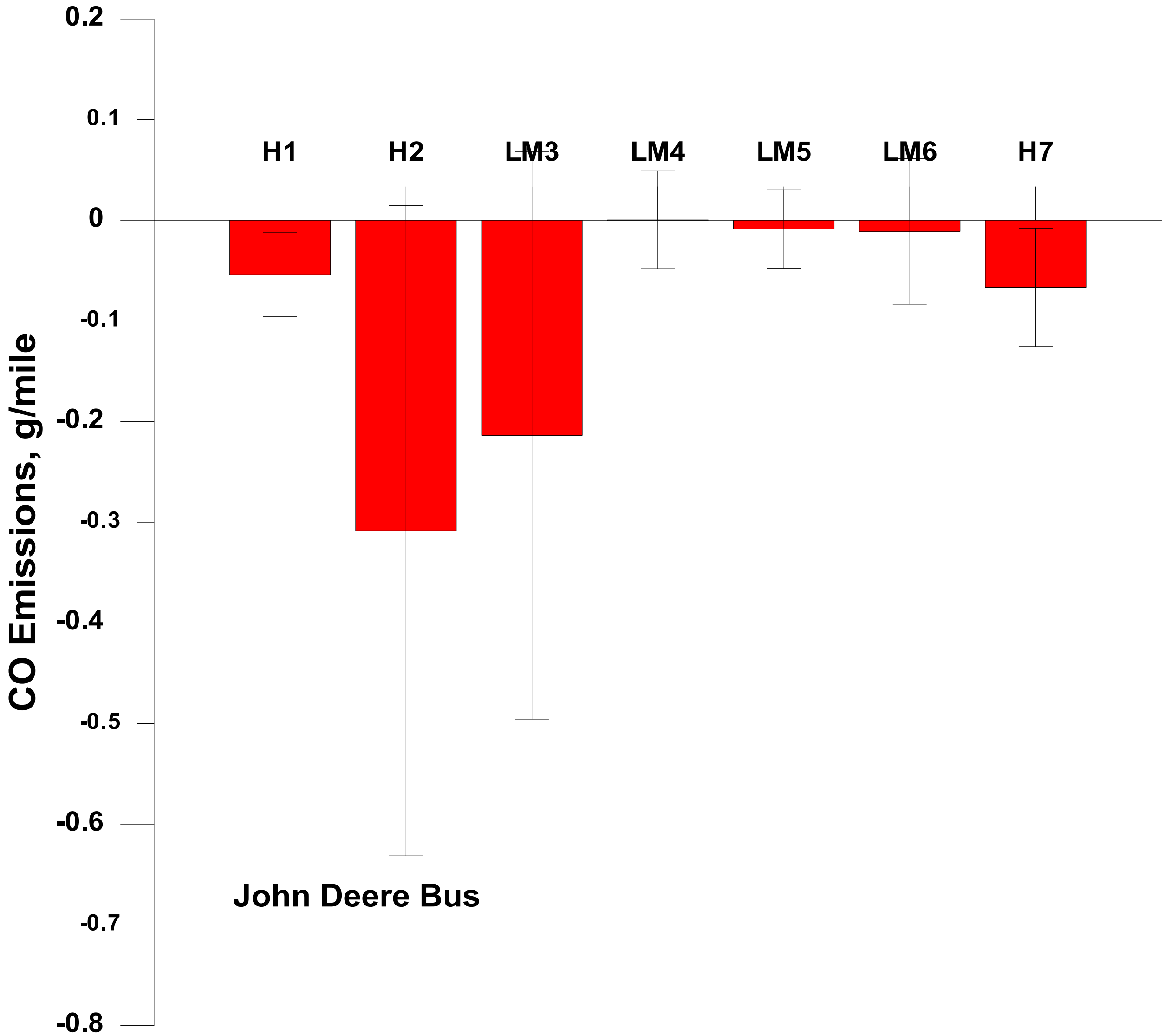
H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

3.5 Carbon Monoxide Emissions

Figure 23 shows CO emissions for the John Deere school bus over the CBD cycle. The CO emissions for the John Deere school bus were at very low levels, close to the measurement background. For the CO emissions, there are no strong effects between the test fuels.

Figure 23: Average CO Emissions for the John Deere Bus



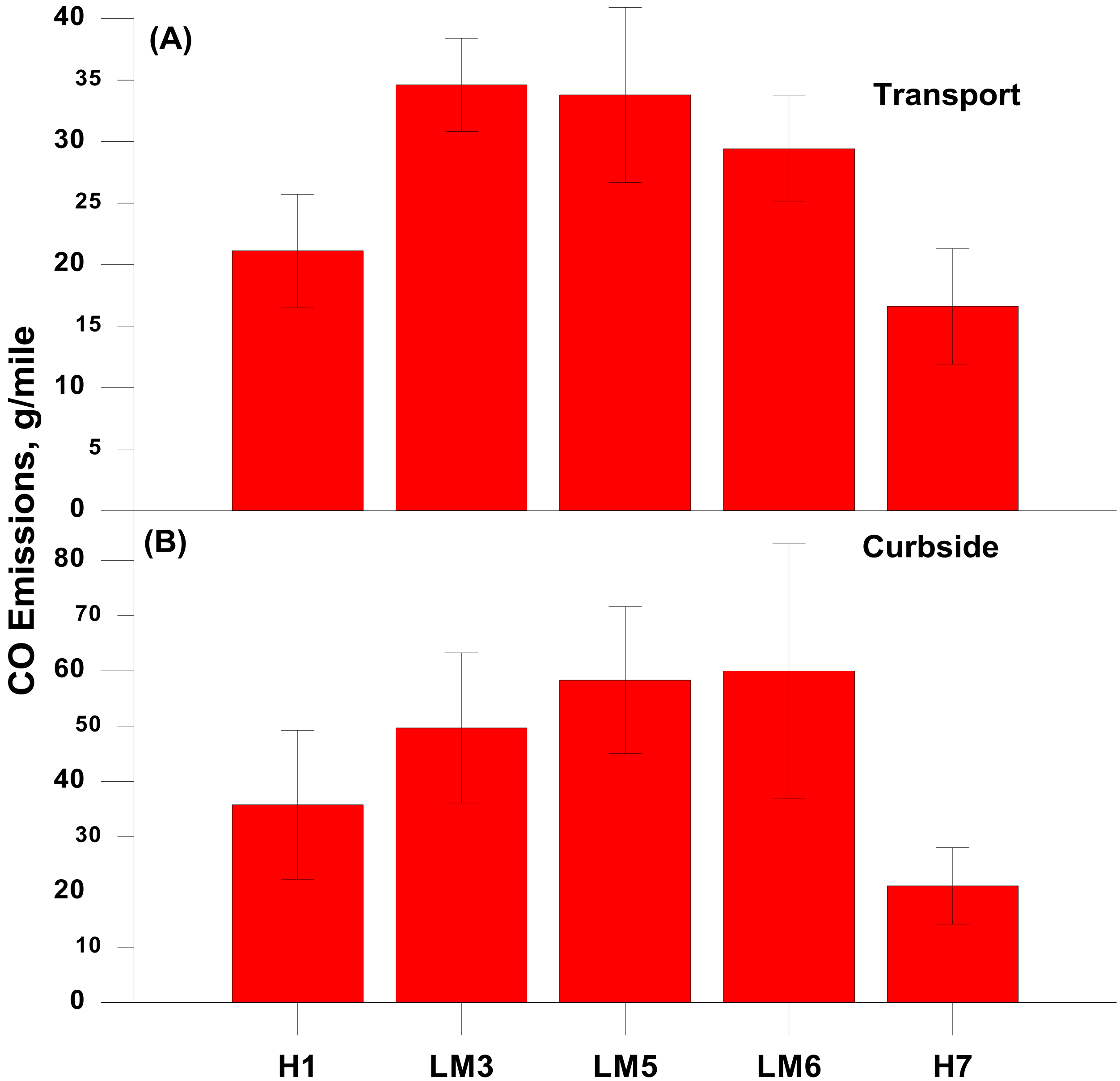
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 24 (a-b) shows the CO emissions for the waste hauler for the transport and curbside segments, while Figure 25 shows the CO emissions for the compaction segment on a bhp-hr basis. The CO emissions for the stoichiometric Cummins Westport ISL-G engine are higher when compared to older lean-burn engines during combustion and across the catalyst. This observation has been seen in other chassis dynamometer test studies on older lean-burn engines (Durbin, T. et al. 2014, Yoon, S. et al. 2012). In these studies, the Cummins Westport ISL-G showed higher CO emissions compared to older lean burn engines. The impact of richer operating conditions for the stoichiometric combustion compared to lean burn combustion caused increased CO emissions. Specifically, richer combustion will lead to both increased engine-out CO as well as a reduction in the efficiency of removing CO over the catalyst.

CO emissions show a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. For the transport and curbside cycles, the increases in CO emissions LM3, LM5, and LM6 are statistically significant compared to both H1 and H7, with the comparison between H1 and LM3 being marginally statistically significant. For the compaction cycle, CO emission levels show marginally statistically significant increases for LM3, LM5, and LM6 compared to H1. Compared to H7, LM3 and LM6 also show higher CO emissions at a marginally statistically significant level. The higher CO emissions could be due to slightly richer combustion for the low methane fuels (Feist, M. 2006, 2009), which could make oxidation of the CO slightly more difficult either during combustion or over the catalyst.

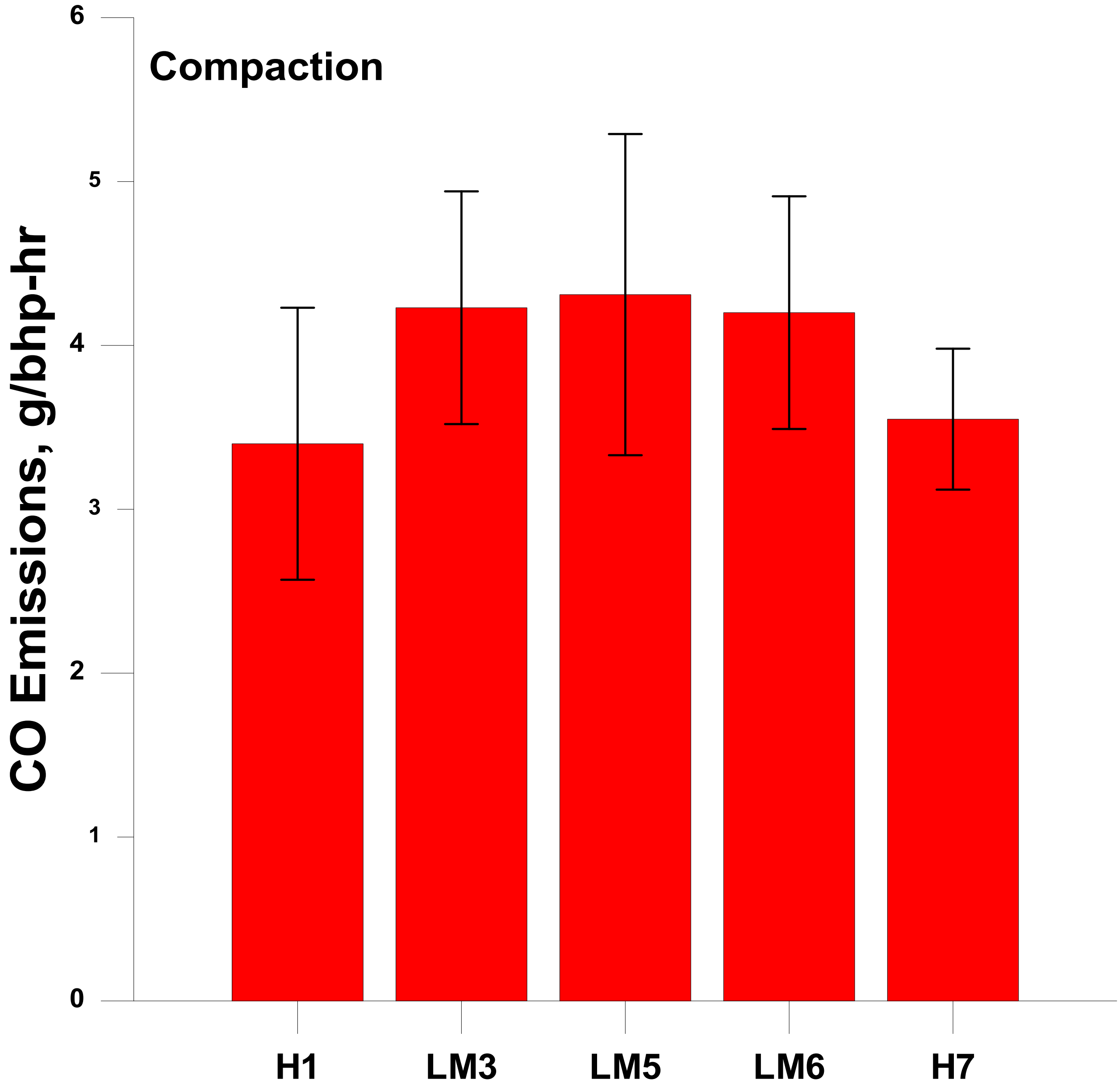
Figure 24 (a-b): Average CO Emissions for Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 25: Average CO Emissions for Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

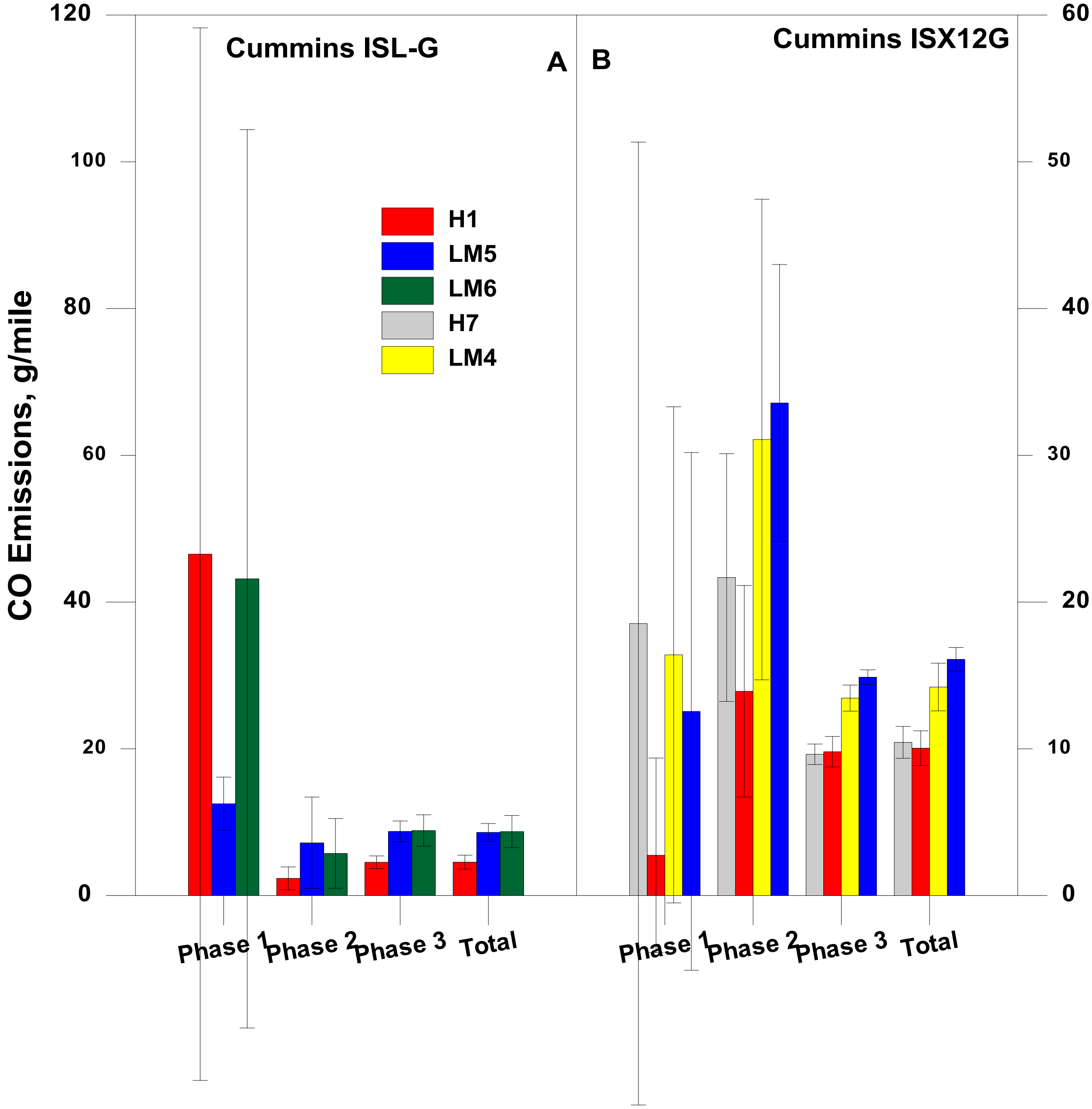
Source: CE-CERT

Figure 26 shows the CO emissions for the Cummins Westport ISL G (A) truck and the Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and the Local Haul duty cycle, respectively. CO emission results from the Cummins engines are significantly higher than from the lean-burn John Deere engine. The impact of richer combustion for the stoichiometric Cummins Westport engines compared to the lean-burn John Deere engine during combustion and across the catalyst caused the higher CO emissions. This observation is consistent with the results of previous chassis dynamometer tests as well as a recent engine dynamometer study that evaluated Cummins Westport ISL, C-Gas Plus, C-Gas, and John Deere engines (Feist, M. 2009, Einewall, P. et al. 2005, Feist,M. et al. 2010, Yoon, S. et al. 2012). In these studies, the Cummins Westport ISL G also shows the highest CO emissions compared to the other engines. The CO emissions for the Cummins Westport ISL G truck and the Cummins Westport ISX12 truck were roughly comparable over the Near Dock and Local Haul Duty cycles.

For the Cummins Westport ISL G truck, the accumulated CO emissions show statistically significant increases of 111.1 percent and 140.8 percent, respectively for LM5 and LM6 compared to H1. For the low speed transient phase, CO emissions show marginally statistically significant increases of 377.7 percent and 285.1 percent, respectively, for LM5 and LM6 compared to H1. For the short high-speed transient phase, CO emissions show statistically significant increases of 112.5 percent and 143.7 percent for LM5 and LM6, respectively, compared to H1.

For the Cummins Westport ISX12 G truck, the accumulated CO emissions show statistically significant increases of 41.5 percent and 60.3 percent, respectively, for the LM4 and LM5 low methane fuels compared to H1 and of 36.1 percent and 54.2 percent, respectively, compared to H7. For the creep phase, although the measurement variability is very large, CO emissions do show a marginally statistically significant increase of 497 percent for LM4 compared to H1. For the low speed transient phase, CO emissions show statistically significant increases of 123.2 percent and 141.1 percent, respectively, for LM4 and LM5 compared to H1 and of 54.9 percent for LM5 compared to H7. For the long high-speed transient phase, CO emissions show statistically significant increases for LM4 and LM5 of 37.3 percent and 51.8 percent, respectively, compared to H1 and of 39.8 percent and 54.6 percent, respectively, compared to H7.

Figure 26: CO Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

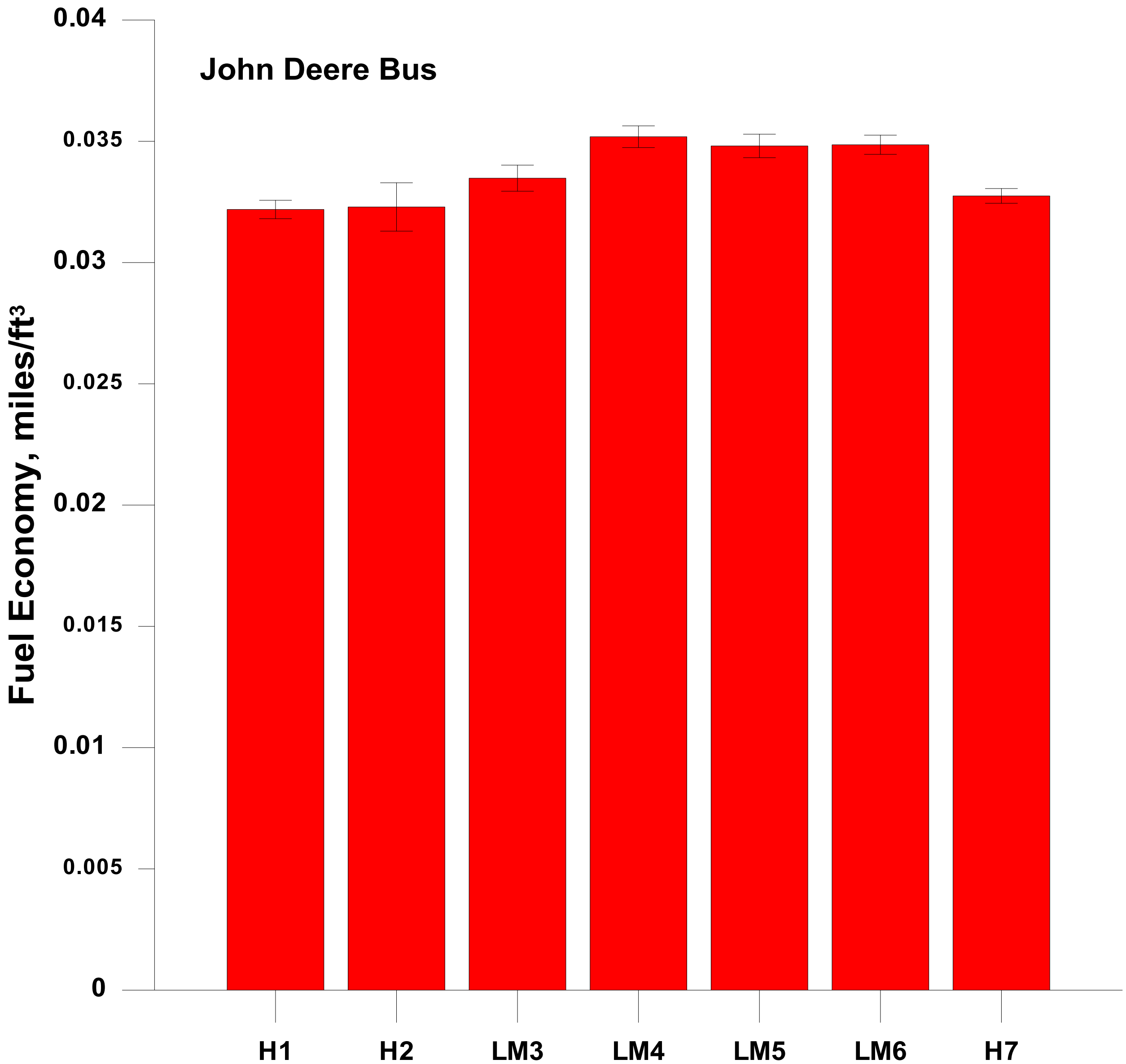
Source: CE-CERT

3.6 Fuel Economy and Carbon Dioxide Emissions

Figure 27 shows the average volumetric fuel economy in miles/ft^3 for the John Deere school bus over the CBD cycle. The formulas used to calculate the volumetric fuel economy and the energy equivalent fuel economy are provided in Appendix C. Fuel economy is 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 calculate how much fuel and fuel carbon the engine uses during operation. As shown in Figure 27, the differences between the various test fuel economies are readily apparent, and in many cases statistically significant, as discussed below.

The low methane fuels with the higher heating values, i.e., LM3, LM4, LM5, and LM6, show higher fuel economy compared to H1, H2, and H7. The fuel economy increases for LM3, LM4, LM5, and LM6 compared to H1 are all statistically significant for the school bus over the CBD cycle, and were on the order of 4 percent, 9.3 percent, 8.1 percent, and 8.3 percent, respectively, relative to H1, with H7 also showing a 1.7 percent increase in fuel economy at a statistically significant level. The same trend also occurs for the low methane fuels when compared to H2, with the increases being statistically significant and on the order of 3.7 percent to 9 percent. Compared to H7, all test fuels show statistically significant differences in fuel economy with the exception of H2. The low methane fuels show increases ranging from 2.2 percent to 7.5 percent, while H1 decreases by 1.7 percent.

Figure 27: Average Volumetric Fuel Economy for the John Deere Bus

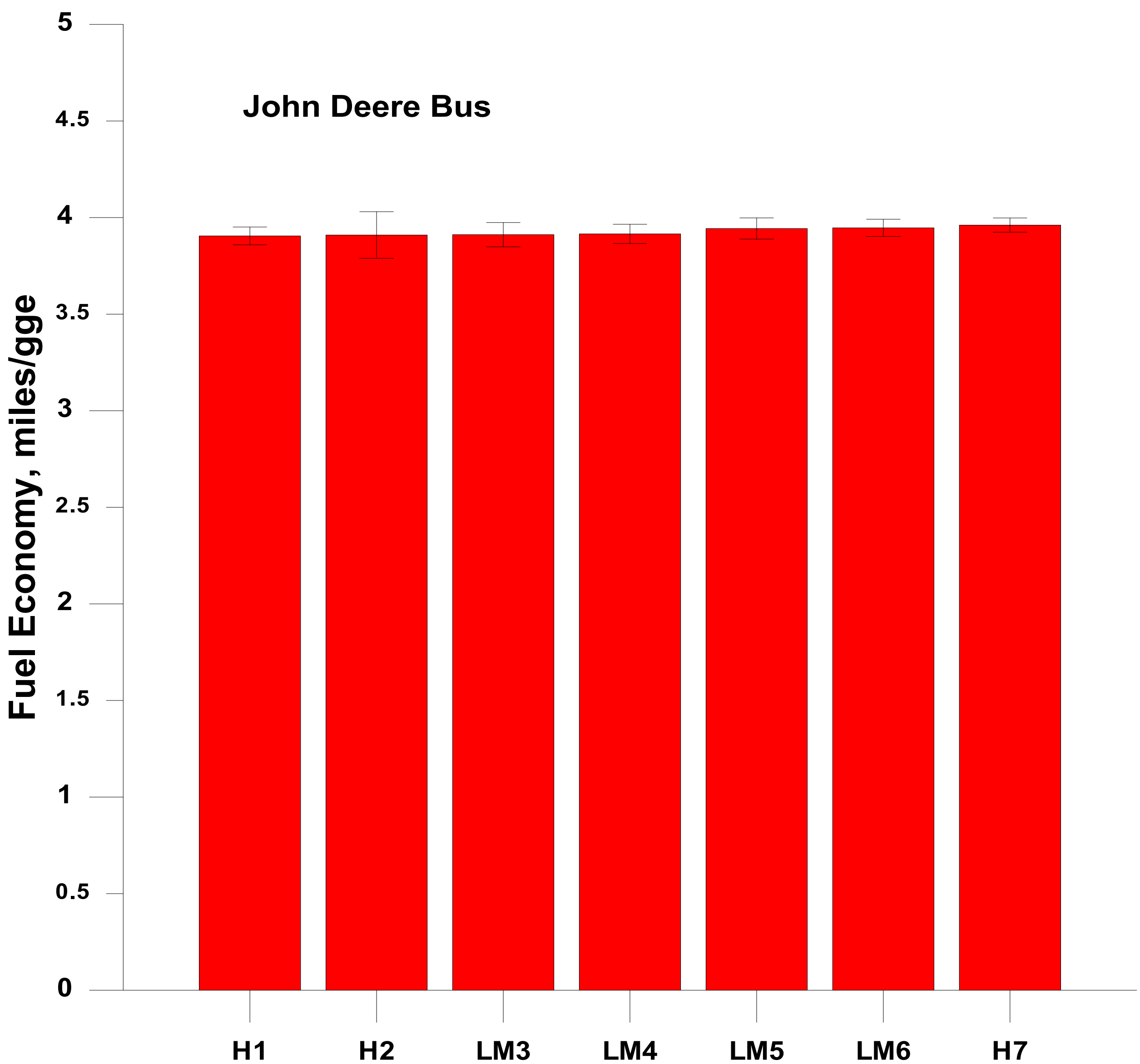


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

In using an energy equivalent basis for fuel economy, the energy differences between the fuels are normalized. The normalized fuels eliminated the energy differences between fuels to provide a more accurate fuel economy evaluation. Figure 28 presents the fuel economy results for the John Deere school bus using the different fuel blends over the CBD test cycle on a gasoline gallon equivalent (GGE) energy basis. The John Deere bus shows comparable fuel economy results between fuels on an energy equivalent basis. Fuel economy does not show significant fuel effects with the exception of H7, which shows a statistically significant increase of 1.4 percent compared to H1.

