**Final Report**

# Evaluation of the Performance and Air Pollutant Emissions of Vehicles Operating on Various Natural Gas Blends – Phase 2

## Contract Number: 12-412

**Prepared for:**

The California Air Resources Board and California Environmental Protection Agency

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**Acronyms and Abbreviations**

ARB ....................................................Air Resources Board
bhp ………………………………… brake horse power
bhp-hr ……………………………… brake horse power - hour
CAI......................................................California Analytical Instruments
CARB..................................................California Air Resources Board
CE-CERT...........................................College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CEC....................................................California Energy Commission
CBD ...................................................Central Business District
CFR ....................................................Code of Federal Regulations
$CH_4$…………………………………Methane
CNG ...................................................compressed natural gas
CO ......................................................carbon monoxide
$CO_2$....................................................carbon dioxide
CPC ....................................................condensation particle counter
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
LPM ...................................................liters per minute
MEL ...................................................CE-CERT's Mobile Emissions Laboratory
MN.....................................................methane number
mL ......................................................milliliter
mpg ....................................................miles per gallon
$m/s^2$ ...................................................meters per second squared
$N_2O$ ....................................................nitrous oxide
NDIR……………………………….non-dispersive infrared detector
NG......................................................natural gas
NGL…………………………………natural gas liquid
NGV...................................................natural gas vehicle

$NH_3$ ....................................................ammonia
nm………………………………….. nanometer
NMHC................................................non-methane hydrocarbons
$NO_x$ ....................................................oxides of nitrogen
OC…………………………………..Oxidation Catalyst
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

**Abstract**

The composition of natural gas (NG) can have an important impact on the emissions and performance of natural gas vehicles (NGVs). With the expansion of NG production via horizontal drilling and hydraulic fracturing as well as the potential of liquefied natural gas (LNG) from the Costa Azul LNG terminal in Baja California, Mexico, there is the potential for a wider range of NG compositions being used throughout California. The objective of the present study was to evaluate the impact of NG composition on the performance and emissions of heavy-duty vehicles. This study evaluated the gaseous and particulate matter (PM) emissions, fuel economy, and other emissions from a NG waste hauler over the Refuse Truck Cycle (RTC) on a heavy-duty chassis dynamometer on a range of five different test fuels. The vehicle was equipped with a 2011 model year spark ignition stoichiometric engine with cooled exhaust gas recirculation (EGR) and a three-way catalyst (TWC). Total hydrocarbons (THC), non-methane hydrocarbons (NMHC), methane ($CH_4$), nitrogen oxides ($NO_x$), formaldehyde, and acetaldehyde emissions for this waste hauler were considerably lower than these emissions from previous studies of lean burn technology engines. This waste hauler did, however, show higher carbon monoxide (CO) and ammonia ($NH_3$) emissions compared to older lean burn engines. The results showed lower $NO_x$ emissions for the low methane fuels (i.e., natural gas fuels with a relatively low methane content) for the transport and curbside cycles. This could be due to richer combustion with these fuels, which would promote greater reduction of $NO_x$ emissions over the TWC. $NO_x$ emissions for the compaction cycle were very low, and were either at the background levels or were considerably below the 0.2 g/bhp-hr standard. THC and $CH_4$ emissions did not show any consistent fuel trends. NMHC emissions showed a trend of higher emissions for the fuels containing higher levels of NMHCs (i.e., ethane, propane, and butane). CO emissions showed a trend of higher emissions for the low methane fuels. The higher CO emissions could be due to slightly richer combustion for the low methane fuels, which could make oxidation of the CO slightly more difficult either during combustion or over the catalyst. Fuel economy/consumption on a volumetric basis showed some differences between the various test fuels. The low methane fuels generally showed higher fuel economy on a volumetric basis compared to the higher MN fuels. Fuel economy/consumption on an energy equivalent basis did not show any statistically significant trends. Carbon dioxide ($CO_2$) emissions did not show any statistically significant trends for either the transport or curbside cycles, but did show some reductions for some fuels for the compaction cycle. PM mass emissions were very low and there were no statistically significant differences between the test fuels. Total particle number emissions did not show strong fuel trends for the different RTC segments. The particle size distributions showed bimodal distributions, with a majority of the particles in the nucleation mode with particle diameters centered from 9 to 11 nm size range. Ammonia emissions showed a trend of higher emissions for the low methane fuels. The higher $NH_3$ emissions could be due to slightly richer combustion for the low methane fuels, which could make oxidation of the $NH_3$ slightly more difficult either during combustion or over the catalyst. Nitrous oxide ($N_2O$) emissions were lower with the low methane fuels. Formaldehyde emissions did not show any statistically significant fuel trends, while acetaldehyde emissions were at or below the background levels for most of the test fuels.