Figure 28: Average Energy Equivalent Fuel Economy for the John Deere Bus

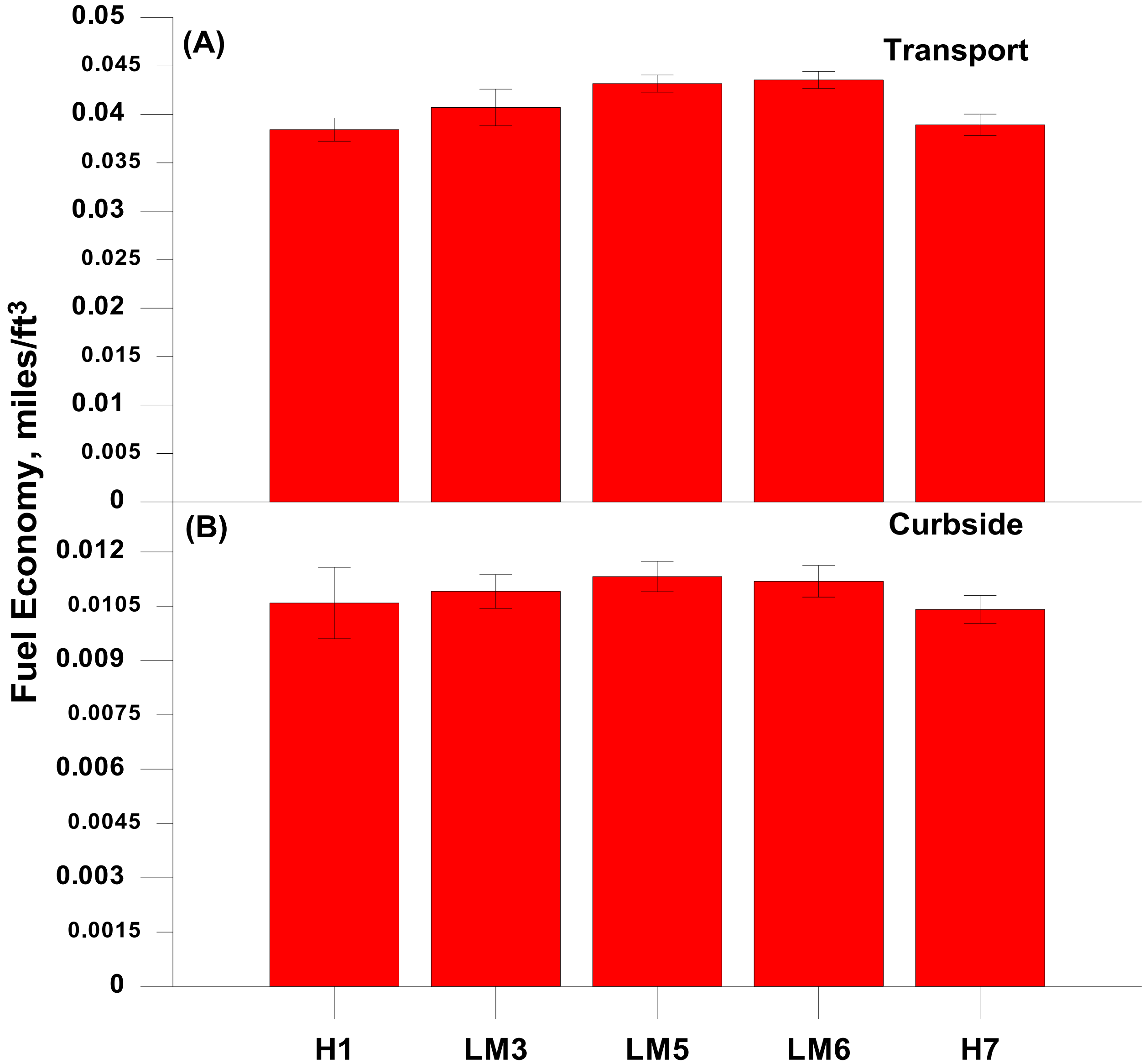


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 29 (a-b) shows the average volumetric fuel economy, respectively, in miles/ft^3 for the waste hauler truck (the transport and curbside segments). Figure 30 shows the volumetric fuel consumption for the waste hauler on a ft^3/bhp-hr basis. The formulas used to calculate the volumetric and energy equivalent fuel economies, as discussed below, are provided in Appendix C. Fuel economy was determined using the carbon balance method. Figure 29 (a-b) and Figure 30 show that various test fuels have differences in fuel economies when fuel economy and consumption are plotted on a volumetric basis. For the transport cycle, statistically significant differences are seen with higher fuel economy for LM3, LM5, and LM6 compared to H1, while LM5 and LM6 show statistically significant and LM3 show marginally statistically significant higher fuel economy compared to H7. The average fuel consumptions for fuels LM3, LM5, and LM6 compared to H1 and H7 are also lower at a statistically significant level for the compaction cycle. These trends are consistent with the fuels with the higher energy content providing higher fuel economy and lower fuel consumption. For the curbside cycle, the only marginally statistically significant and statistically significant differences in fuel economy are higher fuel economy for LM3, LM5 and LM6 compared to H7. The same trends are seen for the legacy waste hauler tested in Phase 1. For this vehicle, the low methane fuels show higher volumetric fuel economy compared to H1, H2, and H7 over the transport and curbside phases of the RTC, while the volumetric fuel consumption is lower for the low methane fuels, consistent with the high energy contents of these fuels (Durbin, T. et al. 2014).

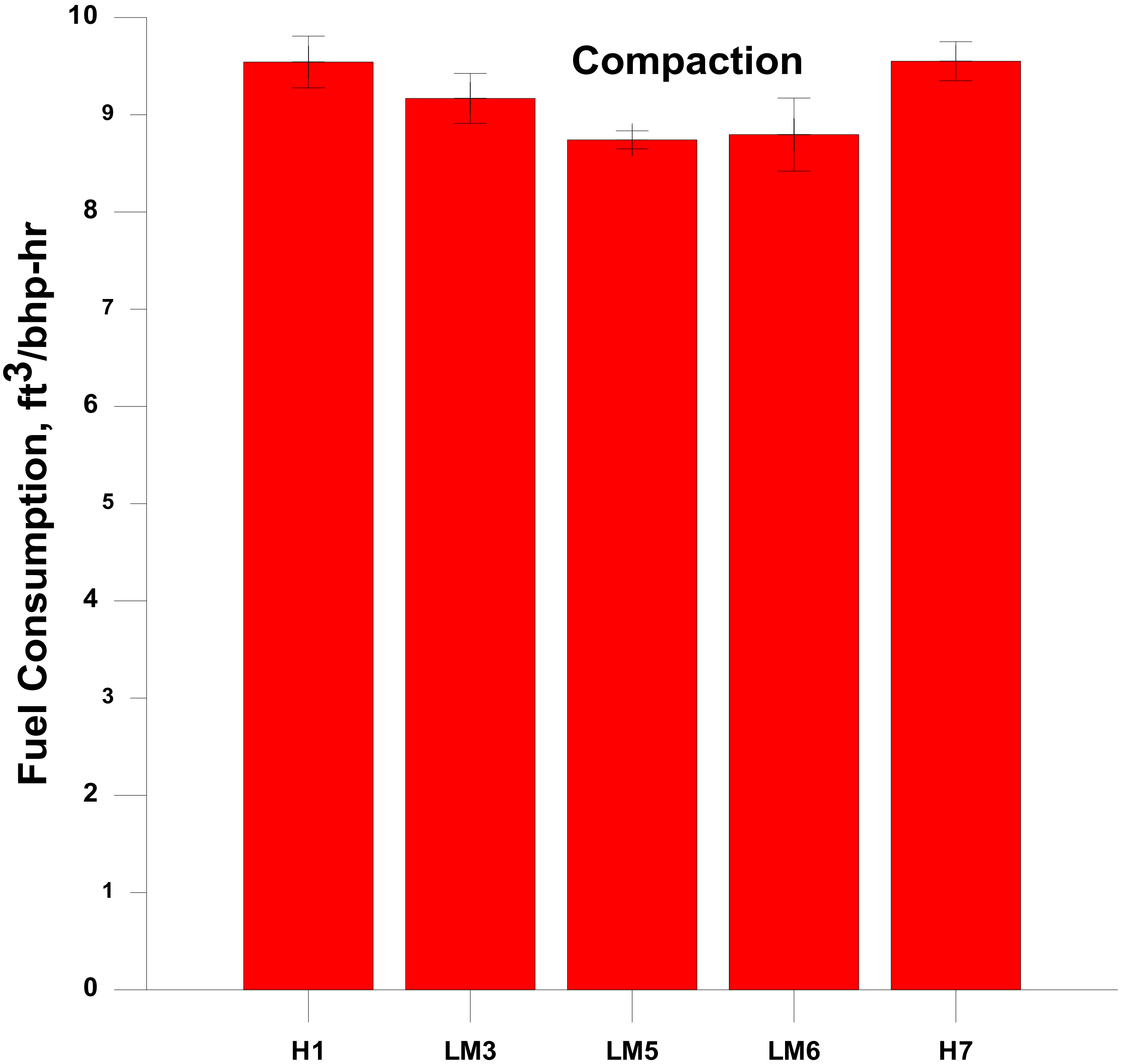
Figure 29 (a-b): Average Volumetric Fuel Economy for the Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 30: Average Volumetric Fuel Consumption for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis

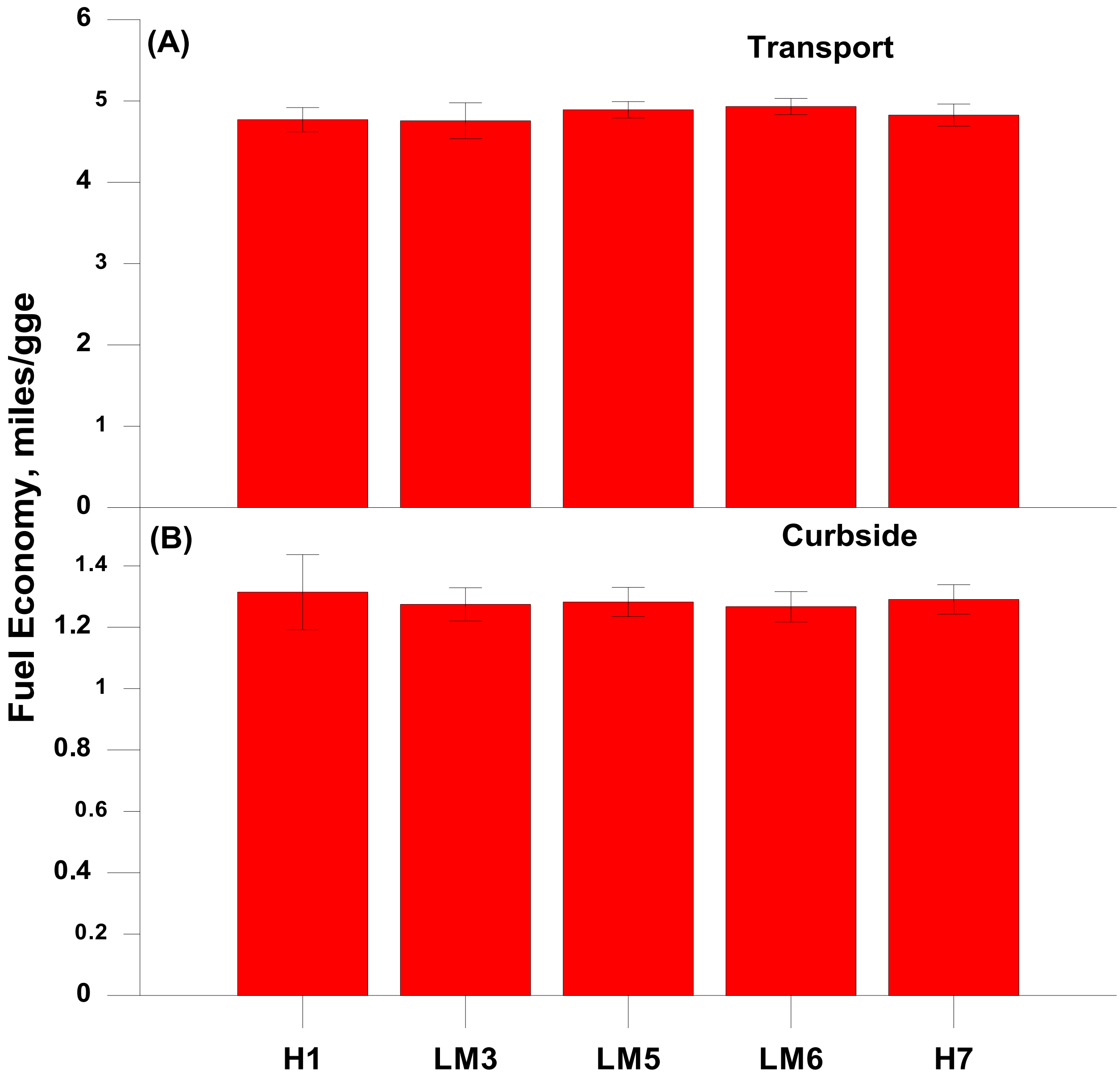


H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Fuel economy on an energy equivalent basis is shown in Figure 31 (a-b) on a gasoline gallon equivalent (GGE) energy basis for the waste hauler for the transport and curbside segments. For the waste hauler, fuel consumption is shown in Figure 32 on a gasoline gallon equivalent energy basis for the compaction segment on a bhp-hr basis. The waste hauler does not show any statistically significant trends in fuel economy or fuel consumption on an energy equivalent basis, with the exception of LM6, which shows a statistically significant increase in fuel consumption relative to H1 for the transport phase. The Phase 1 testing on the legacy waste hauler shows stronger trends in fuel economy on an energy equivalent basis over the RTC (Durbin, T. et al. 2014), with the low methane fuels with higher energy contents showing higher energy equivalent fuel economy/lower fuel consumption compared to the high methane fuels.

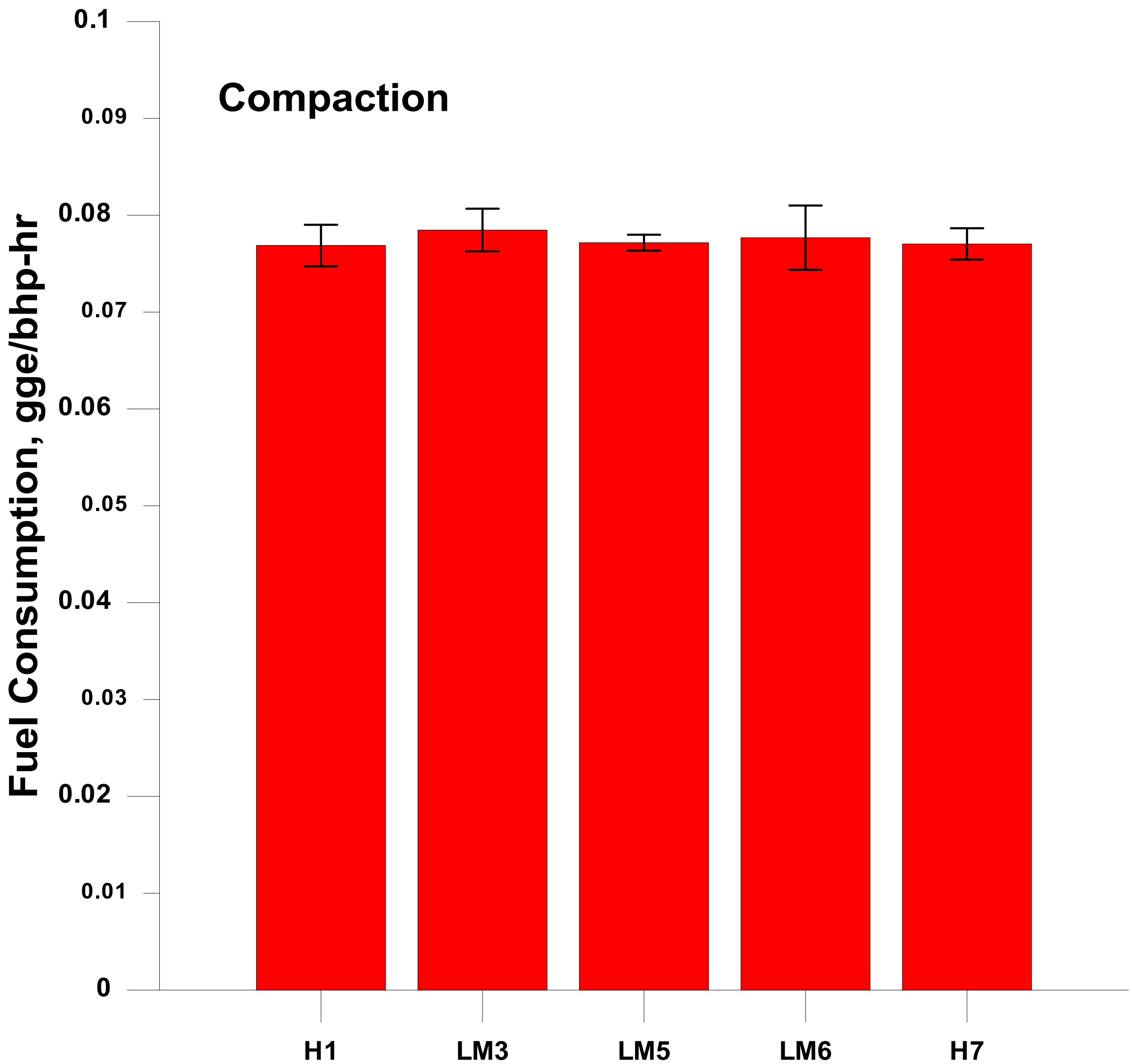
Figure 31 (a-b): Average Energy Equivalent Fuel Economy for the Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 32: Average Energy Equivalent Fuel Consumption for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis



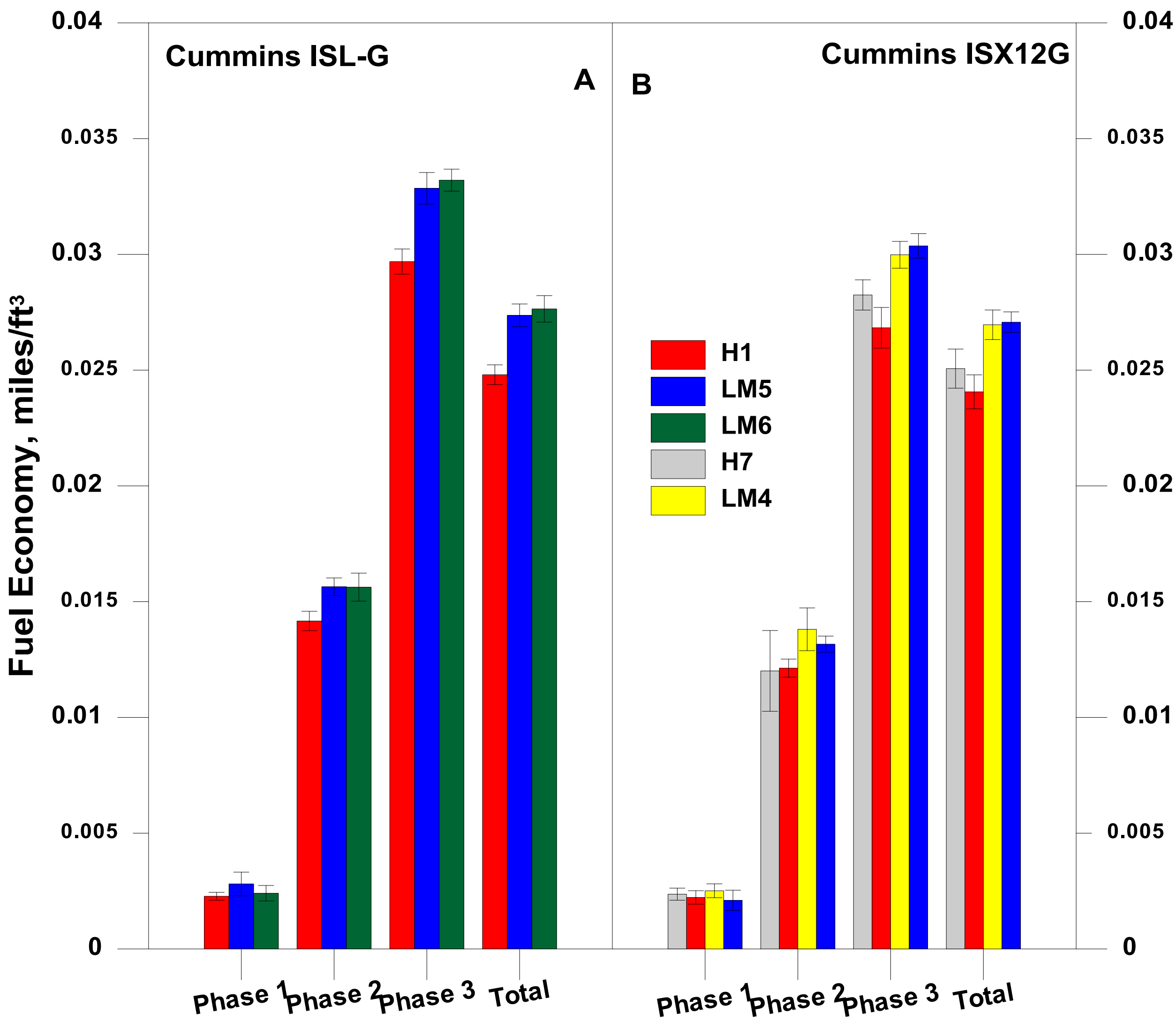
H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Volumetric fuel economy in miles/ft^3 for the Cummins Westport ISL G (A) truck and Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and Local Haul duty cycle, respectively, is shown in Figure 33. The volumetric fuel economy for these two trucks was roughly comparable over the Near Dock and Local Haul Duty Cycles. The highest volumetric fuel economy was found for the high speed transient phase and the lowest volumetric fuel economy was observed for the creep phase.

For the Cummins Westport ISL G truck, the accumulated average volumetric fuel economy shows statistically significant increases of 10.4 percent and 11.5 percent, respectively, for LM5 and LM6 compared to H1. For the creep phase, fuel economy shows a statistically significant increase of 23.4 percent for LM5 compared to H1, while for the low speed transient phase both LM5 and LM6 are higher on the order of 10.5 percent and 10.3 percent, respectively, compared to H1 at a statistically significant level. For the short high-speed transient phase, the LM5 and LM6 low methane fuels show statistically significant increases in fuel economy of 10.7 percent and 11.9 percent, respectively, compared to H1. For the Cummins Westport ISX12 G truck, the accumulated fuel economy shows statistically significant increases of about 12 percent for both LM4 and LM5 and a marginally statistically significant increase of 4.2 percent for H7 compared to H1. For the low speed transient phase, fuel economy shows statistically significant increases of 13.8 percent and 8.5 percent, respectively for LM4 and LM5 compared to H1. For the long high-speed transient phase, fuel economy shows statistically significant increases of 11.7 percent, 13.2 percent, and 5.3 percent for LM4, LM5, and H7, respectively, compared to H1. Compared to H7, all test fuels show statistically significant differences in fuel economy. Compared to H7, LM4 and LM5 show statistically significant increases of 6.1 percent and 7.5 percent, respectively, while H1 shows a statistically significant decrease of 5 percent.

Figure 33: Volumetric Fuel Economy for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases

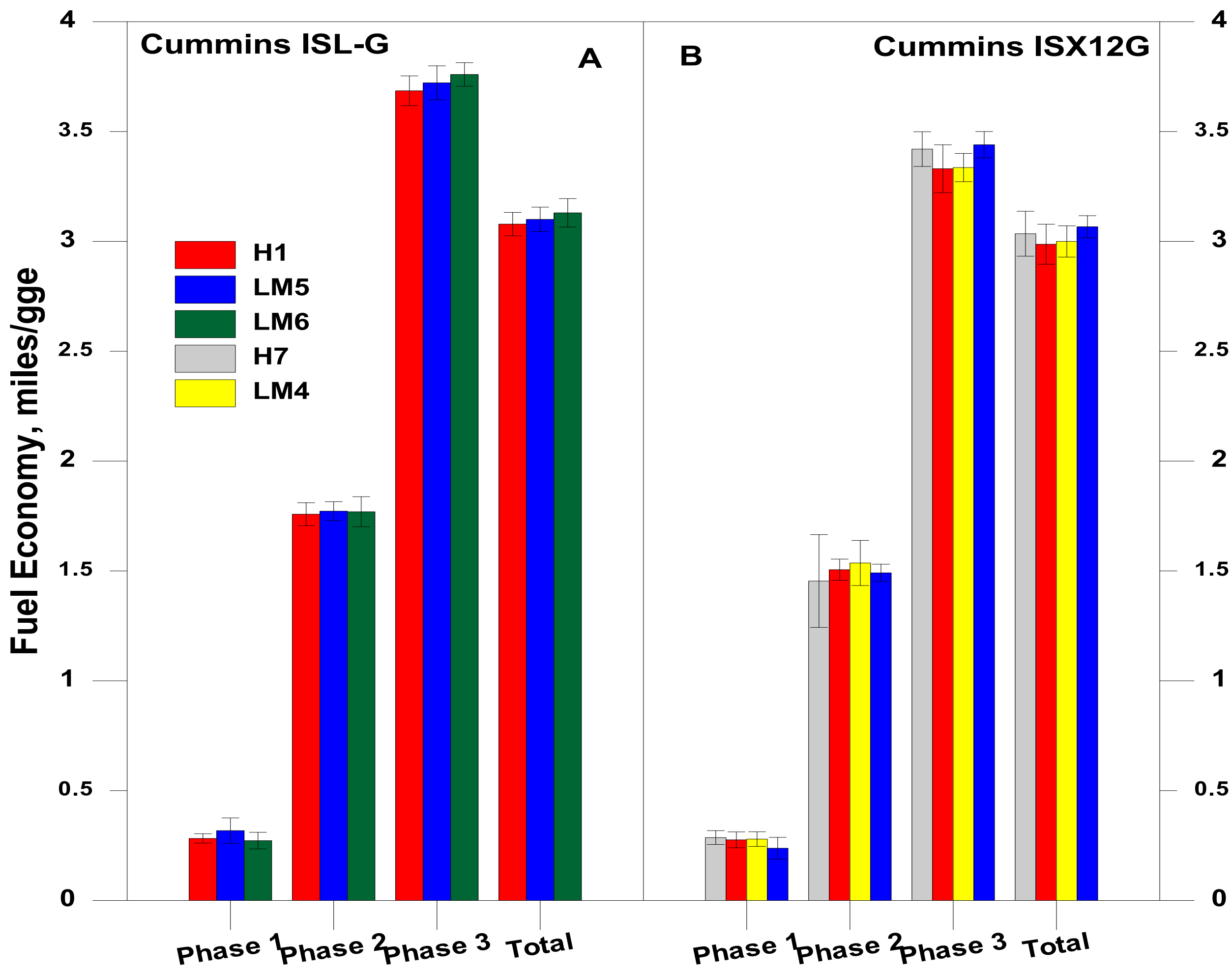


H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

Figure 34 shows the fuel economy results for the Cummins Westport trucks on an energy equivalent basis. Fuel economy on a gasoline gallon equivalent (GGE) energy basis do not show any strong trends between the test fuels for the Cummins Westport ISL G truck over the Near Dock duty cycle and its individual phases. The energy-equivalent fuel economy for these two trucks was roughly comparable over the Near Dock and Local Haul Duty Cycles. The highest energy-equivalent fuel economy was found for the high-speed transient phase and the lowest energy equivalent fuel economy was observed for the creep phase. The only statistically significant effect is seen for the LM6 low methane fuel, which shows an increase of 2 percent compared to H1 at a marginally statistically significant level during the short high-speed transient phase. For the Cummins Westport ISX12 G truck, accumulated fuel economy on an energy equivalent basis shows a marginally statistically significant increase of 2.7 percent for LM5 compared to H1. For the long high-speed transient phase, LM5 also shows a marginally statistically significant increase of 3.3 percent compared to H1. Overall, for both Cummins Westport trucks, the low methane fuels with higher energy contents exhibit higher energy-equivalent fuel economy compared to the H1.

Figure 34: Energy Equivalent Fuel Consumption for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

For the John Deere school bus, CO_2 emissions over the CBD cycle are shown in Figure 35. The CO_2 emissions do not show strong trends between the test fuels over the CBD cycle, with the exception of H7, which shows a statistically significant decrease of 2.3 percent in CO_2 emissions compared to H1. Compared to H7, most test fuels show statistically significant increases in CO_2 emissions ranging from 2.3 percent to 3.5 percent, with the exception of H2.

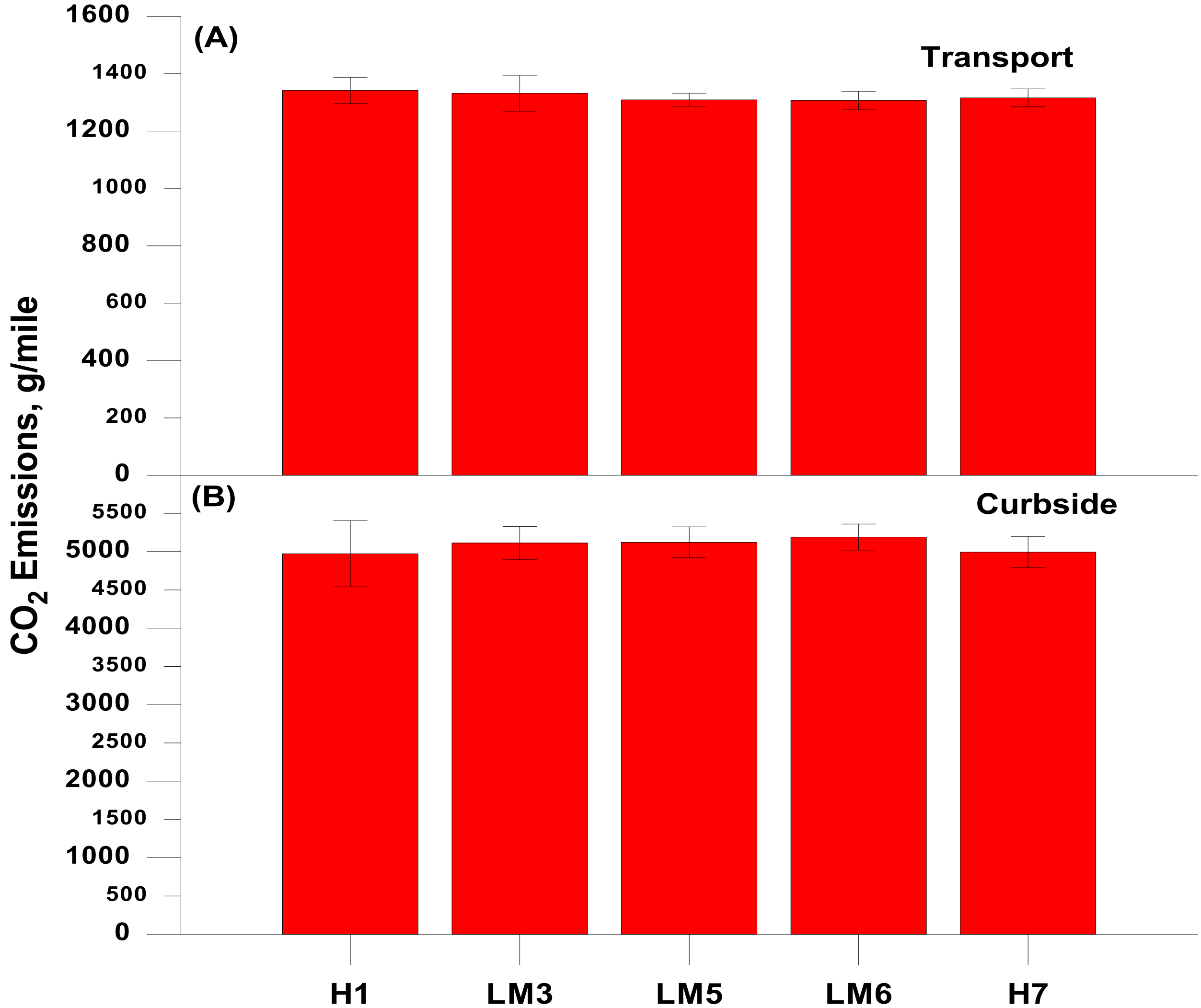
Figure 35: Average CO_2 Emissions for the John Deere Bus

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)

Source: CE-CERT

CO_2 emissions for the waste hauler are shown in Figure 36 (a-b) for the transport and curbside segments. For the curbside segment, CO_2 emissions are higher than those for the transport segment on a per mile basis. No statistically significant fuel effects are found for either the transport or curbside cycles. CO_2 emissions for the waste hauler are shown in Figure 37 for the compaction segment on a bhp-hr basis. For the compaction segment, there is a statistically significant reduction for H7 compared to LM3, LM5, and a marginally statistically significant reduction compared to LM6. H7 does have a higher hydrogen to carbon (H/C) ratio than LM3, LM5, and LM6, so the reduction in CO_2 emissions is consistent with a lower carbon fraction in the fuel, although the H/C is similar to that for H1, which does not show any significant fuel trends. The results for this waste hauler are similar to those for the legacy waste hauler for the compaction phase, with CO_2 emissions being higher for the low methane fuels compared to H1, H2, and H7 (Durbin, T. et al. 2014). The legacy vehicle shows stronger reduction trends in CO_2 emissions for the transport cycle, showing some statistically significant reductions for the low methane fuels compared to H1 and H2, but not H7.

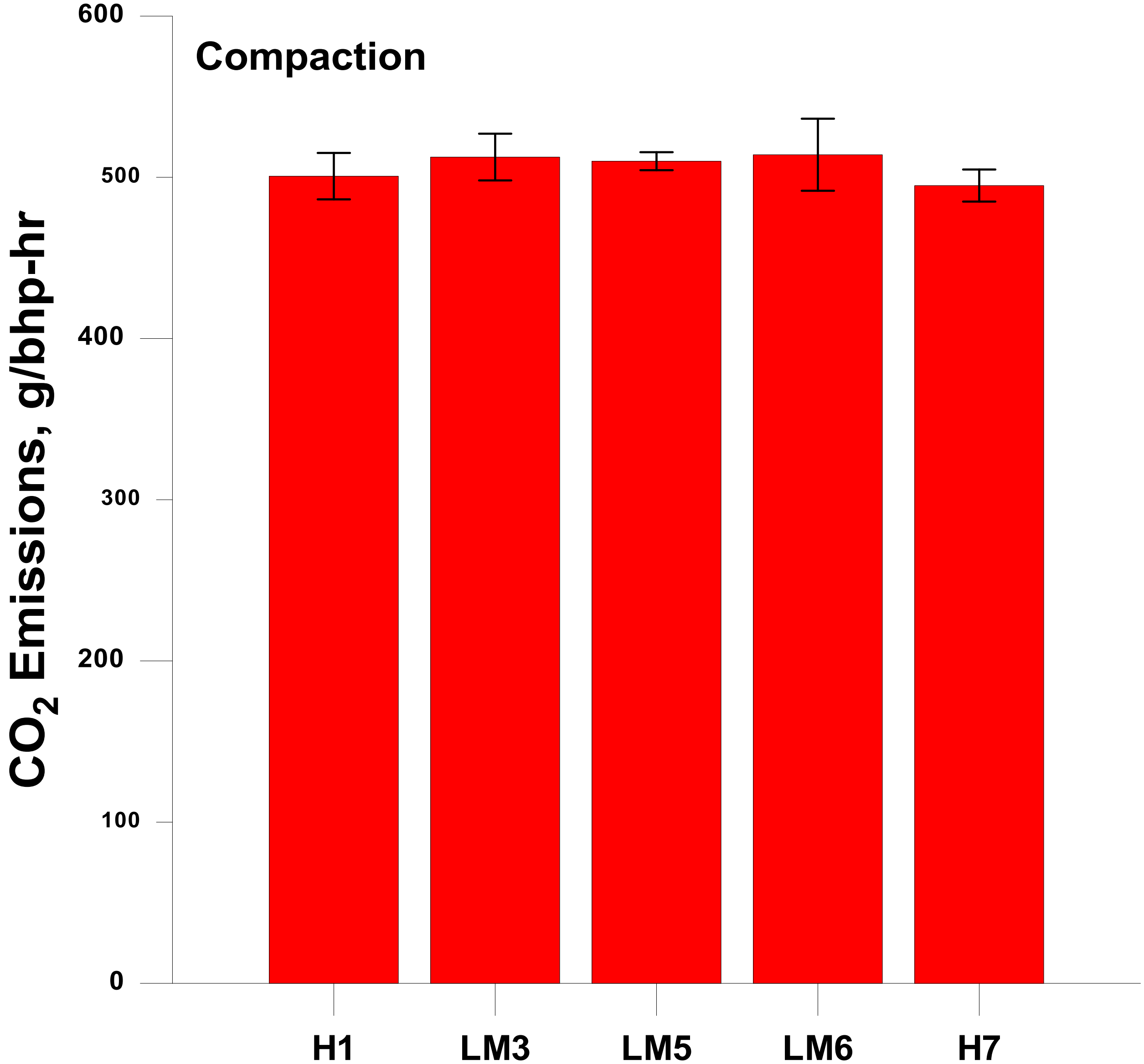
Figure 36 (a-b): Average CO_2 Emissions for the Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 37: Average CO_2 Emissions for the Compaction Segment of the Waste Hauler on an Engine bhp-hr Basis

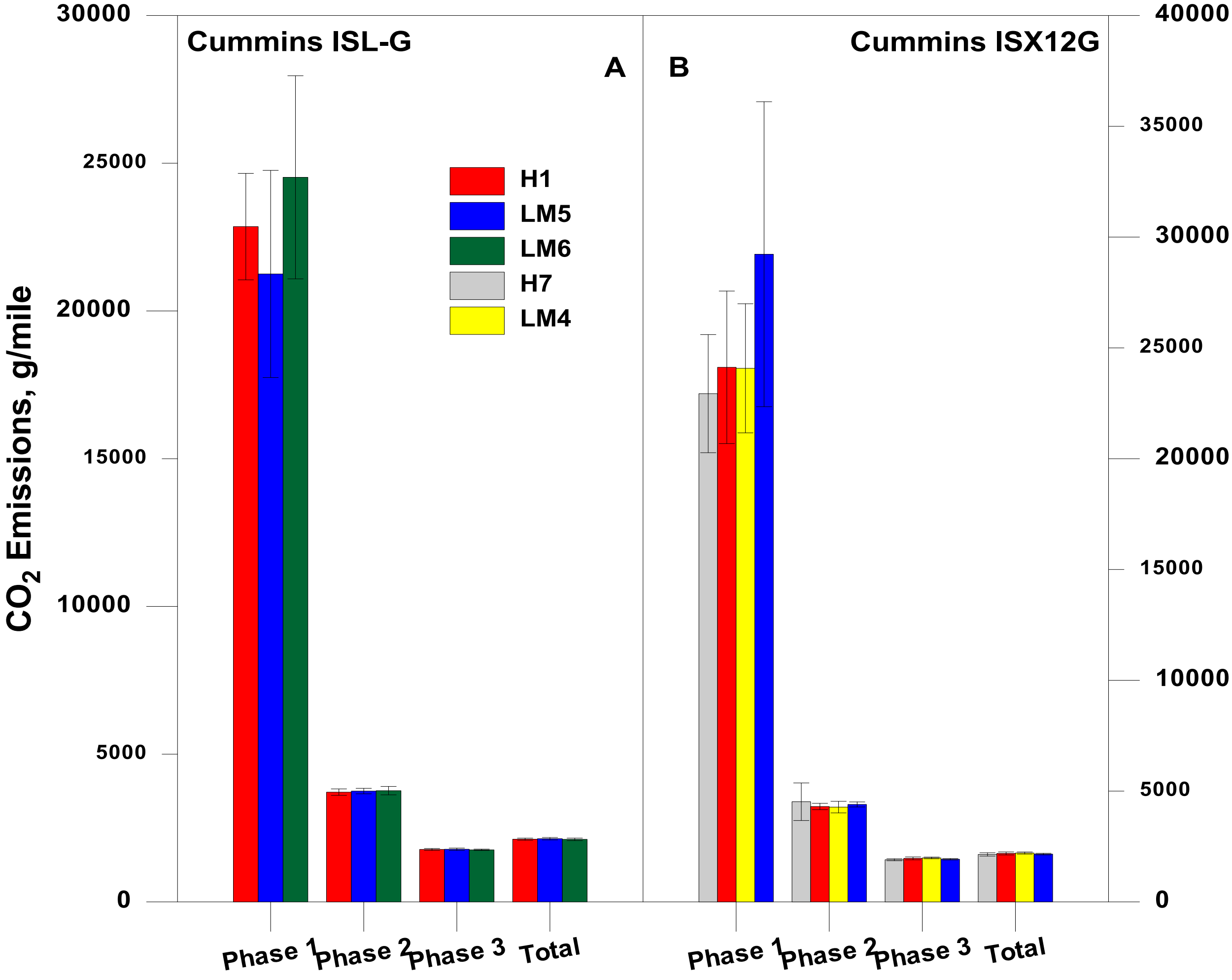


H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 38 shows the CO_2 emissions for the Cummins Westport ISL G (A) truck and Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and the Local Haul duty cycle, respectively. The CO_2 emissions for these two trucks was roughly comparable over the Near Dock and Local Haul Duty Cycles. The highest CO_2 emissions were found for the high speed transient phase and the lowest CO_2 emissions were observed for the creep phase. For the Cummins Westport ISL G truck, CO_2 emissions do not show consistent fuel trends over the entire Near Dock duty cycle and its individual phases. For the Cummins Westport ISX12 G truck, CO_2 emissions do not show strong fuel effects with some exceptions for the low methane fuels. For the creep phase, CO_2 emissions show a marginally statistically significant decrease of 27.4 percent for LM5 compared to H7. For the long high-speed transient phase, CO_2 emissions show a marginally statistically significant decrease of 3.1 percent for H7 compared to H1, whereas LM4 shows a statistically significant increase of 4.3 percent and H1 a marginally statistically significant increase of 3.2 percent compared to H7.

Figure 38: CO_2 Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B) for Their Individual Phases



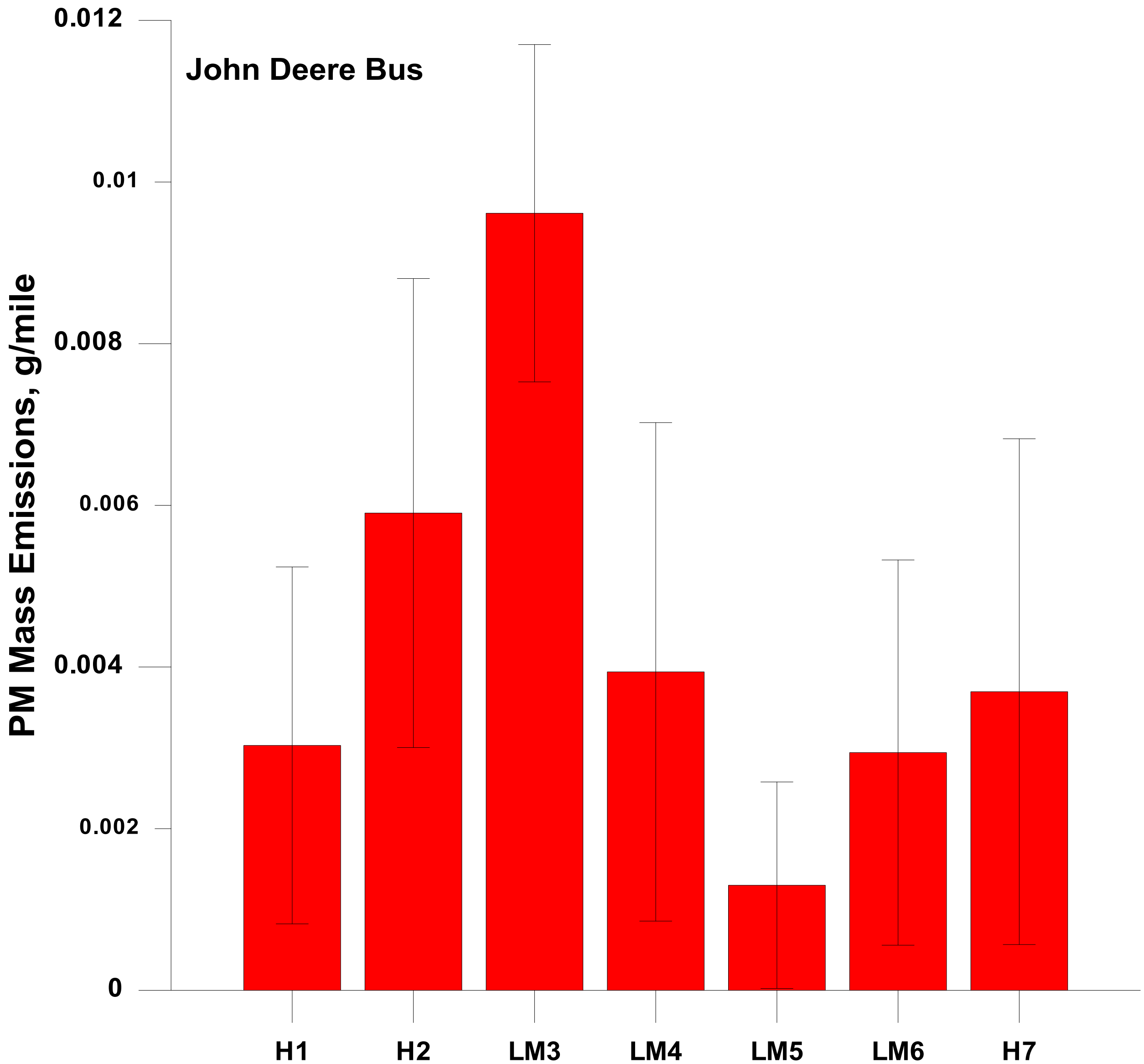
H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN) ; Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

3.7 Particulate Matter Mass Emissions

Figure 39 shows the PM mass emissions for the John Deere school bus over the CBD cycle. The results indicate that total PM mass emissions are low for the lean-burn John Deere engine on an absolute level, and in some cases close to the background levels. During testing with the John Deere engine, there were differences seen in PM mass emissions, some of which could be attributed to fuel effects and other differences in PM mass emissions are within the range of the tunnel background levels. PM mass emissions show a marginally statistically significant increase of 95 percent for H2 and a statistically significant increase of 217 percent for LM3 compared to H1. Compared to H2, PM mass emissions show a statistically significant increase of 63 percent for LM3 and a statistically significant reduction of 78 percent for LM5 is also observed. PM mass emissions are also statistically significantly higher for LM3 relative to H7.

Figure 39: Average PM Emissions for the John Deere Bus



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)

Source: CE-CERT

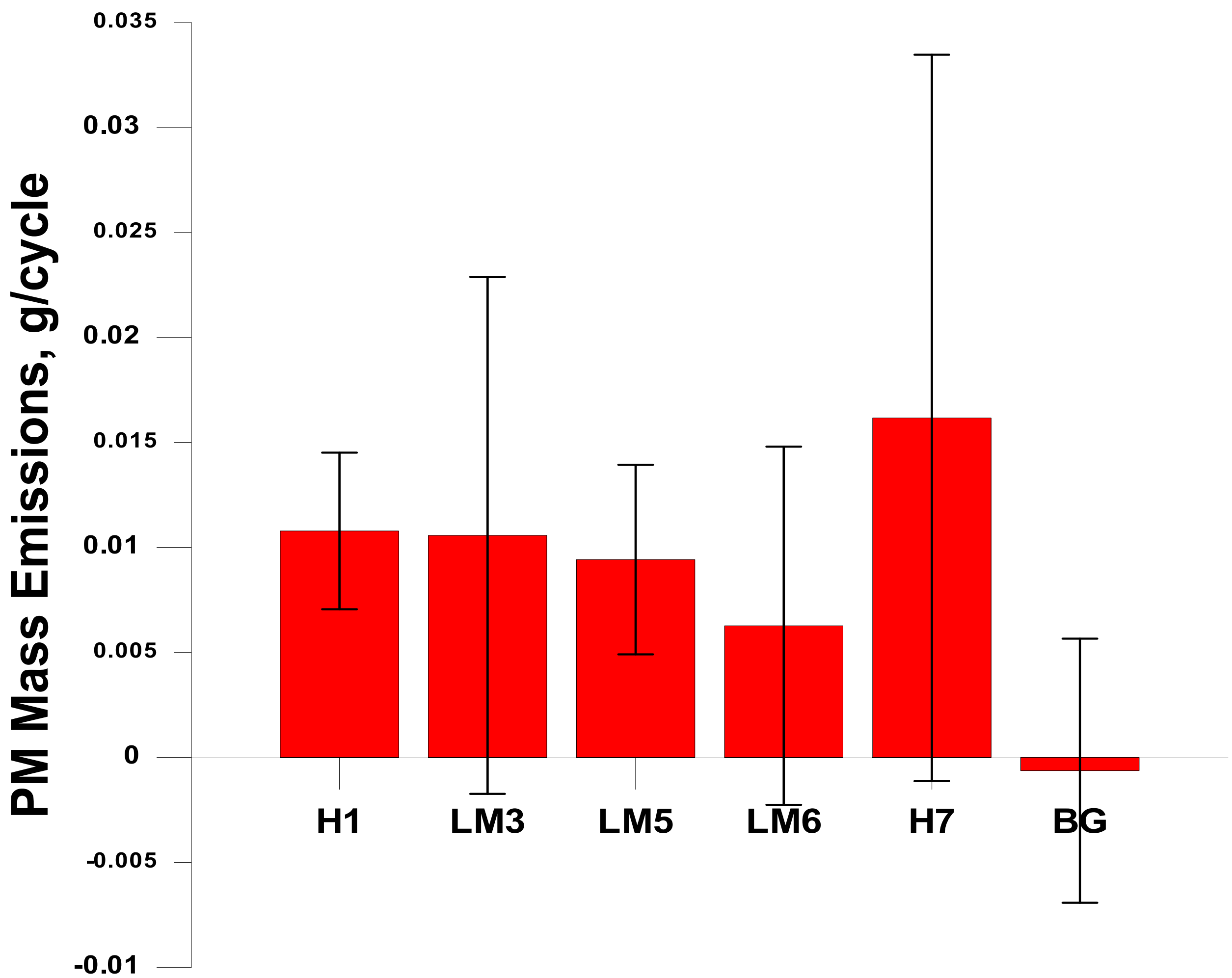
PM mass emissions for the waste hauler are shown in Figure 40 for the composite Refuse Truck Cycle. As explained in the experimental section, PM emissions were collected cumulatively over the entire duration of the RTC due to the expectation of low mass levels emitted; therefore, separate emissions are not available for the curbside, transport, and compaction segments. Instead, PM emissions are shown in terms of g/cycle.