## Executive Summary

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

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

The objective of the present study is to evaluate the impact of NG composition on the performance and emissions of heavy-duty vehicles. For this study, a NG waste hauler was tested over the RTC on a heavy-duty chassis dynamometer on a range of five different test fuels. The test vehicle was a waste hauler 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). The certification value for this engine is provided in Appendix A. Waste hauler truck emissions were evaluated over a RTC that included transport, compaction, and curbside segments.

The test fuels included a historical fuel representative of Texas Pipeline gas (H1), and an L-CNG fuel, which is a natural gas blend produced from liquefied natural gas, identified as H7. Fuel (H1) was also considered to be the base fuel for comparisons. Since NG-fueled waste haulers come equipped for dedicated fueling on either LNG or CNG, an L-CNG fuel was included to capture the LNG fueled base line. Note that LNG refers to North American supplies that have been processed to take out most components heavier than methane. Three fuels with lower levels of methane were also tested, including a Peruvian LNG with nitrogen added to achieve a Wobbe Number of 1385 (LM3), and two fuels with high WN and low MN, one with a high ethane content and the other with a high propane content, identified as LM5 and LM6. The WN and MN are the same for both LM5 and LM6. The fuels were designed to determine whether there are differences due to composition. The main properties of the test fuels are provided in Table ES-1. Note that since these fuels were all used in the Phase 1 test program (contract# 09-416), the fuel names were kept the same as those used in the previous program to maintain consistency between the two studies.

The results of this study are summarized below and in Table ES-2. Comparisons between test fuels were made for regulated exhaust emissions, fuel economy, PM mass, particle number (PN) and particle size distributions, ammonia emissions, $N_2O$ emissions, and carbonyl compounds emissions. Table ES-2 provides the percentage differences between the different fuels compared to the baseline H1 fuel. More detailed emissions results and corresponding p-values for the statistical analyses are provided in Appendix B.

**Table ES-1. Test Fuel Specifications**

| Fuel # | 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 |
| **LM3** | **Peruvian LNG** | 88.3 | 10.5 | 0 | 0 | 1.2 | 0 | 84 | 1385 | 1083 | 3.81 |
| **LM5** | **High Ethane** | 83.65 | 10.75 | 2.7 | 0.2 | 2.7 | 0 | 75.3 | 1385 | 1115 | 3.71 |
| **LM6** | **High Propane** | 87.2 | 4.5 | 4.4 | 1.2 | 2.7 | 0 | 75.1 | 1385 | 1116 | 3.70 |
| **H7** | **L-CNG fuel** | 98.4 | 1.26 | 0.05 | 0.02 | 0.25 | 0 | 104.5 | 1363 | 1023 | 3.97 |

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)

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

- THC, NMHC, $CH_4$, $NO_x$, formaldehyde, and acetaldehyde emissions for the Westport ISL-G waste hauler were considerably lower than these emissions from previous studies of lean burn technology engines.

- The Cummins Westport ISL-G waste hauler did, however, show higher CO and $NH_3$ emissions compared to older lean burn engines. This could be attributed to the richer operation for the stoichiometric engine compared to the lean burn engines, as well as the TWC for the $NH_3$ emissions.

- The results showed reductions in $NO_x$ emissions for the low methane fuels for the transport and curbside cycles. This could be due to richer combustion with these fuels, which would promote greater reduction of $NO_x$ emissions over the TWC. $NO_x$ emissions for the compaction cycle were very low, and were either at the background levels or were considerably below the 0.2 g/bhp-hr standard.

- THC and $CH_4$ emissions did not show any consistent fuel trends. $CH_4$ comprised a majority of the THC emissions, with NMHC emissions representing a smaller fraction of the THC. NMHC emissions showed a trend of higher emissions for the low methane fuels containing higher levels of NMHCs (i.e., ethane, propane, and butane). This trend was seen for all three cycles.

- CO emissions showed a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. The higher CO emissions could be due to slightly richer combustion for the low methane fuels, which could make oxidation of the CO slightly more difficult either during combustion or over the catalyst.