The results indicated that total PM mass emissions were very low for the refuse truck on an absolute level. Although some differences were seen between fuels, these differences were all within the experimental variability. As a result, there were essentially no differences between PM mass for different fuels.

The very low levels of PM mass emissions found in the tailpipe result from combustion that generates low PM levels and as well as the reduction of PM with the TWC. Both the natural gas fuel combustion and the lubricant oil leakage into the combustion chamber generated PM. Natural gas is primarily comprised of methane, which is the lowest molecular weight hydrocarbon and a simpler structure compared to diesel and gasoline fuels (Walkowicz, K. et al. 2003). Natural gas has a reduced tendency to form localized areas of rich combustion and generates unburned and partially oxidized hydrocarbons with lower molecular sizes in the exhaust, resulting in very low PM mass emission levels. The PM contribution from natural gas combustion is expected to be smaller than from entry of the engine lubricant oil. Previous studies have shown that lubricant-oil-based additives and wear metals were a major fraction of the PM mass from NG buses (Thiruvengadam, A. et al. 2014). The low PM levels formed from the combustion process are further reduced as the exhaust stream passes over the catalyst bed. The carbon particles in the exhaust carry adsorbed water-soluble, organic PM compounds. The catalyst bed oxidizes some of the soluble organic fraction (SOF) portion of PM to CO_2 and water.

Testing on the legacy waste hauler in Phase 1 showed higher PM mass emission levels than those reported for the stoichiometric engine (Durbin, T. et al. 2014). Measured PM for the legacy vehicle was in the 0.025 to 0.069 g/cycle range compared to 0.006 to 0.016 g/cycle for the stoichiometric engine. The lower PM emissions for the stoichiometric engine compared to the legacy 2005 lean-burn engine could be attributed to the fact that the stoichiometric engine is designed to meet more stringent emissions standards than the legacy engine, or perhaps a reduction in lubricant oil consumption for the newer stoichiometric engine. Unlike the results reported here, the legacy vehicle exhibited statistically significant reductions in PM mass emissions for the low methane fuels compared to high methane fuels (Durbin, T. et al. 2014). The PM levels for the stoichiometric engine, which are lower than those for the legacy engine, are near the background levels. At such levels, the experimental variability becomes greater on an absolute basis, making it more difficult to measure differences between fuels.

Figure 40: Average PM Emissions for the Waste Hauler

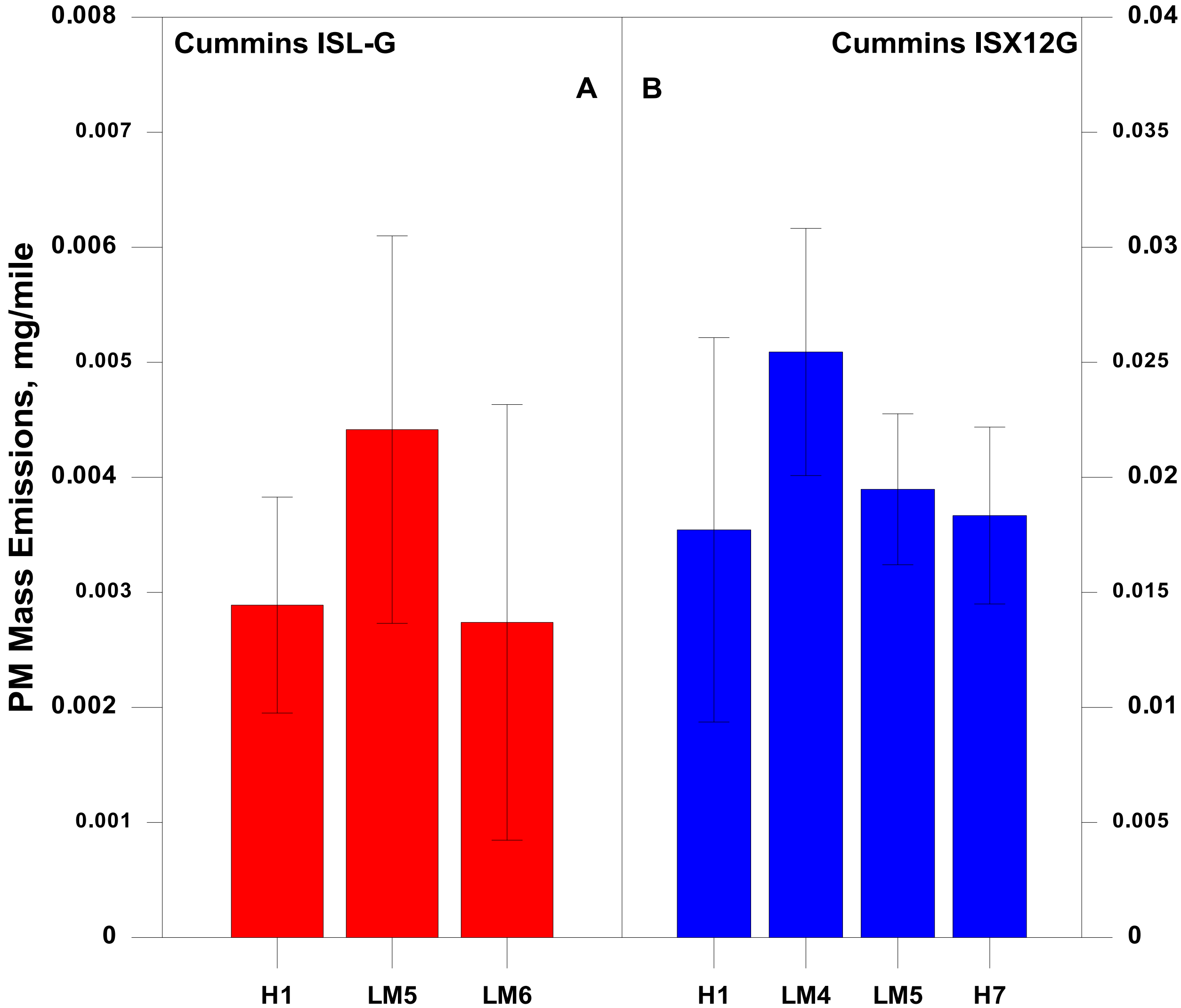


H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN), and BG is the tunnel background level

Source: CE-CERT

Figure 41 shows the PM mass emissions for the Cummins Westport ISL G (A) truck and the Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and Local Haul duty cycle, respectively. PM mass emissions for these two vehicles are collected cumulatively over the entire test cycles, without separating the individual phases. Sampling for carbonyl compounds and the PM mass was done cumulatively over the entire duration of each test cycle due to the low mass levels expected for these pollutants and the corresponding need to collect a sufficient sample for analysis. The Cummins ISL G engine produces significantly lower PM mass emissions than the Cummins ISX12 G engine. For the Cummins Westport ISL G truck, PM mass shows a marginally statistically significant increase of 52.8 percent for LM5 compared to H1. For the Cummins Westport ISX12 G truck, PM mass emissions show a marginally statistically significant increase of 38.8 percent for LM4 compared to H7.

Figure 41: PM Mass Emissions for the Class 8 Trucks Cummins Westport ISL G Over the Near Dock Cycle (A) and Cummins Westport ISX12 G Over the Local Haul Duty Cycle (B)



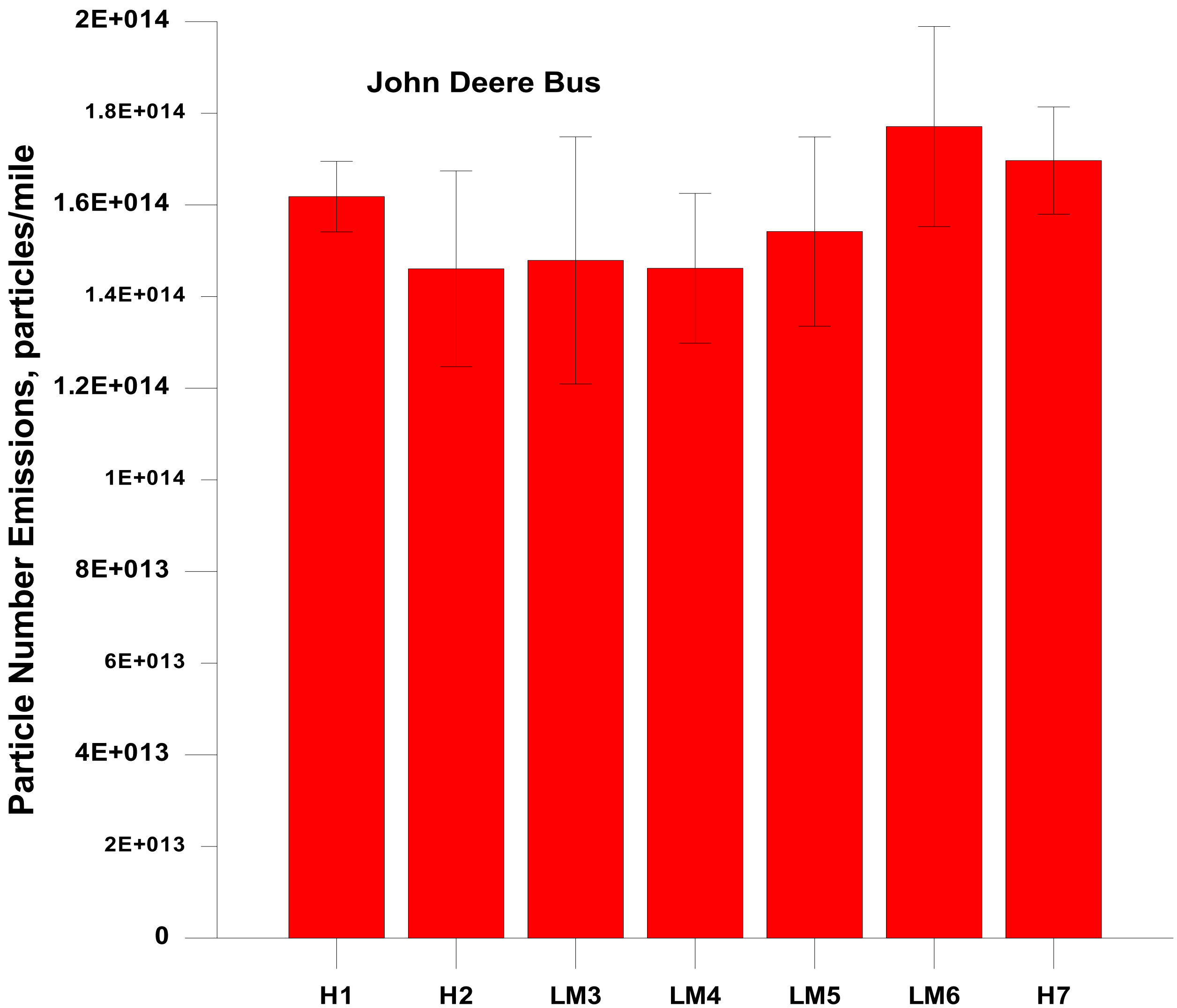
H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

3.8 Particle Number Emissions

Figure 42 presents the particle number (PN) emissions for the John Deere school bus over the CBD cycle. Overall, the low methane fuels and higher flame speed fuels trend lower in PN emissions when compared to the high methane H1 and H7 fuels; however, most of the differences between the test fuels cannot be considered as statistically significant, with some exceptions seen for some fuels. PN emissions show marginally statistically significant decreases of 10 percent and 14 percent, respectively, for LM4 compared to H1 and H7, whereas LM6 shows a statistically significant increase in PN emissions of 21 percent compared to H2. PN emissions for this vehicle were much higher than those emissions tested for the stoichiometric engine vehicles tested for this study and the 2004 lean-burn John Deere bus tested in a previous CE-CERT study (Hajbabaei, M. 2013).

Figure 42: Average PN Emissions for the John Deere Bus



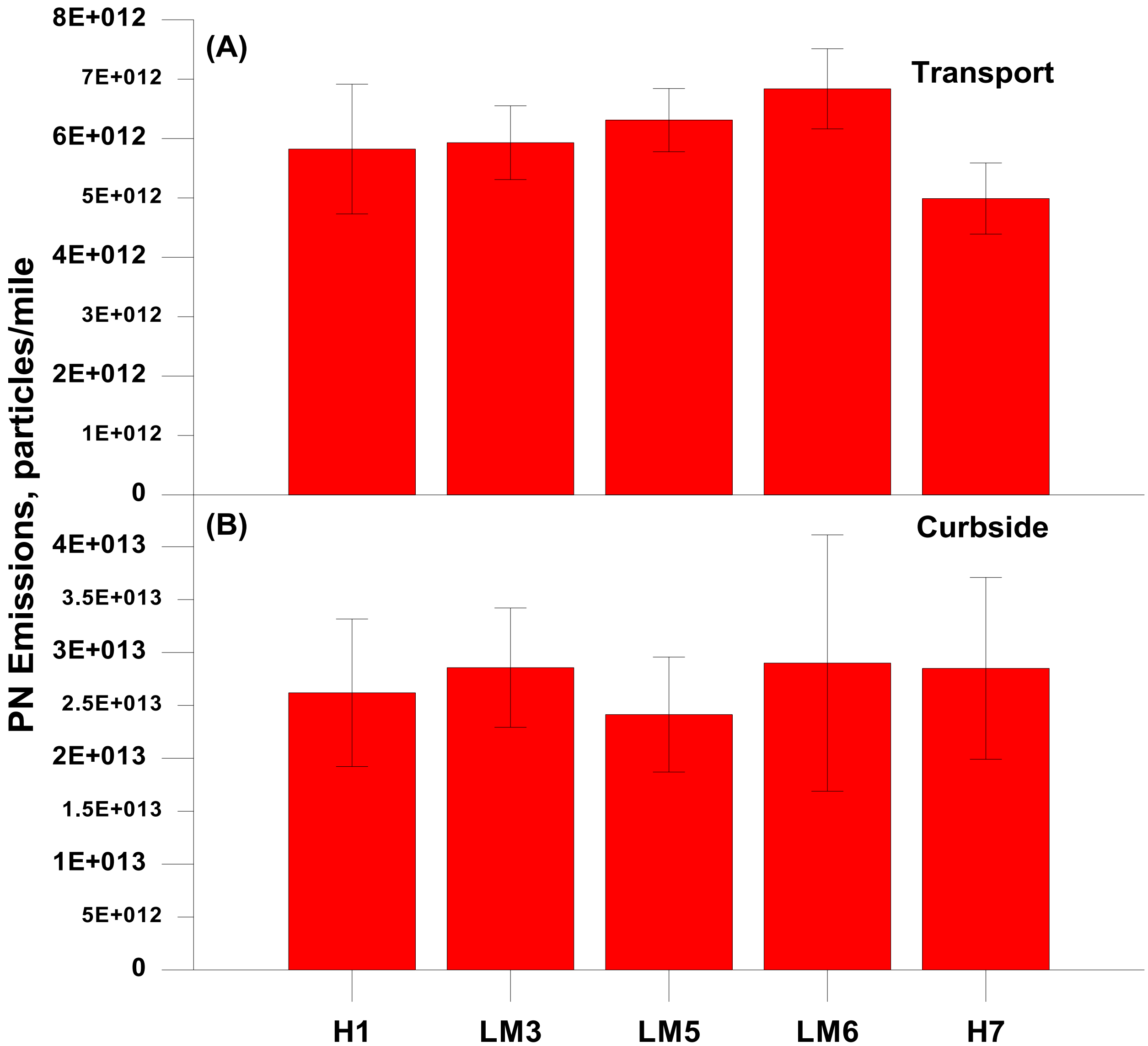
H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

For the waste hauler, PN emissions are shown in Figure 43 (a-b) for the transport and curbside segments and in Figure 44 for the compaction segment on a bhp-hr basis. PN emissions do not show strong fuel trends for either the transport or the curbside segments of the RTC. The transport segment is the only segment where statistically significant differences are observed between fuels. PN emissions show a marginally statistically significant increase of 17.4 percent for LM6 compared to H1. LM5 and LM6 show statistically significant increases in PN emissions of 26.5 percent and 37.0 percent, respectively, while LM3 shows a marginally statistically significant increase of 18.8 percent compared to H7. PN emissions are approximately an order of magnitude higher for the curbside segment compared to the transport segment of the cycle, as the curbside segment covers a much shorter distance and is primarily composed of low speed accelerations and idling periods with little steady state driving. For the compaction segment, there are no statistically significant differences between the test fuels.

In comparing the results obtained from this study to previous work conducted by CE-CERT (Durbin, T. et al. 2014), the similarity in total PN emissions between older and newer technology natural gas engines suggests that PN emissions are largely attributed to lubricant oil and not the changes in the fuel combustion and of after treatment type.

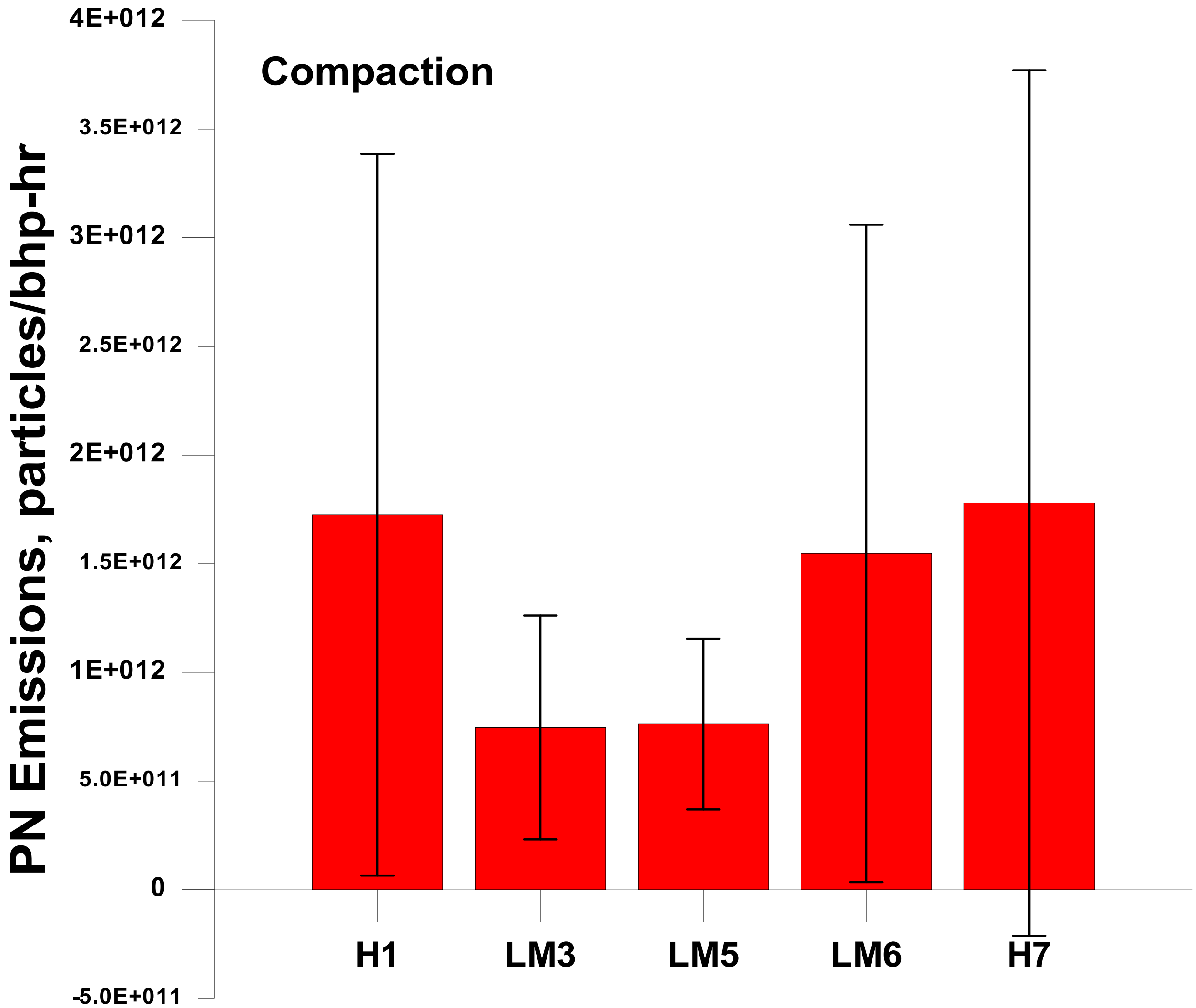
Figure 43: Average PN Emissions for Waste Hauler



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 44: Average PN Emissions for Waste Hauler

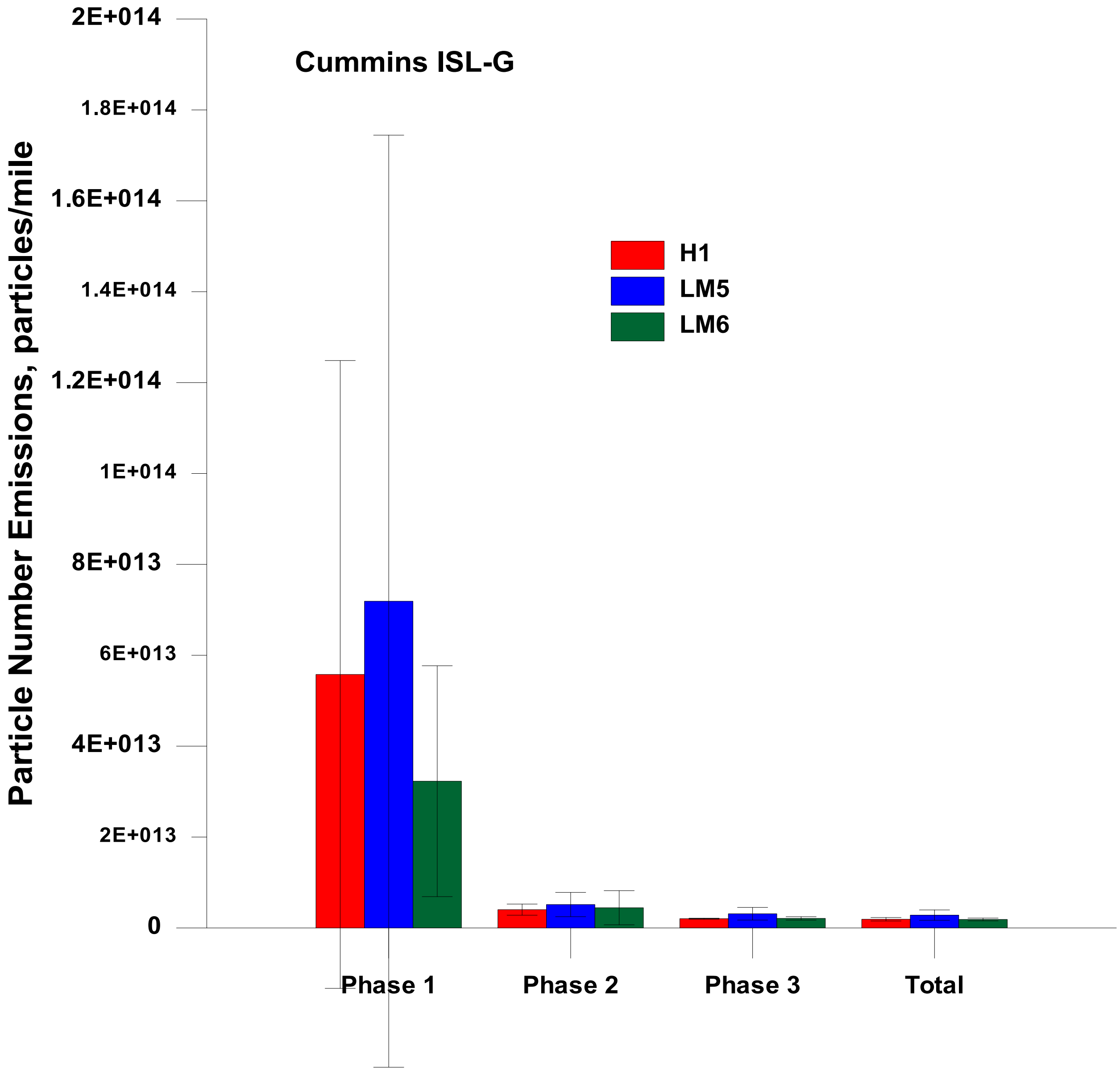


H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

For the Cummins Westport ISL-G truck, PN emissions over the entire Near Dock duty cycle and its individual phases are shown in Figure 45. Although PN emissions for this engine corroborate the PM mass emissions, PN emissions do not show any statistically significant differences between the test fuels. PN emissions for the ISL-G truck are lower than those emitted during the RTC transport and curbside segments for the ISL-G waste hauler.

Figure 45: PN Emissions for the Cummins Westport ISL-G Truck (Near Dock Cycle)



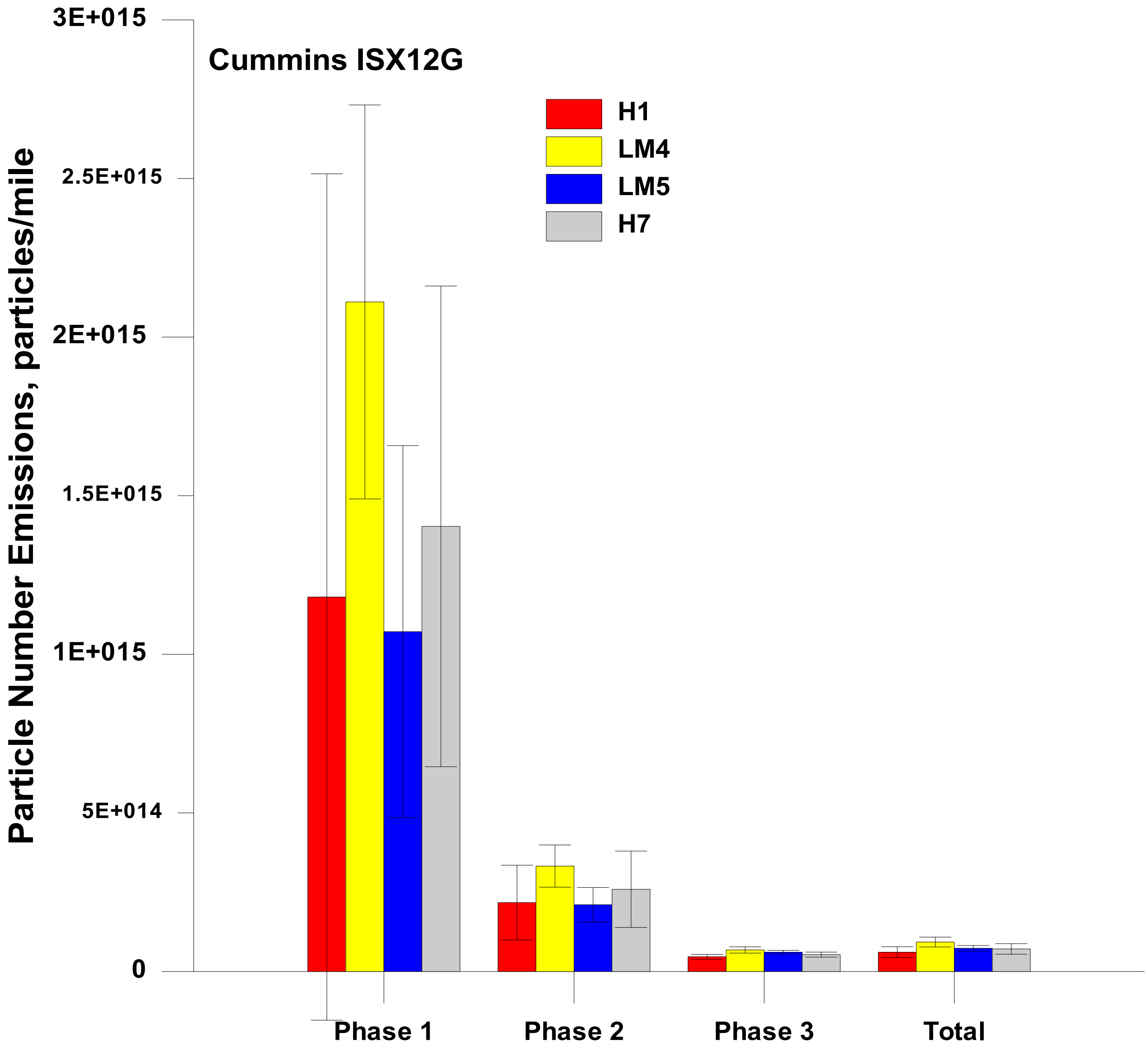
H1: Texas (1339 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN); Phase 1 = creep phase, Phase 2 = a low speed transient phase, and Phase 3 = a short high-speed transient phase.

Source: CE-CERT

For the Cummins Westport ISX12G truck, PN emissions over the Local Haul duty cycle and its individual phases are shown in Figure 46. Emissions of PN for the entire cycle and its individual phases are higher for this vehicle than the Cummins ISL-G truck and the ISL-G waste hauler, but lower than the lean-burn John Deere bus. The low methane fuels, i.e., LM4 and LM5 show statistically significant increases in PN emissions of 46.5 percent and 31.7 percent, respectively, compared to H1 for the long high-speed transient phase 3. The accumulated PN emissions also show a statistically significant increase of 52.7 percent for LM4 compared to H1.

The PN emissions do not show any statistically significant differences between the test fuels for Phase 1 and Phase 2 of the Local Haul duty cycle.

Figure 46: PN Emissions for the Cummins Westport ISLX12G Truck



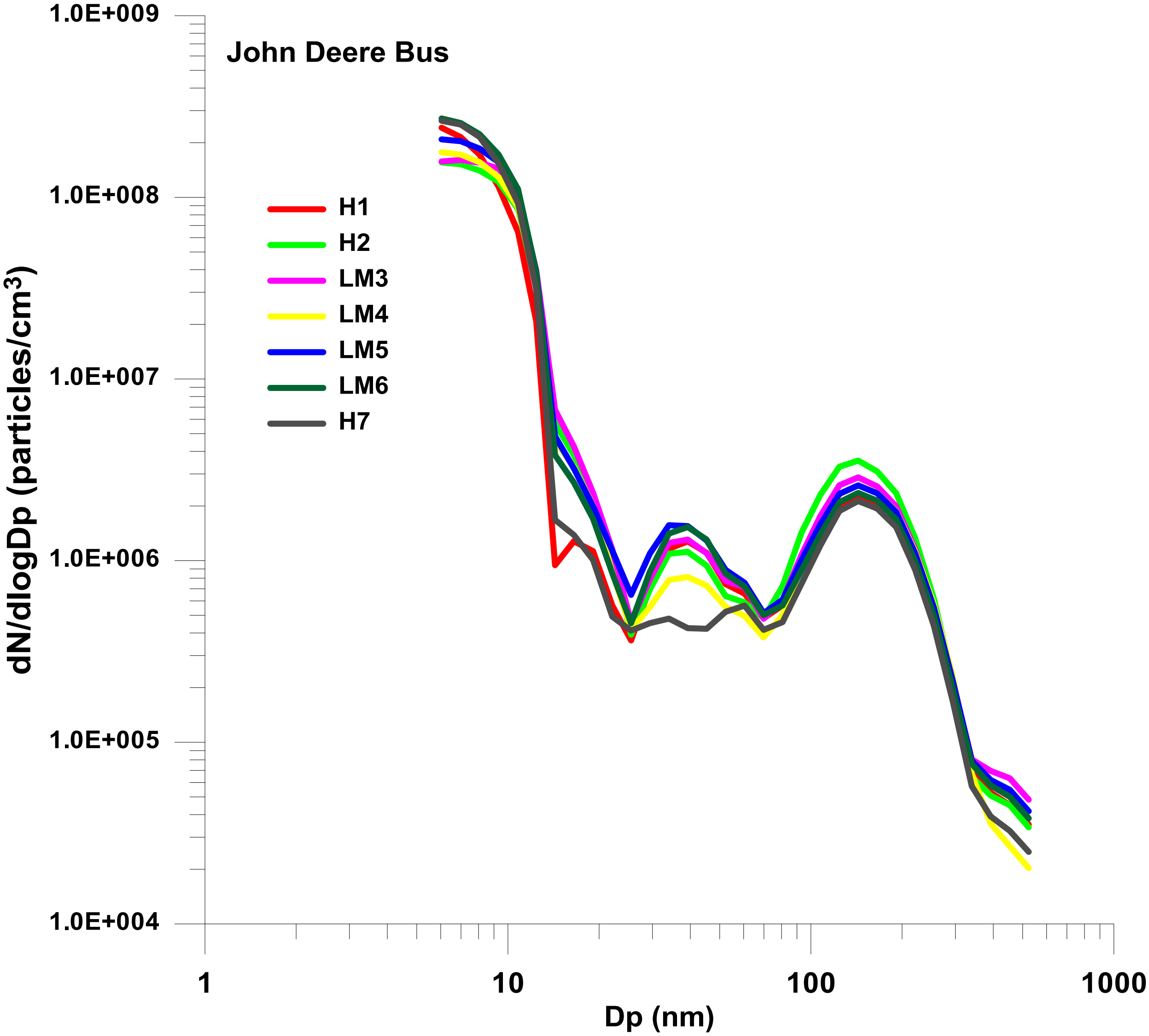
H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase, Phase 2 = a low speed transient phase, and Phase 3 = a long high-speed transient phase.

Source: CE-CERT

3.9 Particle Size Distributions

The average particle size distributions for the John Deere school bus, as obtained with the Engine Exhaust Particle Sizer (EEPS) spectrometer, are shown in Figure 47. The lean-burn John Deere school bus shows higher concentrations of nucleation and accumulation mode particles than all three stoichiometric Cummins Westport engines tested for this program. The nucleation mode particles appear to dominate the particle size distribution profile for this vehicle over the CBD cycle. The particle size distributions for most fuels show particle concentrations in the accumulation mode between $2x10^6$ to $4x10^6$ particles/cubic centimeters (cm^3) for particle diameters from 140 to 145 nm size range, which is much lower than those in the nucleation mode. There are no clear fuel trends in particle size distributions for the John Deere bus.

Figure 47: Average Particle Size Distributions for the John Deere Bus

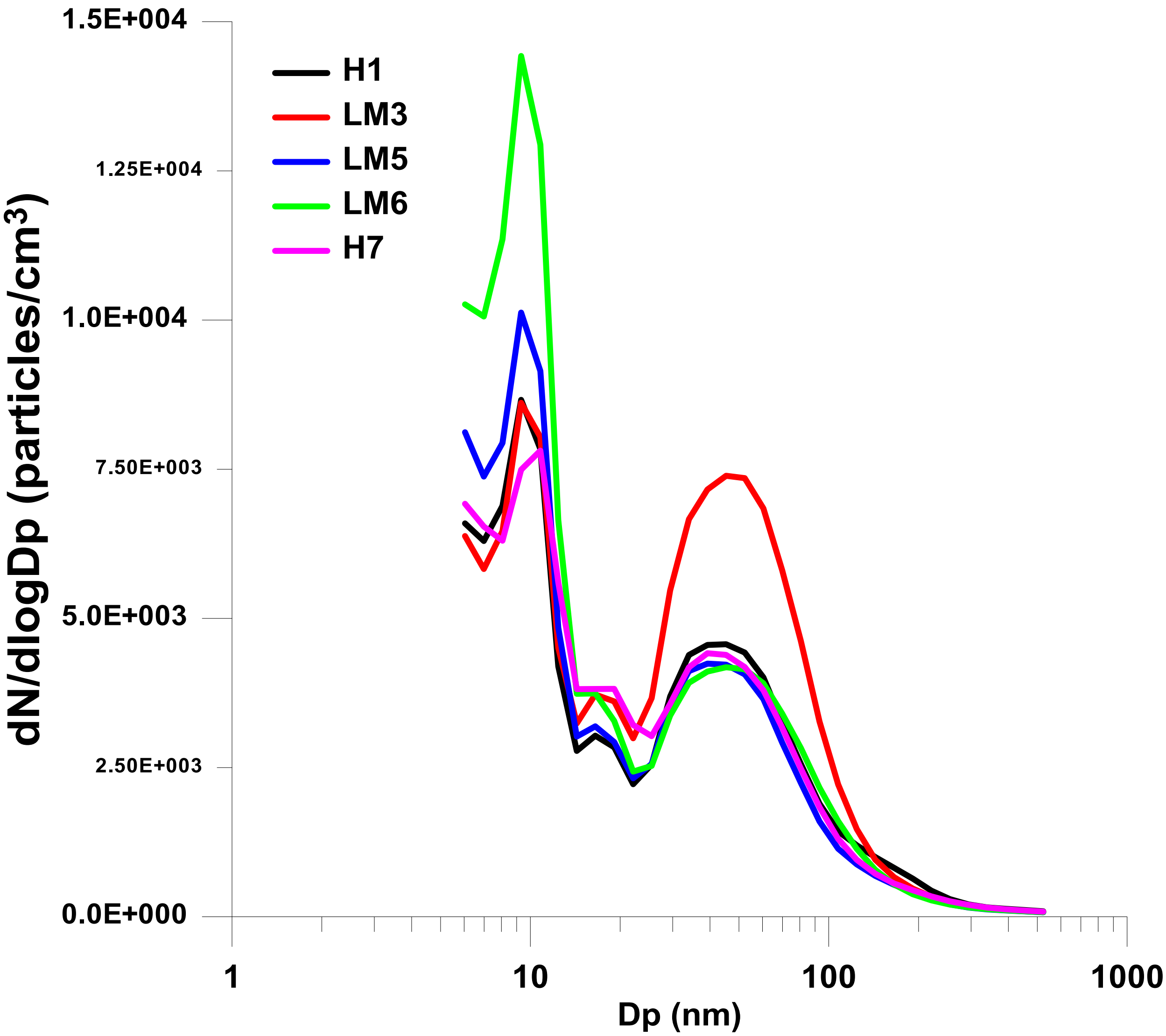


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

For the waste hauler, the average particle size distributions are shown in Figure 48. All fuels show a decidedly bimodal particle size distribution. Exhaust stream particle size distributions for most fuels show particle concentrations in the nucleation mode between $8x10^3$ to $1x10^4$ particles/cm^3 for particle diameters centered from 9 to 11 nanometers (nm) size range. The exception is for LM6, which shows particle concentrations close to $1.4x10^4$ particles/cm^3 for particle diameters around 9 nm in size. Particle size distributions for all test fuels indicate the emission of particles in the accumulation mode ranging from 40 to 45 nm in geometric mean diameter. Concentrations in the accumulation mode are about an order of magnitude lower than particles in the nucleation mode. The findings of this study for the John Deere bus and the Cummins Westport waste hauler are in agreement with previous studies showing that the majority of particles from CNG heavy-duty vehicles are in the nucleation mode (Holmen, B. and Ayala, A. 2002, Jayaratne, E. et al. 2009, Jayaratne, E. et al. 2012, Thiruvengadam, A. et al. 2014). In addition, the results reported here are in agreement with those reported in Phase 1 for the legacy waste hauler, showing that the majority of particles are in the nucleation mode (Durbin, T. et al. 2014).

Figure 48: Average Particle Size Distributions for the Waste Hauler

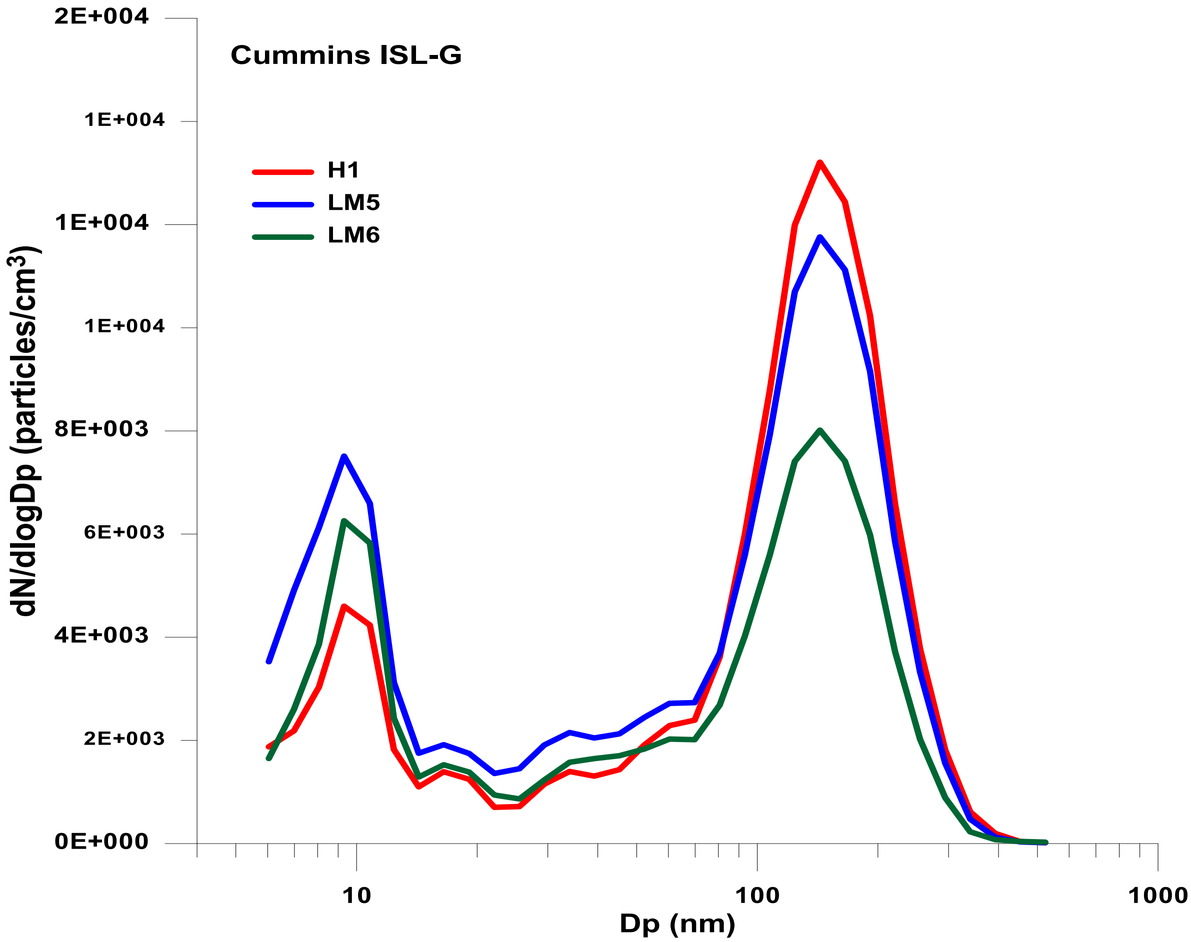


H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 49 illustrates the particle size distributions for the Cummins Westport ISL-G truck over the Near Dock duty cycle. Similar to the waste hauler, the ISL-G truck shows a decidedly bimodal particle size distribution; however, the accumulation mode is the prevalent mode of particle formation for this engine as opposed to the John Deere bus and waste hauler. This finding is interesting since both the waste hauler and the truck are fitted with the same Cummins Westport ISL-G 8.9L engine. The particle size distributions for the three test fuels show particle concentrations in the nucleation mode from $5x10^3$ to $8x10^3$ particles/cm^3 for particle diameters centered from 9 to 10 nm size range. The highest concentrations in nucleation mode particles are seen for the low methane fuels, i.e., LM5 and LM6, compared to H1. For the accumulation mode particles, particle diameters ranging from 140 to 143 nm in size range with particle concentrations from $8x10^3$ to $10x10^4$ particles/cm^3. The high methane H1 fuel produces higher concentrations of accumulation mode particles followed by LM5 and LM6. It should be stressed that the ISL-G truck results in accumulation particles with larger diameters compared to the ISL-G waste hauler.

Figure 49: Average Particle Size Distributions for the Cummins Westport ISL-G Truck



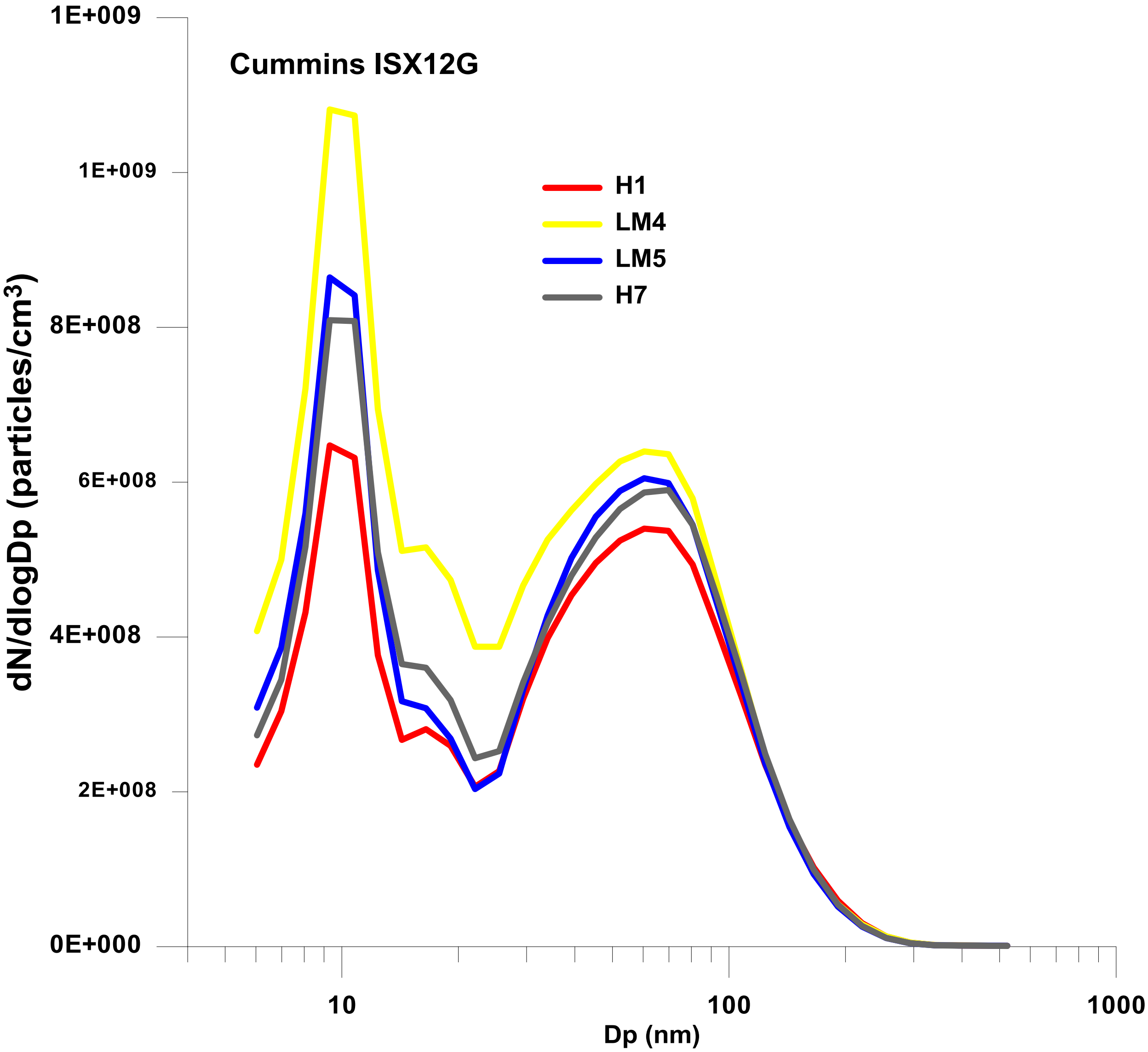
H1: Texas (1339 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN)

Source: CE-CERT

For the Cummins Westport ISX12G truck, average particle-size distributions over the Local Haul duty cycle are shown in Figure 50. Similar to the previous vehicles tested in this study, the ISX12G truck shows a decidedly bimodal particle size distribution. Unlike the particle size distribution profile for the ISL-G truck, but more similar to waste hauler and school bus, the ISX12G truck produces higher concentrations of accumulation mode particles compared to the nucleation mode particles. The particle size distributions for the test fuels show particle concentrations in the nucleation mode from $6x10^8$ to $10x10^{10}$ particles/cm^3 for particle diameters centered from 9 to 10 nm size range. The particle concentrations in the nucleation mode for the ISX12G truck are considerably higher when compared to all three vehicles tested. For the accumulation mode particles, particle concentrations are from $5x10^8$ to $6x10^8$ particles/cm^3 for particle diameters from 60 to 70 nm size range. Compared to ISL-G truck, the ISX12G truck produces higher accumulation-mode particle counts with smaller diameters. For the ISX12G truck, a fuel effect was noticeable with the low methane fuels showing higher accumulation and nucleation-mode particle concentrations than H1 and H7.

In general, it is reasonable to theorize that the observed particle size distributions could be attributed to in-cylinder combustion of lubricant oil, which contributed sulfates nucleating with water to form sulfuric acid particles in the 10 nm peak size. Similar observations were reported by Thiruvengadam et al. (2014) when they tested two 2007 CNG buses fitted with Cummins ISLG280 engines and TWCs. The lubricant oil entry into the combustion chamber is dependent on engine load. Typically low-load operations, such as those applied during the RTC for the Cummins Westport waste hauler, result in insufficient piston ring sealing, which can contribute to the combustion of lubricant oil (Yoon, S. et al. 2012). It is also reasonable to assume that the low-load operation of RTC resulted in lower accumulation mode particles or soot emissions and increased the probability of the formation of inorganic nucleation mode particles. The Cummins ISL-G truck produced less accumulation particles when operated over the Near Dock duty cycle compared to the Cummins ISX12G truck. This result could be due to the third phase of the Near Dock duty cycle (short high-speed transient phase) where the vehicle is subjected to lower speed and load conditions compared to the third phase of the Local Haul duty cycle (long high-speed transient phase). Khalek et al. (1998) explained this phenomenon showing that lubricant oil additives do undergo volatilization when passing through the combustion chamber and a fraction of them renucleate to form nanoparticles.

Figure 50: Particle Size Distributions for the Cummins Westport ISX12G Truck



H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), H7: L-CNG (1370 WN)

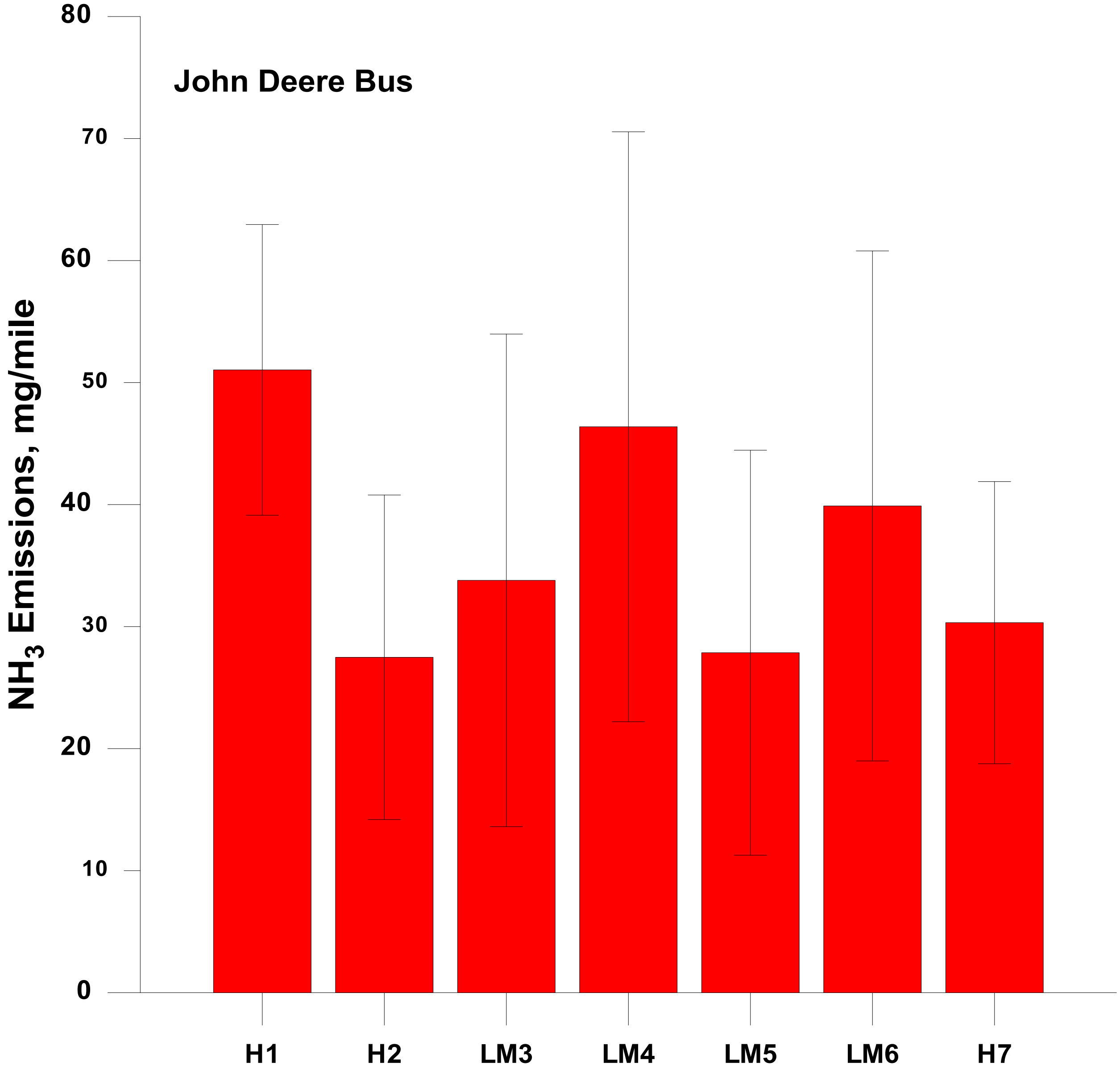
Source: CE-CERT

3.10 Ammonia Emissions

Road traffic is a major source of reactive nitrogen compounds such as NH_3. NH_3 is involved in the formation of secondary aerosols and considered as a toxic pollutant. Ammonia is formed de novo in noble metal-based TWCs; therefore, is a secondary pollutant of the catalytic process rather than a side product of the fuel combustion. NO and H_2, both formed during combustion, are the assumed precursor molecules (Bielaczyc, P. et al. 2012).