- Fuel economy/consumption on a volumetric basis showed some differences between the various test fuels. Specifically, LM3, LM5, and LM6 generally showed higher fuel economy on a volumetric basis compared to H1 and H7. These trends are consistent with the low methane fuels providing higher fuel economy and lower fuel consumption. Fuel economy/consumption on an energy equivalent basis did not show any statistically significant trends. $CO_2$ emissions did not show any statistically significant trends for either the transport or curbside cycles, but did show some statistically significant reductions for H7 compared to LM3 and LM5 and some marginally statistically significant reductions for H7 compared to LM6 for the compaction cycle.

- PM mass emissions were very low for refuse truck on an absolute level, and are at the same levels as the tunnel background. There were no statistically significant differences between test fuels for PM emissions.

- PN emissions did not show strong fuel trends for the different RTC segments. PN emission levels were similar to those found for older heavy-duty NGVs, suggesting a strong contribution from the lubricant oil.

- The particle size distributions showed bimodal distributions, with a majority of the particles in the nucleation mode with particle diameters centered from 9 to 11 nm size range.

- $NH_3$ emissions were found for the stoichiometric Cummins Westport ISL-G at levels higher than those seen for older lean burn engines. $NH_3$ emissions showed a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. The increases in $NH_3$ emissions LM3, LM5, and LM6 were statistically significant compared to both H1 and H7 for all three of the test cycles. The higher $NH_3$ emissions could be due to slightly richer combustion for the low methane fuels, which could make oxidation of the $NH_3$ slightly more difficult either during combustion or over the catalyst.

- $N_2O$ emissions were highly dependent on fuel composition, with low methane fuels showing higher emissions of $N_2O$ compared to high methane fuels. Overall, $N_2O$ emissions corroborate with $NH_3$ emissions and showed an inverse relation to $NO_x$ emissions for the transport and curbside segments.

- Formaldehyde emissions did not show any statistically significant fuel trends, with the exception of LM5 that showed a 54.7% decrease in formaldehyde emissions compared to H1. Acetaldehyde emissions were at or below the background levels for all of the test fuels with the exception of H7.

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

| | | Waste Hauler | | |
|---|---|---|---|---|
| | **Fuel** | **Transport** | **Curbside** | **Compaction bhp-hr** |
| Fuel Economy/Consumption (Volumetric basis) | LM3 | **5.94%** | 3.00% | **-3.92%** |
| | LM5 | **12.37%** | 6.90% | **-8.39%** |
| | LM6 | **13.35%** | 5.65% | **-7.82%** |
| | H7 | 1.30% | -1.69% | 0.09% |
| $CO_2$ | LM3 | -0.73% | 2.82% | 2.36% |
| | LM5 | -2.44% | 2.99% | 1.85% |
| | LM6 | -2.58% | 4.37% | 2.66% |
| | H7 | -1.93% | 0.42% | -1.16% |
| $NO_x$ | LM3 | <u>-13.03%</u> | **-24.34%** | -247.13% |
| | LM5 | **-20.92%** | -11.23% | <u>779.28%</u> |
| | LM6 | -10.00% | **-17.49%** | **1323.28%** |
| | H7 | **15.14%** | **24.26%** | **2085.96%** |
| CO | LM3 | **63.85%** | <u>38.83%</u> | <u>24.34%</u> |
| | LM5 | **59.97%** | **63.02%** | <u>26.72%</u> |
| | LM6 | **39.16%** | **67.67%** | <u>23.42%</u> |
| | H7 | -21.44% | **-41.04%** | 4.18% |
| THC | LM3 | 16.16% | -20.87% | **22.18%** |
| | LM5 | 13.29% | 1.89% | 13.23% |
| | LM6 | -1.25% | -5.95% | <u>16.43%</u> |
| | H7 | -10.30% | -6.67% | 17.27% |
| NMHC | LM3 | **354.88%** | 817.34% | **410.55%** |
| | LM5 | **392.33%** | **1235.87%** | **338.24%** |
| | LM6 | **251.01%** | <u>933.58%</u> | **290.16%** |
| | H7 | 42.60% | 157.80% | 182.33% |
| $CH_4$ | LM3 | -1.35% | **-34.04%** | -1.10% |
| | LM5 | -5.86% | -18.22% | -5.55% |
| | LM6 | -13.81% | -20.89% | 0.72% |
| | H7 | -13.37% | -9.49% | 6.66% |
| $NH_3$ | LM3 | **20.81%** | **54.30%** | **33.98%** |
| | LM5 | **30.62%** | **50.89%** | **39.66%** |
| | LM6 | **27.26%** | **52.61%** | **34.78%** |
| | H7 | 0.04% | -19.66% | 6.78% |

| | | Waste Hauler | | |
|---|---|---|---|---|
| | **Fuel** | **Transport** | **Curbside** | **Compaction bhp-hr** |
| PN | LM3 | 1.84% | 9.07% | -56.73% |
| | LM5 | 8.36% | -7.86% | -55.82% |
| | LM6 | <u>17.42%</u> | 10.72% | -10.31% |
| | H7 | -14.31% | 8.80% | 3.12% |
| | | For the whole cycle | | |
| PM | LM3 | -1.96% | | |
| | LM5 | -12.64% | | |
| | LM6 | -41.86% | | |
| | H7 | 49.90% | | |
| | | For the whole cycle | | |
| Formaldehyde | LM3 | 32.8% | | |
| | LM5 | **-54.7%** | | |
| | LM6 | -39.9% | | |
| | H7 | 60.4% | | |
| | | For the whole cycle | | |
| Acetaldehyde | LM3 | 44.8% | | |
| | LM5 | **-226.2%** | | |
| | LM6 | **-254.9%** | | |
| | H7 | <u>313.2%</u> | | |
| | | For the whole cycle | | |
| $N_2O$ | LM3 | **134.70%** | | |
| | LM5 | **152.52%** | | |
| | LM6 | **107.27%** | | |
| | H7 | -21.71% | | |

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

# 1 Introduction

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

For NGVs, one issue that has been shown to be important with respect to emissions is the effect of changing the composition of the NG fuel. This is part of a broader range of issues which are classified under the term interchangeability, which is the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions. Studies of the effects of NG composition have been conducted for small stationary source engines, such as compressors, heavy-duty engines, and heavy-duty vehicles [12–22,28]. These studies have shown that NG composition can have an impact on emissions. $NO_x$ emissions, for example, were found to increase with increasing Wobbe number (WN) and/or decreasing methane number (MN) in several of these studies [12–22,28]. MN and WN are terms used to describe natural gas quality characteristics. MN is a measure of the knock resistance of a gas, with the knock resistance of a gas increasing with increasing MN. WN is defined as the higher heating value (HHV) of a gas divided by the square root of the specific gravity of the gas with respect to air. The higher the WN of the gas, the greater the heating value per volume of gas that will flow through a hole of a given size in a given amount of time.

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

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

The objective of the present study is to evaluate the impact of NG composition on the performance and exhaust emissions of heavy-duty vehicles. The California Air Resources Board (CARB) is currently revisiting the compressed natural gas (CNG) fuel standards for motor vehicles [27]. Information on the impact of changing NG composition on performance and emissions can be used for regulatory development, to ensure new NG compositions do not have an adverse impact on air quality, and to evaluate the viability of using a broader mixture of NG blends in transportation applications. For this study, a newer NG waste hauler was tested on a range of five different test fuels. The test fuels included fuels representative of Texas Pipeline gas; a fuel representing Peruvian LNG modified to 1385 WN; 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. The testing included measurements of regulated emissions and fuel economy/consumption, as well as measurements of ammonia ($NH_3$), nitrous oxide ($N_2O$), carbonyls, and particle number (PN) and particle size distributions. This report discusses these test results. This study is the continuation of a larger program that included the testing of other light-duty and heavy-duty NGVs on a chassis dynamometer, which is discussed in a previous report [28]. This previous study showed that while NG composition has important impacts on emissions for older vehicles that these impacts may be less pronounced for the latest generation of heavy-duty NGV with the more advanced emission control systems.

# 2 Experimental Procedures

## 2.1 Test Fuels

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

- Fuel H1 is representative of Texas Pipeline gas and serves as the baseline fuel. This fuel is based on actual pipeline data.
- Fuel LM3 is representative of Peruvian LNG that has been modified to meet a WN of 1385 and a MN of 75.
- 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 an L-CNG fuel.

Test fuel H1 represents a historical baseline fuel for Southern California. Test 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. The actual test fuel compositions for H1 was 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. For this program, the wide range of scenarios were examined to evaluate the viability of permitting the use of a broader mixture of NG blends in transportation applications. Fuels LM3, LM5, and LM6 with lower methane contents, and corresponding higher WNs and HHVs, and lower MNs are denoted as low methane fuels throughout this report. The test fuels are presented in Table 2-1.