Figure 51 shows the NH_3 emissions for the John Deere school bus over the CBD test cycle. Emissions of NH_3 are found to be at substantially lower levels for the lean-burn John Deere vehicle compared to the stoichiometric engines, ranging from 27.5 mg/mile to 51.0 mg/mile. In general, NH_3 emissions show a declining trend for all test fuels compared to H1. Emissions of NH_3 show statistically significant reductions of 46.2 percent, 45.4 percent, and 40.6 percent for H2, LM5, and H7, respectively, compared to H1. H1 shows statistically significant increases in NH_3 emissions of 85.7 percent compared to H2. Overall, NH_3 emissions do not show consistent fuel effects for the John Deere bus, since most of the differences were between the high methane fuels.

Figure 51: Average NH_3 Emissions for the John Deere Bus



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)

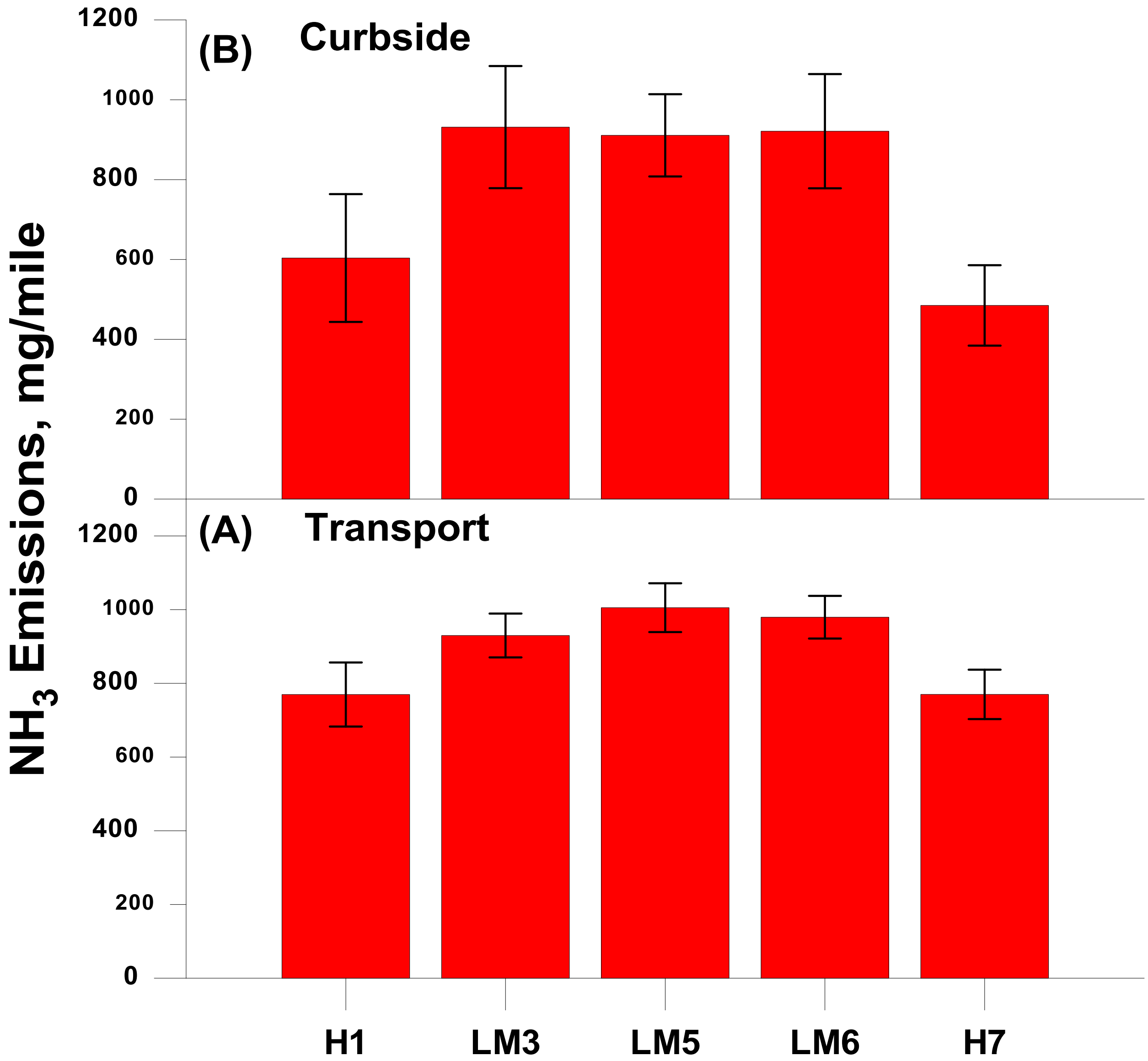
Source: CE-CERT

Figure 52 (a-b) shows the NH_3 emissions for the waste hauler for the transport and curbside segments, while Figure 53 shows the NH_3 emissions for the compaction segment on a bhp-hr basis. NH_3 emissions are found at much higher concentrations compared to the lean-burn John Deere engine. NH_3 emissions ranged from 769 mg/mile to 1,005 mg/mile for the transport phase and from 485 mg/mile to 931 mg/mile for the curbside phase. For comparison, NH_3 emissions for the waste hauler with a C Gas Plus lean burn engine in our previous study ranged from 26.4

mg/mile to 37.1 mg/mile and from 81.1 mg/mile to 115.9 mg/mile for the transport and curbside phases, respectively (Durbin, T. et al. 2014). NH_3 emissions are generally higher for the low methane fuels, i.e., LM3, LM5, and LM6. The increases in NH_3 emissions for LM3, LM5, and LM6 are statistically significant compared to both H1 and H7 for all three of the test cycles.

For TWC-equipped stoichiometric natural gas engines, the production of NH_3 takes place in the presence of hydrogen molecules, which are produced during periods of rich air-fuel mixtures. A water gas shift reaction involving CO and water or steam reforming reactions involving CH_4 and water in the exhaust can form hydrogen (Majia-Centeno, I. et al. 2007, Huai, T. et al. 2003, Gandhi, H. et al. 1974). It has been suggested that hydrogen produced in the water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) could be a major contributor to NH_3 formation through the overall reaction of $2NO + 2CO + 3H_2 \rightarrow 2NH_3 + 2CO_2$. Fuel composition appears to have played some role in NH_3 emissions under the present test conditions. The higher NH_3 emissions for the low methane fuels could be due to slightly richer combustion (Feist, M. 2006). It is also known that oxidation of methane with a standard TWC with platinum/palladium/rhodium is difficult to achieve than oxidation of heavier components ethane and propane. Due to the lower reactivity of CH_4 over the TWC, an increase in the proportion of CH_4 in the engine-out exhaust gas flux would decrease the quantity of hydrogen available for ammonia formation. This CH_4 reaction over the TWC could explain why there were lower ammonia emissions observed for the high methane fuels compared to LM3, LM5, and LM6. The presence of higher CO levels also facilitates the NH_3 formation in the exhaust of a TWC-equipped stoichiometric natural gas vehicle. Under the present test conditions, the low methane fuels showed higher CO emissions over all three phases of the RTC resulting in higher NH_3 emissions.

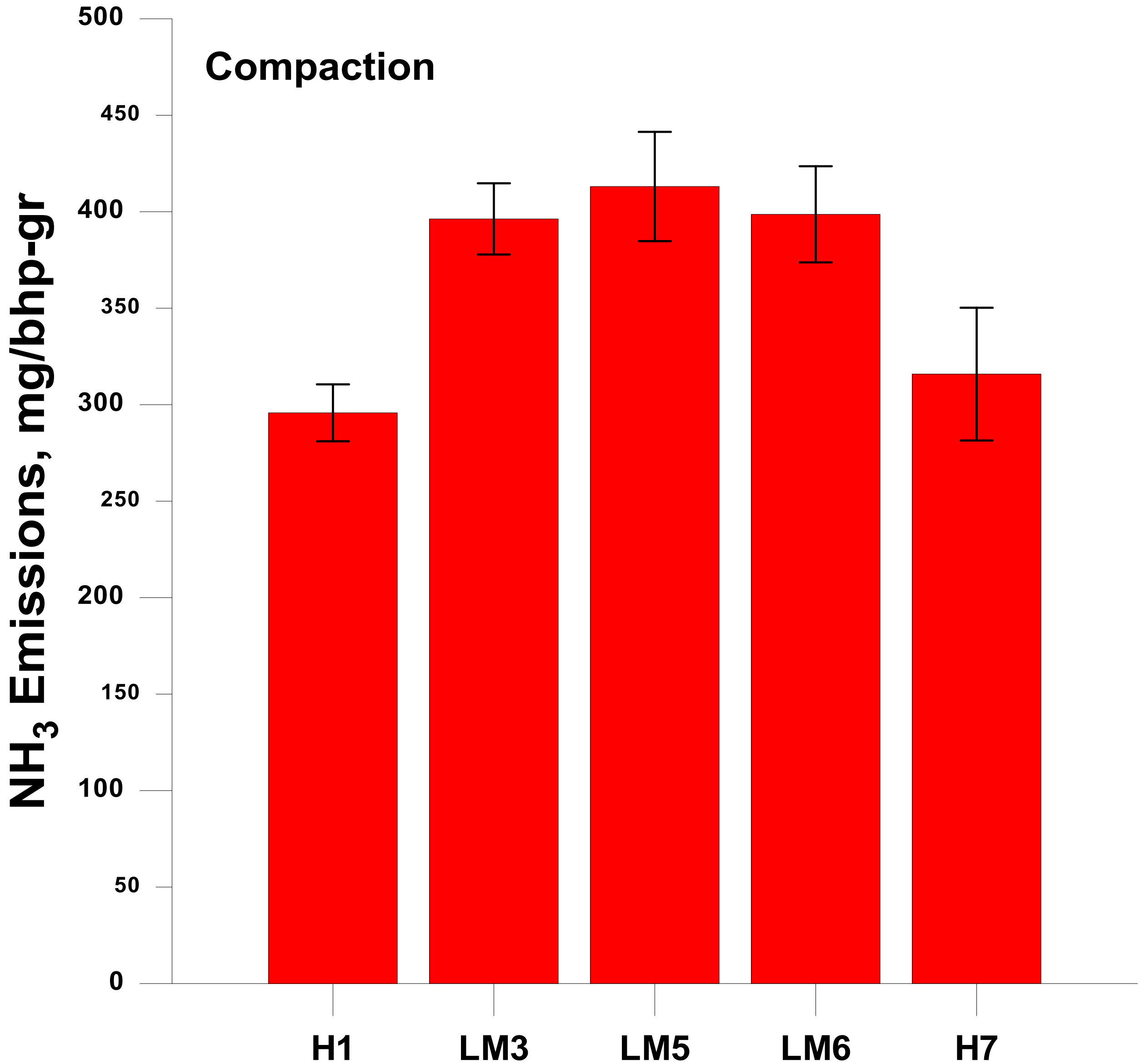
Figure 52 (a-b): Average NH_3 Emissions for Waste Hauler Transport and Curbside Segments



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 53: Average NH_3 Emissions for Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis



H1: Texas (1339 WN), LM3: Peruvian LNG (1385 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

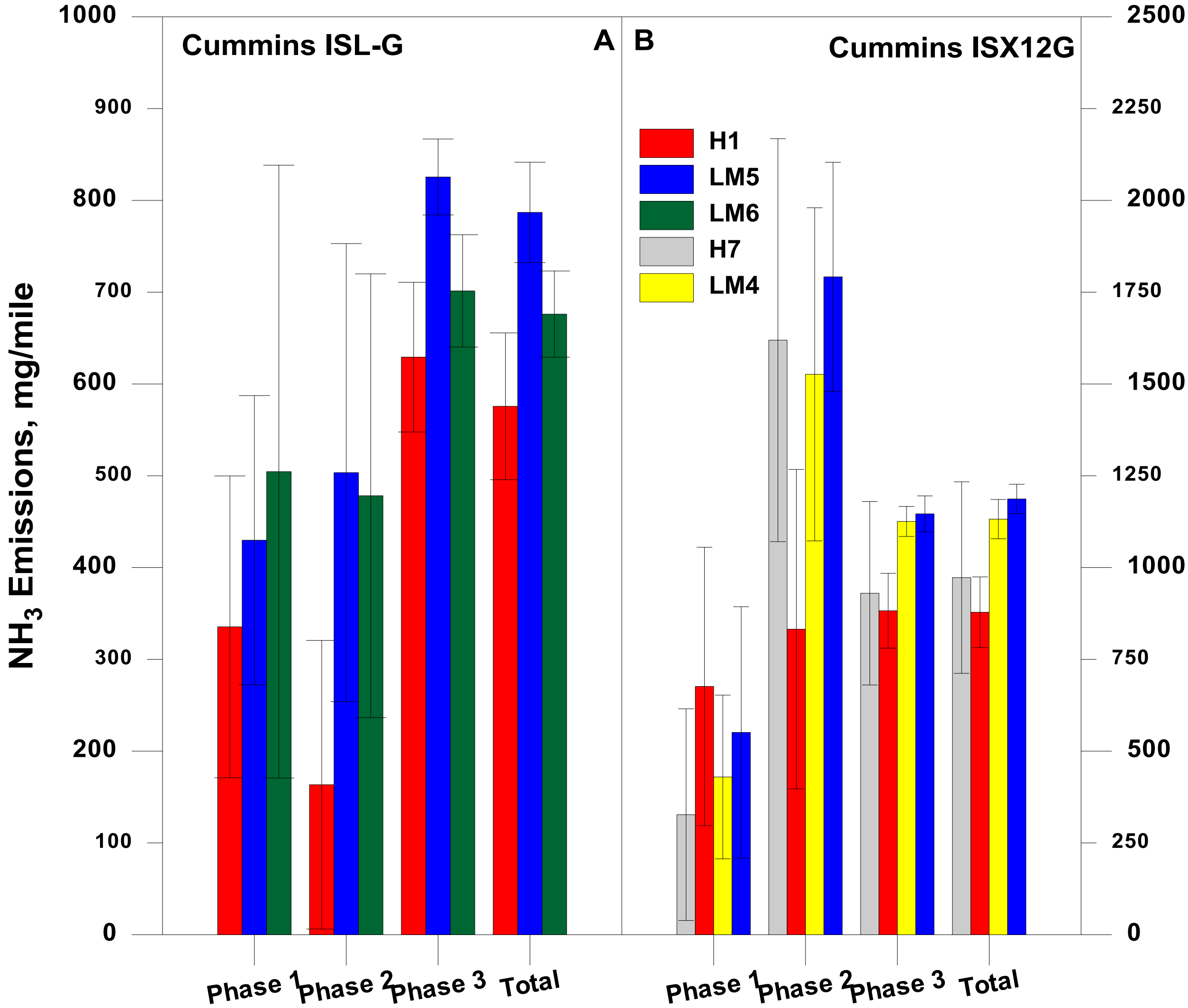
Source: CE-CERT

Figure 54 shows the NH_3 emissions for the Cummins Westport ISL G (A) truck and the Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and the Local Haul duty cycle, respectively. Both the stoichiometric Cummins engines produce significantly higher NH_3 emissions than the lean-burn John Deere engine in Figure 51. This finding is similar to other results from the literature (Hajbabaei, M. et al. 2013). Comparing the two trucks, the NH_3 emissions were higher for the Cummins Westport ISX12 G truck than the Cummins Westport

ISL G truck. Additionally, for both Cummins engines NH_3 emissions are higher for the low methane fuels, i.e., LM4, LM5, and LM6, compared to H1 and H7. The higher NH_3 emissions for the Cummins engines could be due to the fact that the low methane/higher Wobbe number/higher flame speed fuels can produce higher exhaust temperatures and possibly slightly richer air-fuel ratios. The conditions for the formation of hydrogen as a precursor and NH_3 as reaction product could be enhanced for the low methane fuels. Ammonia is a secondary pollutant formed during the NOx reduction process over the TWC, with the formation dependent to the presence of both nitrogen oxide (NO) and hydrogen (H_2) in the exhaust stream. For TWC-equipped stoichiometric natural gas engines, the production of NH_3 takes place in the presence of hydrogen molecules, which form during periods of rich air-fuel mixtures. Hydrogen can also form from a water gas shift reaction involving CO and water or steam reforming reactions involving CH_4 and water in the exhaust (Majia-Centeno, I. et al. 2007, Huai, T. et al. 2003, Gandhi, H. et al. 1974).

For the Cummins Westport ISL G truck, accumulated NH_3 emissions show statistically significant increases of 36.7 percent and 17.4 percent, respectively for LM5 and LM6 compared to H1. For the low speed transient phase, NH_3 emissions also show statistically significant increases of 208.1 percent and 192.6 percent, respectively, for LM5 and LM6 compared to H1, while for the short high-speed transient phase the LM5 low methane fuel showed an increase of 31.2 percent compared to H1 at a statistically significant level. For the Cummins Westport ISX12 G truck, accumulated NH_3 emissions show statistically significant increases of 28.9 percent and 35.1 percent for LM4 and LM5, respectively, compared to H1, while LM5 also shows a marginally statistically significant increase of 22.0 percent compared to H7. For the low speed transient phase, NH_3 emissions show statistically significant increases of 83.4 percent, 115.3 percent, and 94.6 percent for LM4, LM5, and H7, respectively, compared to H1; whereas, H1 shows a statistically significant reduction of 48.6 percent compared to H7. For the long high-speed transient phase, NH_3 emissions show statistically significant increases of 27.6 percent and 29.9 percent, respectively, for LM4 and LM5 compared to H1.

Figure 54: NH_3 Emissions for the Cummins Westport ISL G (A) and Cummins Westport ISX12 G (B) Class 8 Trucks Over the Near Dock Cycle and the Local Haul Duty Cycle



H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

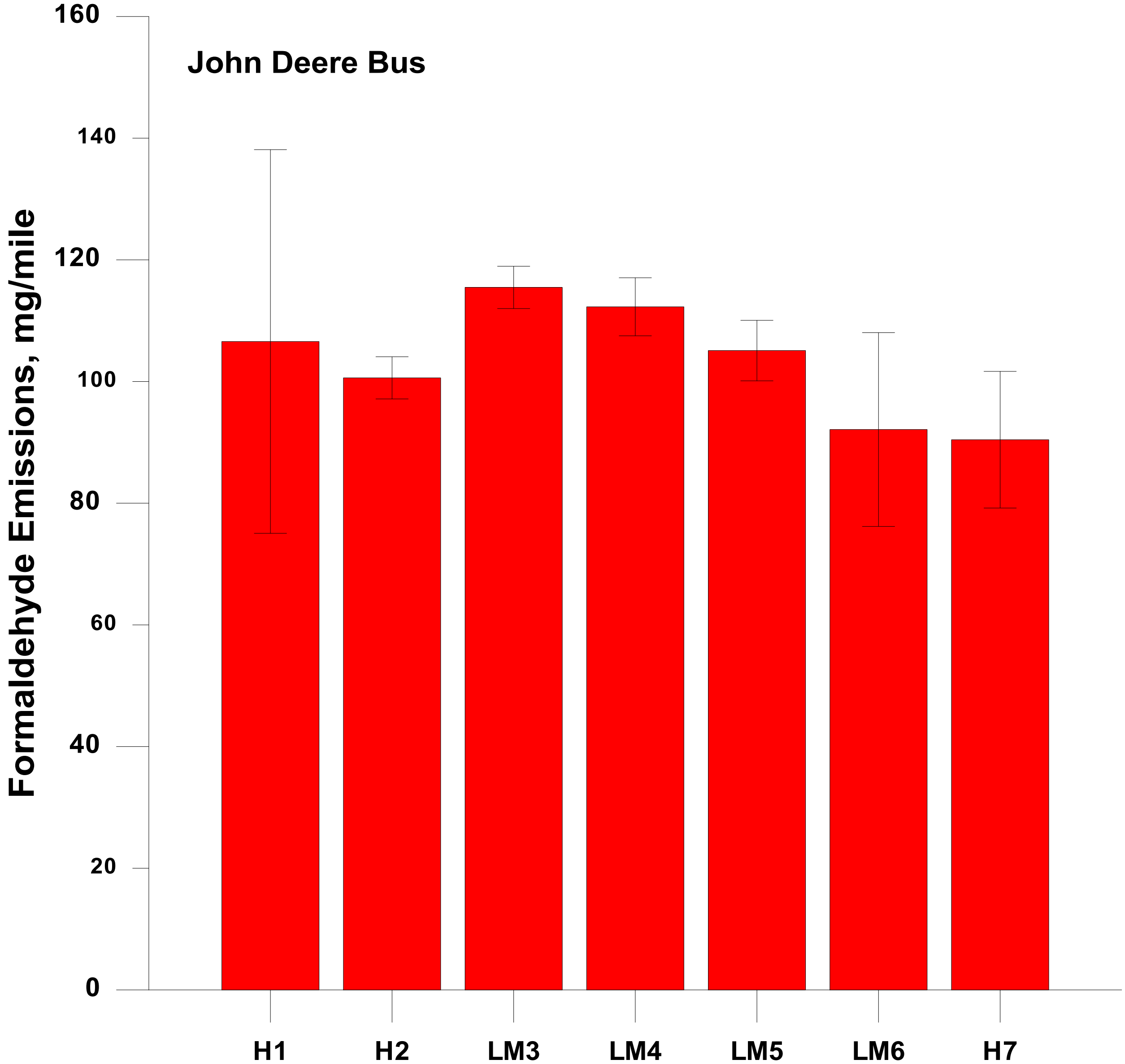
Source: CE-CERT

3.11 Carbonyl Emissions

Figure 55 and Figure 56 show the average formaldehyde and acetaldehyde emissions, respectively, for the lean-burn John Deere school bus over the CBD cycle. Formaldehyde and acetaldehyde emissions are the most prominent measured carbonyl emissions, with formaldehyde emissions being the highest. Formaldehyde and acetaldehyde are the lower molecular weight aldehydes, having one and two carbons, respectively. Generally, formaldehyde emissions do not show strong fuel trends over the CBD cycle with the exception of LM3 and LM4 fuels, which show statistically significant increases of 14.8 percent and 11.6 percent, respectively, compared to H2 and 27.7 percent and 24.2 percent, respectively, compared to H7. Formaldehyde emissions follow the same trends as the NMHC emissions, with the high methane fuels producing lower formaldehyde emissions.

Acetaldehyde emissions show clearer trends, with the low methane fuels producing higher concentrations of acetaldehyde emissions. Overall, acetaldehyde emissions show statistically significant increases of 41.9 percent and 50.6 percent, respectively, for LM4 and LM5, and marginally statistically significantly increases of 29.3 percent and 48.9 percent, respectively, for LM3 and LM6 all compared to H1. Compared to H7, acetaldehyde emissions show statistically significant increases of 34.8 percent, 47.9 percent, 57.1 percent, and 55.3 percent, respectively, for LM3, LM4, LM5, and LM6. Similar to formaldehyde emissions, acetaldehyde emissions follow that same trends as for the NMHC emissions, but opposite to the trends for the THC emissions.