In addition, the CNG fueled waste hauler was run on an L-CNG, identified as H7. Test fuel H7 was included to capture the base line for waste haulers that fuel on LNG. Because a CNG waste hauler was tested, a L-CNG fuel, rather than an LNG fuel, was used. L-CNG is LNG which has been vaporized to a gas at the fueling station. Although L-CNG was included as a test fuel to represent a waste hauler operating on LNG, it should be noted that a LNG waste hauler would never see LM3, LM5, LM6 because these fuels have inert 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 then refrigerated to minus 260 degrees for conversion to LNG. The L-CNG for this study was obtained from a commercial refueling station in the local area, and the properties were obtained from a sample of the fuel pulled during the course of testing.

**Table 2-1. Test Fuel Specifications**

| Fuel # | 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 |
| **LM3** | **Peruvian LNG** | 88.3 | 10.5 | 0 | 0 | 1.2 | 0 | 84 | 1385 | 1083 | 3.81 |
| **LM5** | **High Ethane** | 83.65 | 10.75 | 2.7 | 0.2 | 2.7 | 0 | 75.3 | 1385 | 1115 | 3.71 |
| **LM6** | **High Propane** | 87.2 | 4.5 | 4.4 | 1.2 | 2.7 | 0 | 75.1 | 1385 | 1116 | 3.70 |
| **H7** | **L-CNG fuel** | 98.4 | 1.26 | 0.05 | 0.02 | 0.25 | 0 | 104.5 | 1363 | 1023 | 3.97 |

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

### 2.1.1 Fuel Composition and Rich and Lean Combustion

It should be noted that 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 [14,15]. 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. Similarly, 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 said to be richer than the initial condition.

## 2.2 Test Vehicle

A waste hauler fitted with a 2011 model year, 8.9L stoichiometric spark ignited Cummins Westport ISL-G engine with cooled exhaust gas recirculation (EGR) and a three-way catalyst (TWC) was used for this program. This vehicle was selected to represent the latest engine technology available for natural gas engines. The main technical specifications of the engine are provided in Table 2-2. The certification Executive Order for the engine tested is provided in Appendix A. The waste hauler was provided by Waste Management.

**Table 2-2. Engine Specifications**

| | |
|---|---|
| **Manufacturer** | Cummins Westport |
| **Engine Model** | ISL-G |
| **Model Year** | 2011 |
| **Vehicle Type** | Waste Hauler |
| **Engine Family** | BCEXH0540LBH |
| **Engine Type** | Stoichiometric<br>Spark-ignited<br>Turbocharged, EGR |
| **Horsepower** | 320 HP |
| **Number of Cylinders** | 6 |
| **Bore and Stroke** | 114 mm x 145 mm |
| **Displacement** | 8.9 L |
| **Compression Ratio** | 12:1 |
| **Peak Torque** | 1000 ft-lbs. @ 1300 rpm |
| **Aftertreatment** | TWC |
| **Certification Level (g/bhp-hr)** | NMHC: 0.08<br>$NO_x$:0.13<br>CO:14.2<br>PM:0.002 |