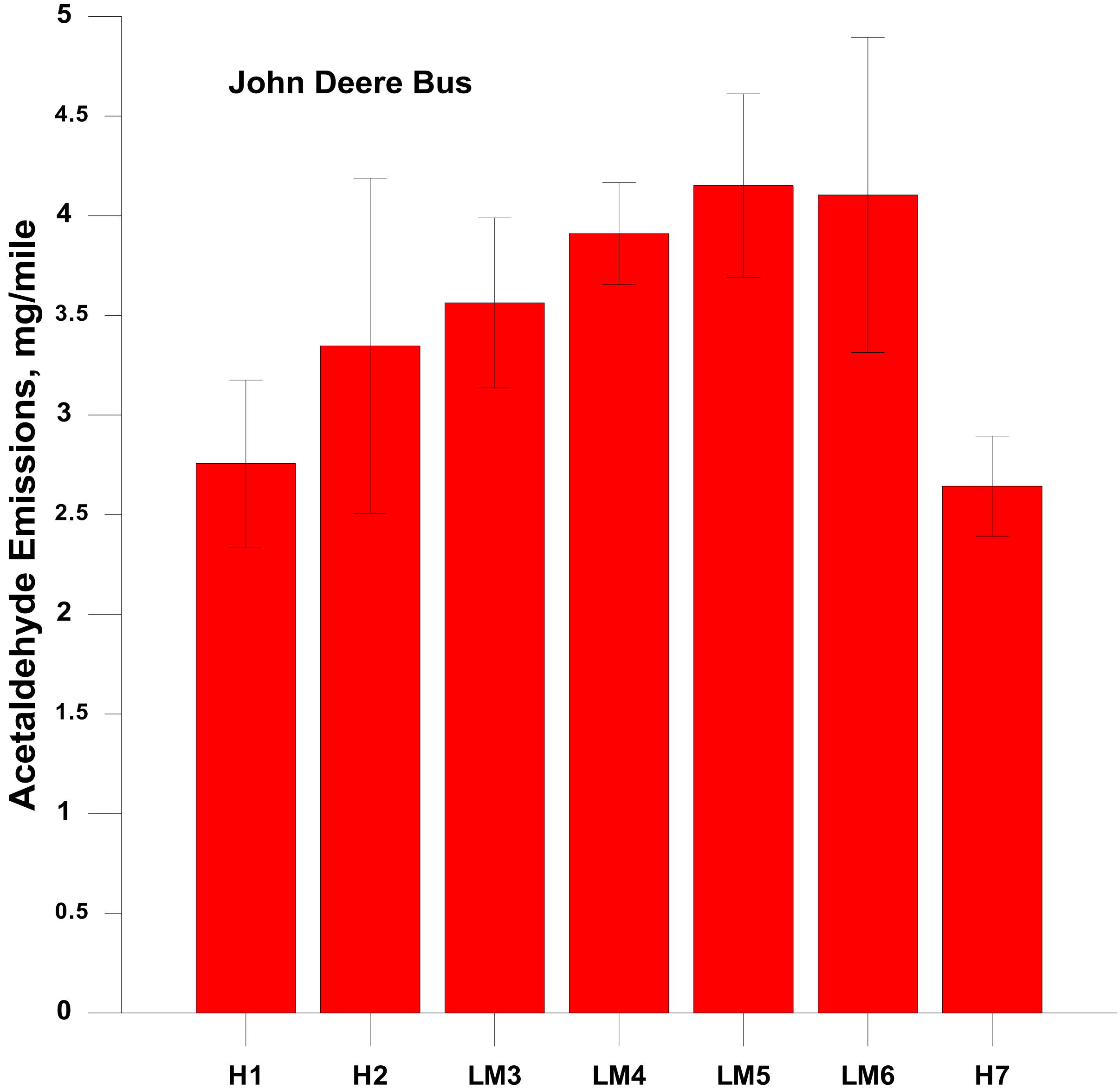
Figure 55: Average Formaldehyde Emissions for the John Deere Bus



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)

Source: CE-CERT

Figure 56: Average Acetaldehyde Emissions for the John Deere Bus

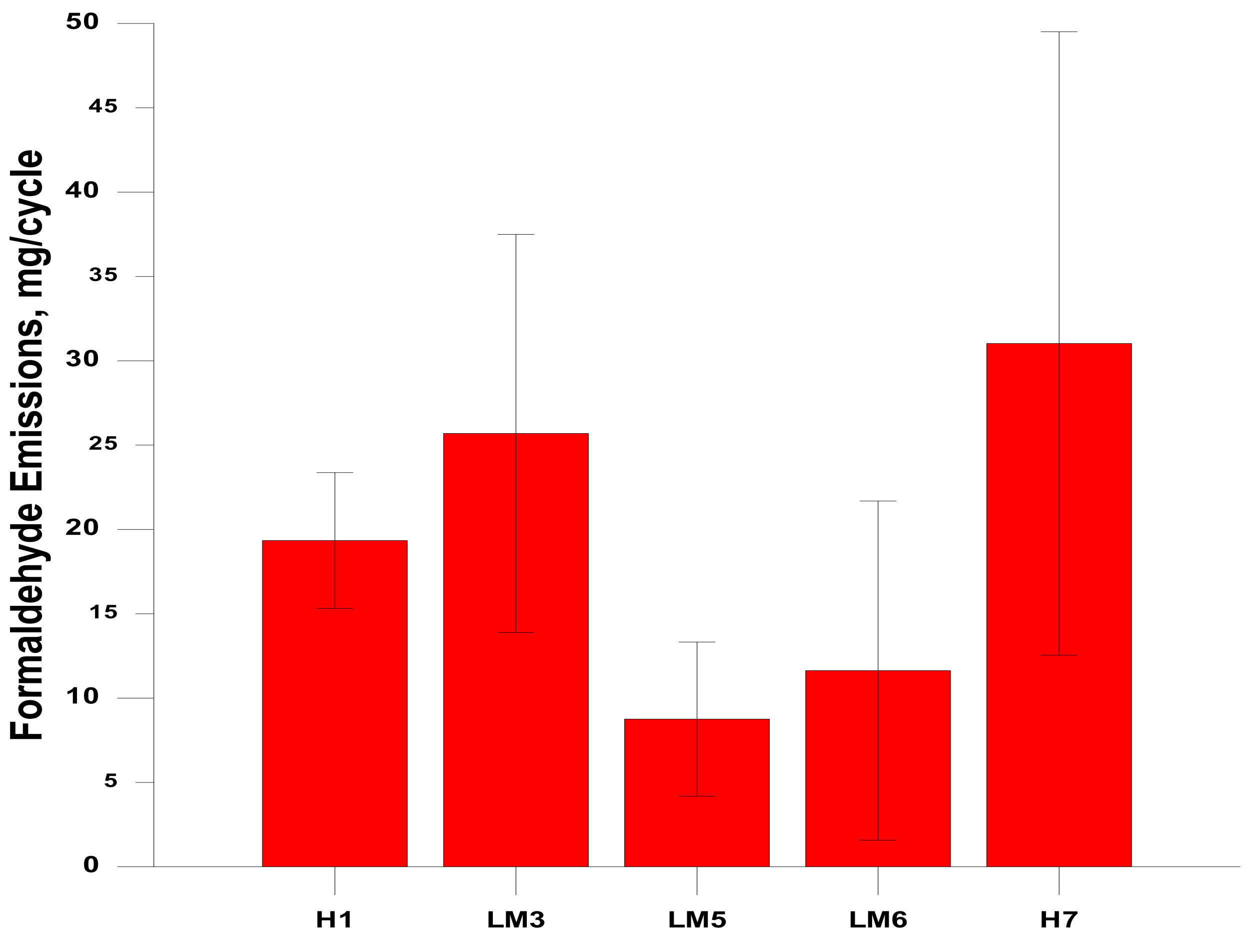


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 57 and Figure 58 show the average composite formaldehyde and acetaldehyde emissions, respectively, from the waste hauler truck. Similar to the PM emissions, the aldehyde emissions are presented in terms of mg/cycle because 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. Formaldehyde and acetaldehyde emissions are typically the most prominent measured carbonyl emissions, with formaldehyde emissions being the highest. Formaldehyde and acetaldehyde are the lower molecular weight aldehydes, having one and two carbons, respectively. Our results are consistent with previous studies showing that the dominant carbonyl emissions from CNG vehicles come from the lowest molecular weight compounds (Thiruvengadam, A. et al. 2011, Kado, N. et al. 2008, Okomoto, R. et al. 2006, Durbin et al. 2014). Formaldehyde emissions do not show any statistically significant fuel trends, with the exception of LM5 that shows a 54.7 percent decrease in formaldehyde emissions compared to H1 at a statistically significant level. Acetaldehyde emissions are at or below the background levels for most of the test fuels. Specifically, for all the test fuels with the exception of H7, the emissions results are either negative or have error bars that extent below zero. Acetaldehyde emissions show a marginally statistically significant increase of 313 percent for H7 relative to H1. The legacy refuse hauler tested in Phase 1 showed higher levels of formaldehyde and acetaldehyde compared to the refuse hauler in this study, with these two being the dominant aldehydes in the tailpipe (Durbin et al. 2014). The legacy vehicle exhibited strong trends for both aldehydes over the RTC, with the high methane fuels showing increased formaldehyde and acetaldehyde emissions compared to the low methane fuels.

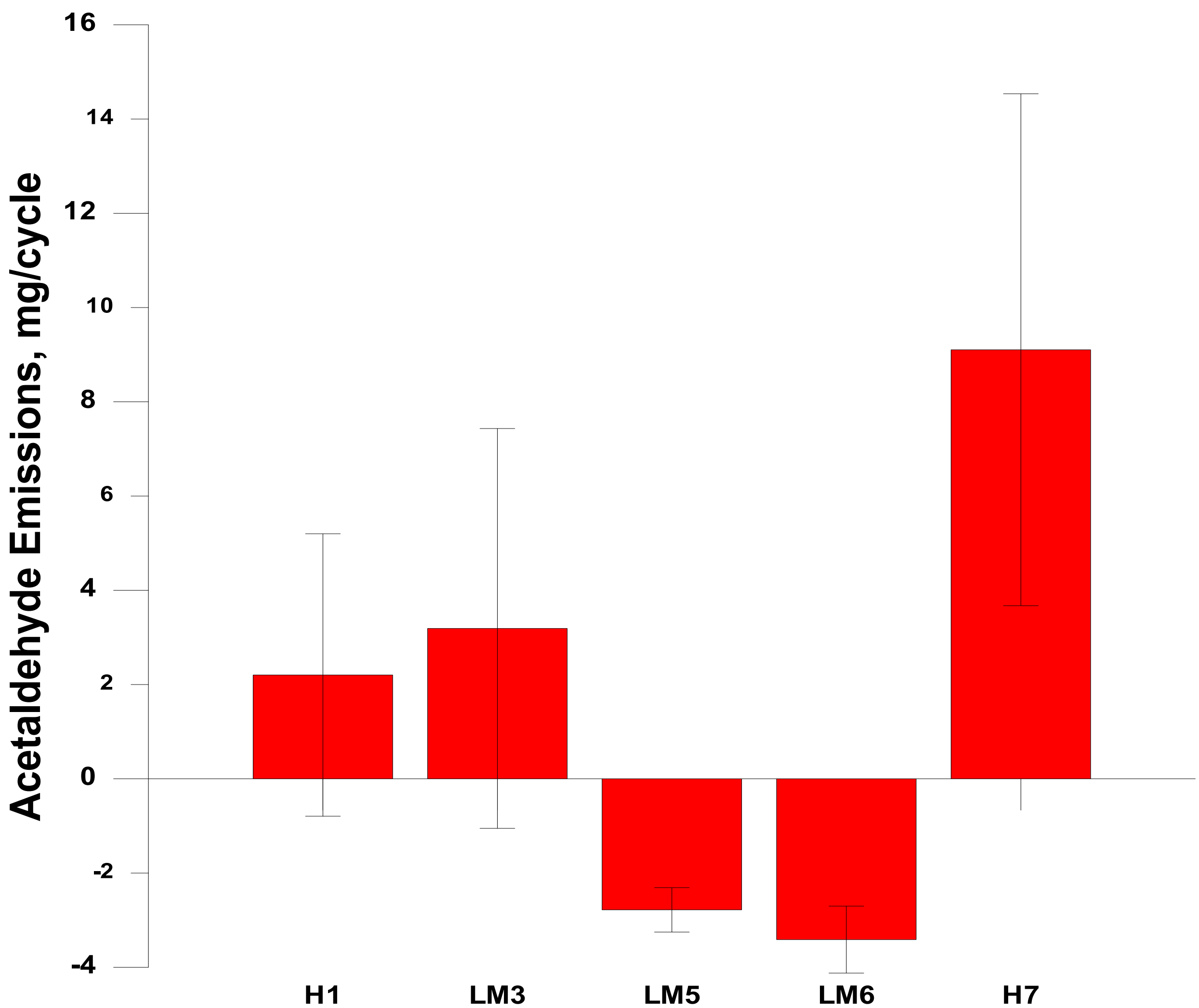
Figure 57: Average Formaldehyde Emissions for Waste Hauler



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)

Source: CE-CERT

Figure 58: Average Acetaldehyde Emissions for Waste Hauler Truck

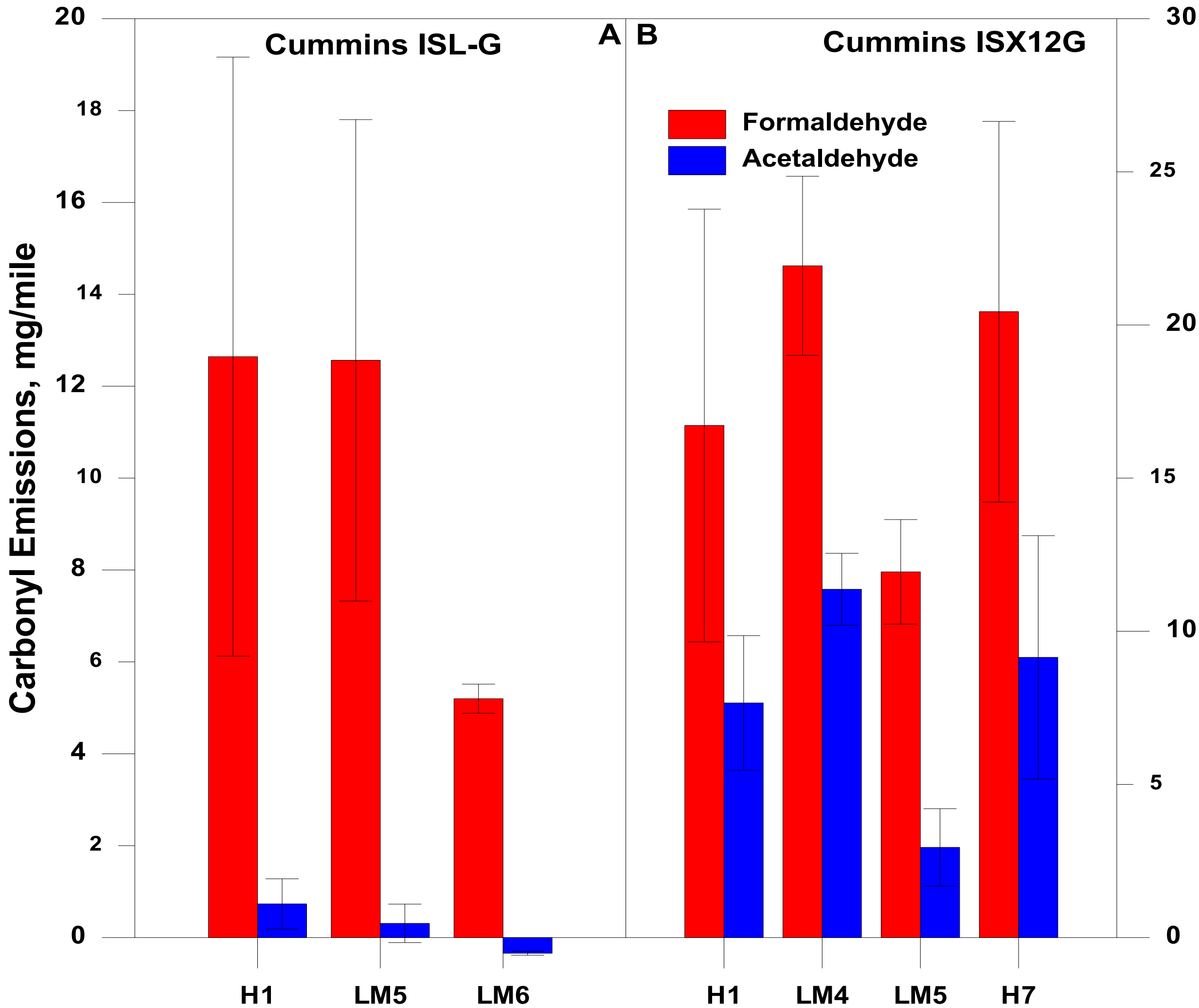


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 59 shows the formaldehyde and acetaldehyde emissions for the Cummins Westport ISL G (A) truck and Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and the Local Haul duty cycle, respectively. Formaldehyde and acetaldehyde emissions for these two vehicles were collected cumulatively over the entire test cycles, without separating the individual phases. Similar to the John Deere engine and the waste hauler truck, formaldehyde is the predominant aldehyde in the tailpipe for both Cummins engines followed by acetaldehyde, with the Cummins Westport ISX12 G engines showing higher aldehyde concentrations than the Cummins Westport ISL G engine. For the Cummins Westport ISL G engine, formaldehyde emissions show a declining trend for the low methane fuels and follow similar patterns with the THC emissions. However, there are no statistically significant differences between the test fuels for either the formaldehyde or the acetaldehyde emissions over the Near Dock duty cycle. For the Cummins Westport ISX12 G truck, formaldehyde emissions show a marginally statistically significant decrease of 41.6% for LM5 compared to H7, whereas acetaldehyde emissions show statistically significant decreases of 61.6% and 67.8%, respectively, for LM5 compared to H1 and H7. Formaldehyde and acetaldehyde emissions are also in agreement with THC emissions for this engine, but not with NMHC emissions.

Figure 59: Formaldehyde and Acetaldehyde Emissions for the Cummins Westport ISL G (A) and Cummins Westport ISX12 G (B) Class 8 Trucks Over the Near Dock Cycle and the Local Haul Duty Cycle



H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

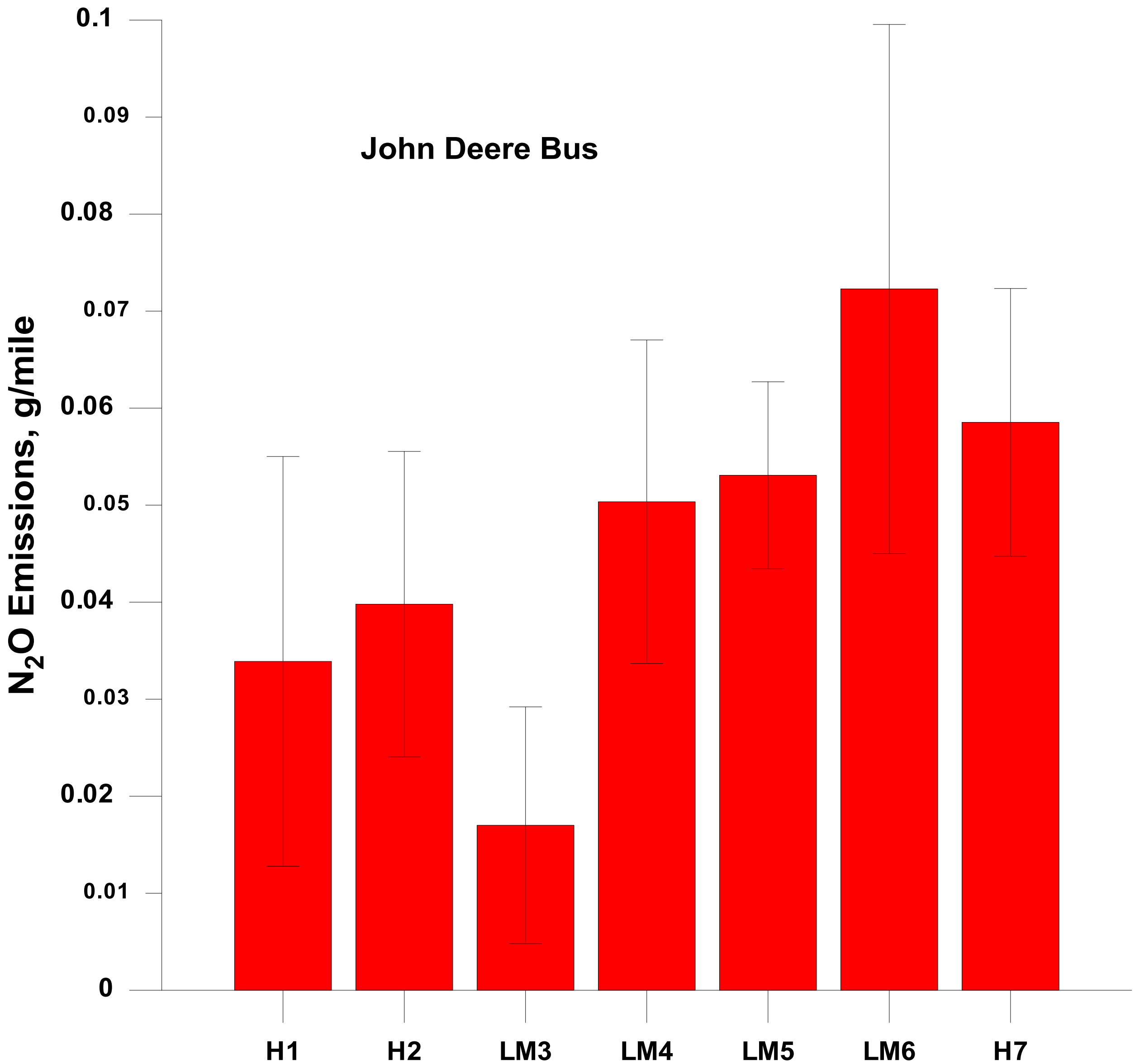
Source: CE-CERT

3.12 Nitrous Oxide Emissions

Nitrous oxide (N_2O) is both a toxic pollutant and a greenhouse gas. Although aftertreatment systems produce limited N_2O, it is included in recent greenhouse gas regulations, which count N_2O as CO_2 equivalents. N_2O counts as a CO_2 equivalent because, according to the Fifth Assessment Report (AR5), N_2O has a lifetime of approximately 121 years in the atmosphere and a Global Warming Potential (GWP) of 265 based on a 100 year time horizon (265 times more powerful than CO_2 on heat trapping effects) (Myhre, G. et al. 2013). Besides, N_2O is the major source of NOx in the stratosphere; therefore, an important natural regulator of stratospheric ozone.

Figure 60 shows the N_2O emissions for the John Deere school bus over the CBD test cycle. For the lean burn John Deere engine, N_2O emissions trend higher for the low methane fuels, i.e., LM3, LM4, LM5, and LM6, compared to the high methane fuels of H1, H2, and H7. Emissions of N_2O show marginally statistically significant increases of 40 percent, 38 percent, 79 percent, and 45 percent for LM3, LM4, LM5, and LM6, respectively, compared to H1. Compared to H2, the increases in N_2O emissions are on the order of 144 percent, 140 percent, 211 percent, and 152 percent for LM3, LM4, LM5, and LM6, respectively, at a statistically significant level; however, compared to H7 the increases in N_2O emissions are on the order of 49 percent, 47 percent, 91 percent, and 55 percent for LM3, LM4, LM5, and LM6, respectively, at a statistically and marginally statistically significant level.

Figure 60: N_2O Emissions for the John Deere Bus

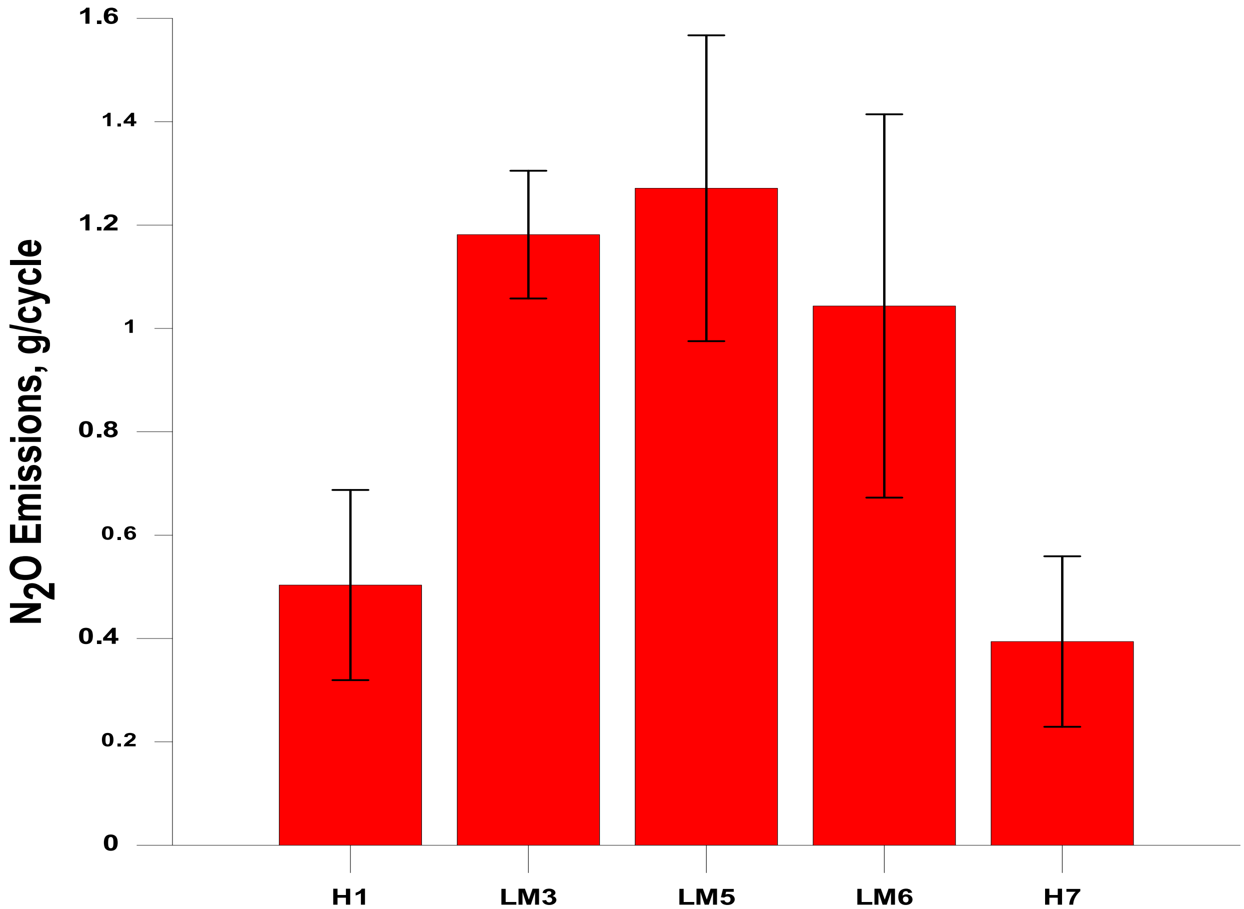


H1: Texas (1339 WN), H2: Rocky Mtn (1361 WN), LM3: Peruvian LNG (1385 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN)

Source: CE-CERT

Figure 61 shows the composite N_2O emissions for the waste hauler over the RTC. N_2O emissions ranged from 0.39 g/cycle to 1.27 g/cycle. Low methane fuels result in higher emissions of N_2O compared to the high methane fuels. The fuels LM3, LM5, and LM6 show statistically significant increases in N_2O emissions of 134.7 percent, 152.5 percent, and 107 percent and 200 percent, 223 percent, and 165 percent, respectively, compared to H1 and H7. N_2O emissions corroborate with NH_3 emissions and show an inverse relation to NOx emissions for the transport and curbside segments, as shown in Figure 8 (a-b).

Figure 61: N_2O Emissions for the Waste Hauler over the RTC



H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)

Source: CE-CERT

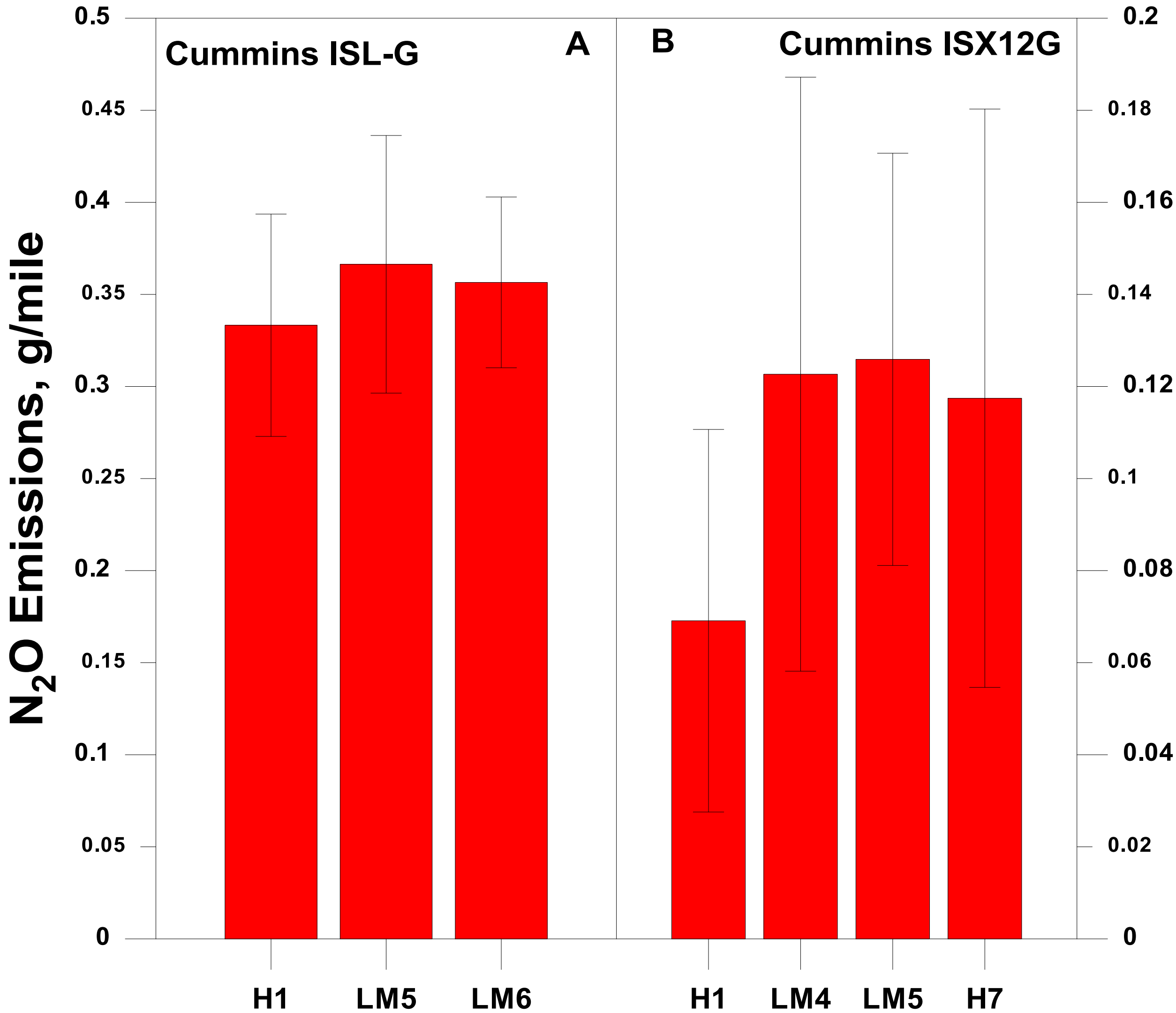
Figure 62 shows the N_2O emissions for the Cummins Westport ISL G (A) truck and the Cummins Westport ISX12 G (B) truck over the Near Dock duty cycle and the Local Haul duty cycle, respectively. In contracts to the NH_3 emissions, the Cummins Westport ISL G truck showed higher N_2O emissions compared to the Cummins Westport ISX12 G truck. Analogous to the John Deere bus and the waste hauler, both trucks show higher N_2O emissions for the low methane fuels. However, the differences in N_2O emissions between the test fuels are not statistically significant for either of the test vehicles.

Overall, our results show that selectivity towards N_2O emissions is highly dependent on fuel composition. All vehicles show a systematic increase in N_2O emissions with the low methane fuels, independent the engine technology and aftertreatment control. N_2O forms as an intermediate during the catalytic reduction of nitric oxide (NO) to molecular nitrogen (N_2). At high temperatures, NO is reduced to N_2; however, at lower temperatures, N_2O is an intermediate product. Some of the reactions involve, which take place between species adsorb on the surface of the TWC, are shown below (Gong, J. et al. 2013, Dasch, J. 1992, Behrentz, E. 2004). The richer combustion that gives rise to higher levels of CO and hydrogen (via the water-gas shift reaction) on the catalyst surface, will also promote the formation of N_2O. Hence, the increases in N_2O emissions for the low methane fuels are consistent with the corresponding increases seen for CO and hydrogen emissions for these fuels, especially for the stoichiometric Cummins Westport ISLG waste hauler, Cummins Westport ISL G truck, and Cummins Westport ISX12 G truck. For the lean burn John Deere engine, CO emissions are very low due to the presence of an OC and do not follow the same patterns as N_2O emissions. However, N_2O emissions corroborate with NOx emissions for this vehicle, suggesting that the low methane fuels produce more nitrogenous species under the present test conditions.

$$2NO + CO \xrightarrow{Pt/Pd/Rh} N_2O + CO_2$$

$$2NO + H_2 \xrightarrow{Pt/Pd/Rh} N_2O + H_2O$$

Figure 62: N_2O Emissions for the Cummins Westport ISL G (A) and Cummins Westport ISX12 G (B) Class 8 Trucks Over the Near Dock cycle and the Local Haul Duty



H1: Texas (1339 WN), LM4: Middle East LNG (1428 WN), LM5: Hi Ethane (1385 WN), LM6: Hi Propane (1385 WN), H7: L-CNG (1370 WN); Phase 1 = creep phase and Phase 2 = a low speed transient phase for both trucks. For the ISL-G Phase 3 is a short high-speed transient phase and for the ISX12G Phase 3 is a long high-speed transient phase.

Source: CE-CERT

CHAPTER 4: Summary

As the demand for NG in California and the production of NG throughout the United States. both expand, there is potential for a wider range of NG compositions to be used in NGVs. It is important to evaluate whether changing NG composition will have adverse impacts on the emissions or performance of NGVs. The current study addressed 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, three to seven blends of natural gas with different fuel compositions were tested. The fuels represent a range of compositions from fuels with high levels of methane and correspondingly lower energy contents and Wobbe numbers to fuels with higher levels of heavier hydrocarbons and correspondingly higher energy contents and Wobbe numbers. Emission testing was performed on a school bus (with a 2005 lean-burn combustion spark ignited engine and an oxidation catalyst), a waste hauler (with a 2011 stoichiometric spark ignited engine with cooled EGR and TWC) and two Class 8 trucks (one truck with a 2012 stoichiometric spark ignited engine with cooled EGR and TWC and one truck with a 2013 stoichiometric spark ignited engine with cooled EGR and TWC) on CE-CERT's heavy-duty chassis dynamometer. The John Deere school bus was tested over the CBD test cycle, the waste hauler was tested over the Refuse Truck cycle, while the Cummins Westport trucks were tested over the Near Dock duty cycle and the Local Haul duty cycle, respectively. The results of the test program show that fuel composition, engine operating conditions, and driving cycles had effects on the formation of exhaust emissions for all three vehicles. Consistent fuel effects were not seen for most of the pollutants for the newest technology vehicles with the stoichiometric engine with a TWC, however.

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

4.1 2005 John Deere School Bus

John Deere school bus emissions were evaluated over the Central Business District cycle on seven of the test fuels. Overall, the lean-burn John Deere engine show the strongest fuel effects for most of the pollutants compared to the stoichiometric Cummins trucks. Most pollutants show some fuel effects over the CBD cycle. The low methane fuels show higher NOx, NMHC, formaldehyde and acetaldehyde emissions, but lower THC and CH_4 emissions. Fuel economy/consumption on a volumetric basis shows increases for the low methane fuels with higher energy contents. Fuel economy/consumption on an energy equivalent basis and carbon dioxide emissions does not show strong trends. CO emissions are close to the tunnel background levels and showed practically no fuel effects, while both increases and decreases are seen for the PM mass emissions. Particle number show similar fuel trends over the three cycle segments, but the fuels showing lower particle numbers include some high methane fuels (i.e., H2) and some low methane fuels (i.e., LM3 and LM4). Ammonia emissions show some fuel differences, but no consistent fuel trends over the CBD cycle. Additionally, ammonia emissions are found at substantially lower levels than the stoichiometric Cummins engines.

4.2 2011 Cummins Westport ISL G Waste Hauler

The Cummins Westport ISL G waste hauler was tested on the Refuse Truck cycle on test fuels H1, H7, LM3, LM5, and LM6. THC, NMHC, CH_4, NOx, formaldehyde, and acetaldehyde emissions for the Westport ISL-G waste hauler are considerably lower than these emissions from previous studies of lean burn technology engines. The Cummins Westport ISL-G waste hauler does; however, show higher CO and NH_3 emissions compared to older lean burn engines. The results show reductions in NOx emissions for the low methane fuels for the Transport and Curbside cycles, which could be due to richer combustion with these fuels. NOx emissions for the compaction cycle are very low. CO and NH_3 emissions, on the other hand, showed a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. THC and CH_4 emissions do not show any consistent fuel trends, while NMHC emissions show a trend of higher emissions for the fuels containing higher levels of NMHCs (i.e., ethane, propane, and butane). Fuel economy/consumption on a volumetric basis shows some differences between the various test fuels, with LM3, LM5, and LM6, with low methane fuels showing higher fuel economy on a volumetric basis compared to H1 and H7. Fuel economy/consumption on an energy equivalent basis and CO_2 emissions does not show significant trends, except for some CO_2 reductions for H7 compared to LM3, LM5, and LM6 for the compaction cycle. PM mass and acetaldehyde emissions are very low for refuse truck on an absolute level, are at the same levels as the tunnel background, and do not show statistically significant differences between test fuels. PN emissions and formaldehyde emissions do not show strong fuel trends for the different RTC segments. The particle size distributions show bimodal distributions, with a majority of the particles in the nucleation mode with particle diameters centered from 9 to 11 nm size range. N_2O emissions show significant fuel effects, with the low methane fuels resulting in higher emissions of N_2O compared to high methane fuels.

4.3 2012 Cummins Westport ISL G Truck

The Cummins Westport ISL G truck was tested on the Near Dock duty cycle, which is a segment of the drayage truck port cycle. Testing was conducting for only three of the main test fuels, namely, H1, LM5, and LM6. Low methane fuels show lower THC and CH_4 emissions. For the NMHC emissions, there are some, but not consistent, increases with low methane fuels. The low methane fuels show lower NOx emissions, while CO and NH_3 emissions show increases with the low methane fuels. Low methane fuels with higher energy contents show higher fuel economy on a volumetric basis. One of the low methane fuels shows higher PM mass emissions, while formaldehyde, acetaldehyde, and CO_2 emissions do not show any significant fuel trends. Particle size distributions show a bimodal particle size profile, with the accumulation mode being the prevalent particles.

4.4 2013 Cummins Westport ISX12 G

The truck with a 2013 Cummins Westport ISX12 G was tested over the Local Haul duty cycle, and was the newest technology tested during this program. In general, most of the gaseous emissions for this engine are found at higher concentrations when compared to the Cummins ISL G engines. NMHC, CO, and NH_3 emissions are higher for the low methane fuels, while NOx, THC, and CH_4 emissions are lower for some low methane fuels. Volumetric fuel economy and energy equivalent fuel economy are higher for the low methane fuels. CO_2, PM mass, formaldehyde and acetaldehyde emissions do not show strong trends between the test fuels. The particle size distributions present a decidedly bimodal distribution and show a nucleation peak around 10 nm. The accumulation mode particles range from 60 to 70 nm size range.

4.5 General

The results show that fuel composition, engine operating conditions, and driving cycle have effects on the formation of exhaust emissions from all test vehicles. In general, low methane fuels show higher NOx and NMHC emissions and improved fuel economy on a volumetric basis, but lower THC and CH_4 emissions. While these phenomena are particularly strong for the older lean-burn John Deere engine, the newer stoichiometric Cummins engines also showed relatively strong trends. For the gaseous toxic pollutants, such as formaldehyde and acetaldehyde, the lean-burn technology bus shows the most consistent trends with the low methane fuels showing higher emission levels of formaldehyde and acetaldehyde compared to the high methane fuels. The stoichiometric Cummins vehicles with TWC systems show significantly higher NH_3 emissions than the lean-burn engine with the OC. For NH_3 emissions, the fuel effect is particularly strong with the low methane fuels showing higher NH_3 emissions than the high methane fuels. The trends for PM mass and particle number emissions are not as consistent. Particle size distributions for all test vehicles show bimodal distributions with the accumulation mode particles dominating the particle size distribution profile for most of the test vehicles.

CHAPTER 5: Conclusions and Recommendations

As the demand for NG in California and the production of NG throughout the United States 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 these issues. These results may also be used in CARB's ongoing process to amend the California NG fuel standards for motor vehicles.

In this study, three to seven blends of natural gas with different fuel compositions were tested. The fuels represent a range of compositions from fuels with high levels of methane and correspondingly lower energy contents and Wobbe numbers to fuels with higher levels of heavier hydrocarbons and correspondingly higher energy contents and Wobbe numbers. Emission testing was performed on one school bus (a bus with a 2005 lean-burn combustion spark ignited engine and an OC), on a waste hauler with a 2011 stoichiometric spark ignited engine and a TWC, and on two Class 8 trucks with 2012 and 2013 stoichiometric spark ignited engines and a TWC, respectively, on CE-CERT's heavy-duty chassis dynamometer.

The results show that fuel composition, engine operating conditions, and driving cycle have effects on the formation of exhaust emissions from all test vehicles. The older vehicle shows trends that are generally consistent with those of previous studies. Low methane fuels show higher NOx and NMHC emissions and higher fuel economy on a volumetric basis but lower emissions of THC and CH_4. For the gaseous toxic pollutants, such as formaldehyde and acetaldehyde, the lean-burn technology bus shows the most consistent trends with the low methane fuels showing higher emission levels of formaldehyde and acetaldehyde compared to high methane fuels. The stoichiometric Cummins vehicles with TWC systems show significantly higher NH_3 emissions than the lean-burn engine with the OC. For NH_3 emissions, the fuel effect is particularly strong with the low methane fuels showing higher NH_3 emissions than the high methane fuels. The trends for PM mass and particle number emissions are not as consistent. Particle size distributions for all test vehicles show bimodal distributions with the accumulation mode particles dominating the particle size distribution profile for most of the test vehicles.

The results suggest that natural gas fuel composition can have an impact on emissions for older technology heavy-duty vehicles, even for fuels within pipeline specifications, albeit at the extreme ranges of what might be found in the pipeline. Control of natural gas specification is still needed for older technology heavy-duty NGVs. Newer heavy-duty natural gas engines can run on a wider range of NG fuels with varying composition, consistent with the Phase 1 results of this program, and that this holds true for a wider range of applications, such as waste haulers and port trucks.

GLOSSARY

Term	Definition
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
CO_2	carbon dioxide
CPC	condensation particle counter
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
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	nonmethane hydrocarbons
NOx	nitrogen oxides
OC	Oxidation Catalyst
PAHs	polycyclic aromatic hydrocarbons
PM	particulate matter
PN	particle number
SCAQMD	South Coast Air Quality Management District
SOF	soluble organic fraction
tcf	trillion cubic feet
TDL	tunable diode laser
THC	total hydrocarbons
TWC	Three-Way Catalyst
UCR	University of California, Riverside
WN	Wobbe number - higher heating value divided by the square root of the specific gravity with respect to air
WVU	West Virginia University

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APPENDIX A:
Engine Certification value

2005 John Deere 8.1L 6081H School bus

California Environmental Protection Agency AIR RESOURCES BOARD	DEERE POWER SYSTEMS GROUP OF DEERE	EXECUTIVE ORDER A-108-0037 New On-Road Heavy-Duty Engines

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]
2005	5JDXH08.1067	8.1	CNG	Diesel	MHDD	TBI, TC, CAC, ECM, O2S,OC

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
8.1	6081H : [6081HFN04G (250), 6081HFN04H (250), 6081HFN04E (250), 6081HFN04F (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;
[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; WU (prefix) =warm-up catalyst; DPF=diesel particulate filter; 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=exhaust gas recirculation; 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; (2004may26)

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.1 (urban bus) or 13 CCR 1956.8 (other than urban bus); 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, in g/bhp-hr, 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 1956.1 or 13 CCR 1956.8 are in parentheses.) [4]

	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO
STD	*	*	*	*	1.5	1.5	15.5	15.5	0.01	0.01	*	*
FEL	*	*	*	*	*	*	*	*	*	*	*	*
CERT	*	*	*	*	1.2	1.5	0.1	0.2	0.01	0.01	*	*
NTE	*		*		1.875		19.375		0.0125		*	

[4] g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; EURO=Euro III European Steady-State Cycle; 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;

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

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.

Executed at El Monte, California on this 1st day of February 2005.

Raphael Susnowitz
for Allen Lyons, Chief
Mobile Source Operations Division

2011 Cummins Westport ISL G Waste Hauler

California Environmental Protection Agency AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0537 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 [6]
2011	BCEXH0540LBH	8.9	CNG/LNG	Diesel	HHDD	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 280 / 3517;FR93282 (280), ISL G 260 / 3517;FR93284 (260), ISL G 250 / 3517;FR93287 (250) ISL G 320 / 3517;FR93276 (320), ISL G 300 / 3517;FR93279 (300)

* =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	0.08	0.08	0.13	0.01	*	*	14.2	11.6	0.002	0.001	*	*
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.

Executed at El Monte, California on this 23 day of December 2010.

Annette Hebert

Annette Hebert, Chief
Mobile Source Operations Division

2012 Cummins Westport ISL-G 8.9L truck

California Environmental Protection Agency AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0563 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 [6]
2012	CCEXH0540LBH	8.9	CNG/LNG	Diesel	HHDD	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 280 / 3519;FR93282 (280), ISL G 260 / 3519;FR93284 (260), ISL G 250 / 3519;FR93287 (250) ISL G 320 / 3519;FR93276 (320), ISL G 300 / 3519;FR93279 (300)

* =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	0.08	0.08	0.13	0.01	*	*	14.2	11.6	0.002	0.001	*	*
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.

Executed at El Monte, California on this 18 day of October 2011.

Annette Hebert

Annette Hebert, Chief
Mobile Source Operations Division

2013 Cummins Westport ISX12G 11.9 L truck

California Environmental Protection Agency **Air Resources Board**	**CUMMINS INC.**	**EXECUTIVE ORDER A-021-0591** **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 [6]
2013	DCEXH0729XBA	11.9	CNG/LNG	Diesel	HHDD	TBI, TC, CAC, ECM, EGR, TWC, HO2S	EMD

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

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
11.9	ISX12 G400 / 3647;FR20288 (400), ISX12 G385 / 3647;FR20290 (385), ISX12 G 350 / 3647;FR20292 (350), ISX12 G350 / 3647;FR20296 (350), ISX12 G 330 / 3647;FR20298 (330), ISX12 G 320 / 3647;FR20300 (320)

* =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;

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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	0.03	0.01	0.15	0.03	*	*	8.7	6.4	0.003	0.01	*	*
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)**

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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), 13 CCR 1971 (engine manufacturer diagnostic) 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.

Executed at El Monte, California on this 3rd day of April 2013.

for **Annette Hebert, Chief**
Mobile Source Operations Division

APPENDIX B. Emissions Test Results

Averages, percentage differences, and P-values

2005 John Deere 8.1L 6081H school bus

	THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	CO_2 g/mile	NH_3 g/mile	miles/gge	miles/ft³	Forma mg/mile	Acetal mg/mile	PM mg/mile
H1	14.068	12.912	1.140	-0.054	10.99	1658.7	51.040	3.905	0.032	106.578	2.756	0.003
H2	13.943	12.510	1.440	-0.308	12.25	1655.0	27.486	3.910	0.032	100.608	3.347	0.006
LM3	12.685	10.507	2.213	-0.214	14.68	1660.4	33.791	3.911	0.033	115.476	3.563	0.010
LM4	11.616	9.489	2.181	0.000	14.85	1678.3	46.378	3.915	0.035	112.284	3.910	0.004
LM5	12.189	9.595	2.658	-0.009	13.81	1667.7	27.862	3.943	0.035	105.087	4.151	0.001
LM6	12.434	10.150	2.349	-0.011	12.56	1666.7	39.890	3.947	0.035	92.105	4.104	0.003
H7	12.918	11.746	1.181	-0.067	11.73	1620.7	30.324	3.961	0.033	90.437	2.643	0.004

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1)

2011 Cummins Westport 8.9L ISL-G 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	3.09	2.94	0.15	21.13	0.83	769.67	1341.87	4.770	0.038	5.82E+12
LM3	3.59	2.90	0.69	34.62	0.72	929.85	1332.05	4.757	0.041	5.93E+12
LM5	3.50	2.77	0.75	33.80	0.66	1005.35	1309.14	4.892	0.043	6.31E+12
LM6	3.05	2.53	0.54	29.41	0.75	979.46	1307.24	4.932	0.044	6.84E+12
H7	2.77	2.55	0.22	16.60	0.96	770.02	1315.94	4.826	0.039	4.99E+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	8.86	9.06	-0.15	35.77	8.31	603.71	4972.83	1.314	0.011	2.62E+13
LM3	7.01	5.97	1.07	49.67	6.28	931.54	5112.92	1.274	0.011	2.86E+13
LM5	9.03	7.41	1.69	58.32	7.37	910.96	5121.65	1.282	0.011	2.41E+13
LM6	8.33	7.16	1.24	59.98	6.85	921.33	5190.06	1.267	0.011	2.90E+13
H7	8.27	8.20	0.09	21.09	10.32	484.99	4993.96	1.291	0.010	2.85E+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	0.31	0.30	0.02	3.40	0.0004	295.79	500.72	0.077	9.542	1.73E+12
LM3	0.38	0.29	0.09	4.23	-0.0006	396.29	512.56	0.078	9.168	7.47E+11
LM5	0.36	0.28	0.08	4.31	0.0035	413.09	510.00	0.077	8.742	7.62E+11
LM6	0.37	0.30	0.07	4.20	0.0056	398.66	514.01	0.078	8.796	1.55E+12
H7	0.37	0.32	0.05	3.55	0.0086	315.85	494.89	0.077	9.551	1.78E+12

2012 Cummins Westport 8.9L ISL-G truck

		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	CO_2 g/mile	NH_3 g/mile	miles/gge	miles/ft^3	Formal mg/mile	Acetal mg/mile	PM mg/mile
H1	Total[1]	4.601	4.543	0.073	4.611	9.005	2122.59	575.674	3.079	0.025	12.643	0.733	0.0028
	Phase 1	199.204	186.233	12.957	40.371	162.175	22855.37	335.433	0.282	0.002			
	Phase 2	13.137	12.788	0.379	1.514	28.312	3714.88	163.421	1.758	0.014			
	Phase 3	2.161	2.230	-0.056	4.746	5.495	1776.40	629.230	3.686	0.030			
LM5	Total	3.658	3.379	0.328	9.735	7.088	2139.27	786.925	3.100	0.027	12.564	0.309	0.0044
	Phase 1	134.386	107.503	27.690	3.834	163.472	21253.02	429.803	0.318	0.003			
	Phase 2	9.016	8.118	1.007	7.232	22.228	3751.17	503.434	1.772	0.016			
	Phase 3	1.935	1.950	0.021	10.084	3.921	1782.17	825.508	3.722	0.033			
LM6	Total	3.880	3.979	-0.021	11.101	5.701	2117.68	676.097	3.130	0.028	5.199	-0.341	0.0027
	Phase 1	167.856	160.653	9.728	40.163	165.727	24523.82	504.533	0.272	0.002			
	Phase 2	9.046	9.397	-0.163	5.831	20.805	3764.99	478.265	1.769	0.016			
	Phase 3	2.149	2.262	-0.066	11.564	2.736	1762.04	701.416	3.760	0.033			

[1] The individual phases are Phase 1 = creep phase, Phase 2 = a low speed transient phase, and Phase 3 = a short high-speed transient phase.

2013 Cummins Westport 11.9L ISX12G truck

		THC g/mile	CH_4 g/mile	NMHC g/mile	CO g/mile	NOx g/mile	CO_2 g/mile	NH_3 g/mile	miles/gge	miles/ft^3	PM mg/mile	Formal mg/mile	Acetal mg/mile
H1	Total[2]	1.969	1.924	0.050	10.046	0.507	2188.21	878.248	2.987	0.024	0.018	16.71	7.66
	Phase 1	46.931	44.736	2.245	2.748	4.525	24123.85	676.144	0.276	0.002			
	Phase 2	20.628	19.636	1.013	13.921	2.163	4304.65	832.175	1.506	0.012			
	Phase 3	0.508	0.537	-0.025	9.802	0.376	1964.85	882.330	3.331	0.027			
LM4	Total	1.919	1.765	0.176	14.211	0.514	2205.78	1131.954	3.000	0.027	0.02545	21.93	11.37
	Phase 1	52.935	50.346	3.342	16.404	2.620	24078.69	429.650	0.279	0.003			
	Phase 2	17.084	15.136	2.122	31.076	1.472	4278.85	1526.259	1.536	0.014			
	Phase 3	0.626	0.620	0.016	13.456	0.401	1985.17	1125.560	3.336	0.030			
LM5	Total	1.917	1.776	0.159	16.099	0.409	2157.66	1186.863	3.067	0.027	0.01948	11.93	2.945
	Phase 1	49.032	45.508	3.987	12.550	4.548	29227.82	550.977	0.238	0.002			
	Phase 2	17.929	15.416	2.613	33.566	1.460	4398.62	1791.834	1.491	0.013			
	Phase 3	0.672	0.706	-0.022	14.884	0.324	1925.69	1146.363	3.440	0.030			
H7	Total	2.281	2.294	0.001	10.439	0.512	2142.28	972.635	3.035	0.025	0.018	20.43	9.148
	Phase 1	73.481	71.317	2.491	18.537	5.955	22936.17	326.990	0.286	0.002			
	Phase 2	23.072	22.067	1.090	21.669	2.182	4520.54	1619.363	1.454	0.012			
	Phase 3	0.570	0.661	-0.083	9.628	0.376	1903.36	929.983	3.420	0.028			

[2] The individual phases are Phase 1 = creep phase, Phase 2 = a low speed transient phase, and Phase 3 = a long high-speed transient phase.

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. 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.