## 2.3 Test Cycles

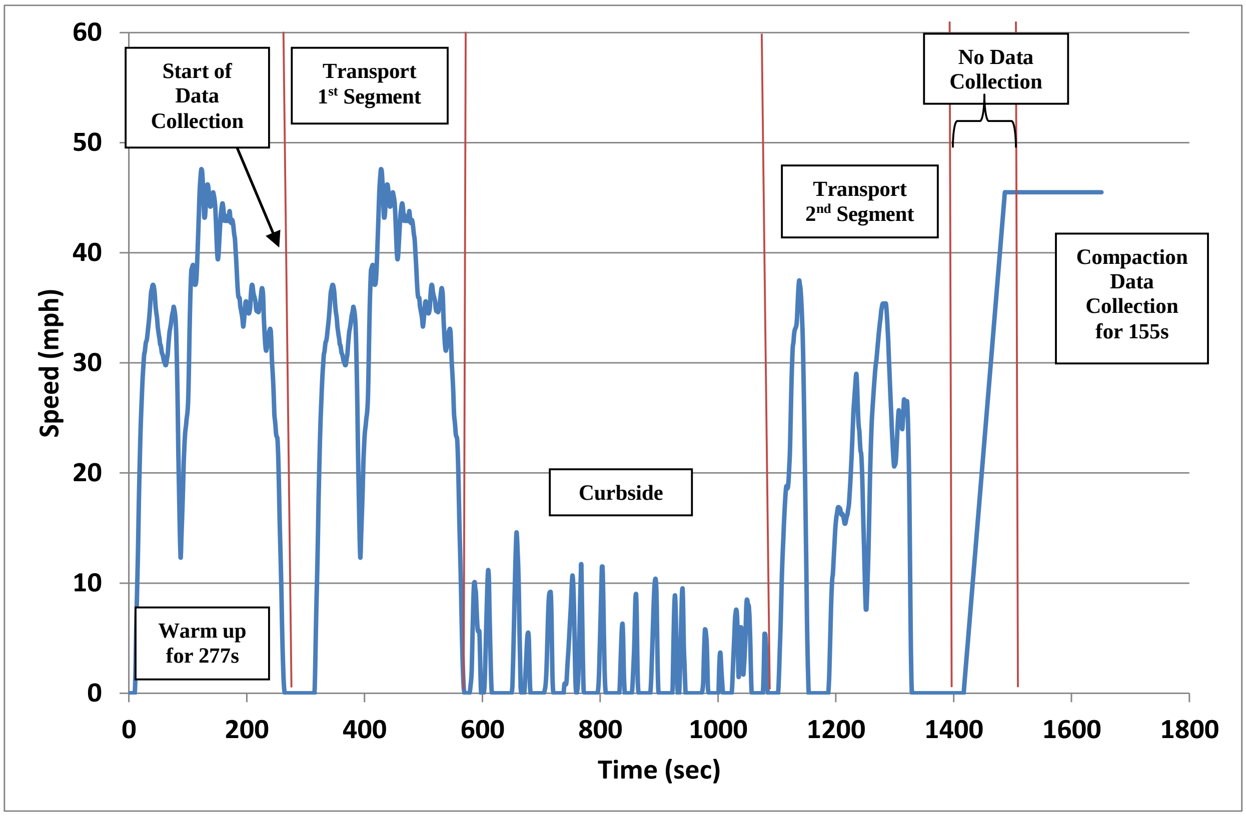
The testing for the waste hauler was performed on the William H. Martin (WHM) refuse truck cycle. The test matrix was randomized to allow some measure of the experimental reproducibility. Six tests were run on each vehicle/fuel combination for all vehicles, except as noted otherwise in the Appendix. The test matrix for the heavy-duty chassis dynamometer testing is provided below in Table 2-3.

**Table 2-3. Chassis Dynamometer Test Matrix**

| Test Day | Morning Schedule (assumes 3 replicates) | Afternoon Schedule (assumes 3 replicates) |
|---|---|---|
| **WHM Refuse Cycle** | | |
| 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 |

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

**Figure 2-1. Refuse Truck Cycle [23]**




The vehicle was warmed up in the morning over a single iteration of the Refuse Truck Cycle on the fuel that is 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, all tests were conducted as “hot running” tests, with the 277 second warm-up. The road load coefficients and test weight (i.e., 33,520 lbs.) used were the same as that used in the Phase 1 of the refuse hauler testing [28].

## 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 which 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 dyno 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% FS 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, which are both measured digitally and thus easy to maintain their accuracy. The torque transducer is calibrated as per CFR 1065 and is a standard method used for determining accurate and reliable wheel loads. A picture of a typical vehicle set up on the chassis dynamometer is provided in Figure 2-2.

The emissions measurements were obtained using CE-CERT's Mobile Emissions Laboratory (MEL). For all tests, standard emissions measurements of total hydrocarbons (THC), NMHC, methane ($CH_4$), CO, $NO_x$, carbon dioxide ($CO_2$), and PM, were measured. CO and $CO_2$ emissions were measured with a 602P nondispersive infrared (NDIR) analyzer from California Analytical Instruments (CAI). THC, NMHC, and $CH_4$ emissions were measured with 600HFID flame ionization detector (FID) from CAI. $NO_x$ emissions were measured with 600HPLC chemiluminescence analyzer from CAI. Measurements were also made of $NH_3$ using a Unisearch Associates Inc. LasIR S Series Tunable Diode Laser (TDL) unit that is incorporated in 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 weighing procedure guidelines of the Code of Federal Regulations (CFR).

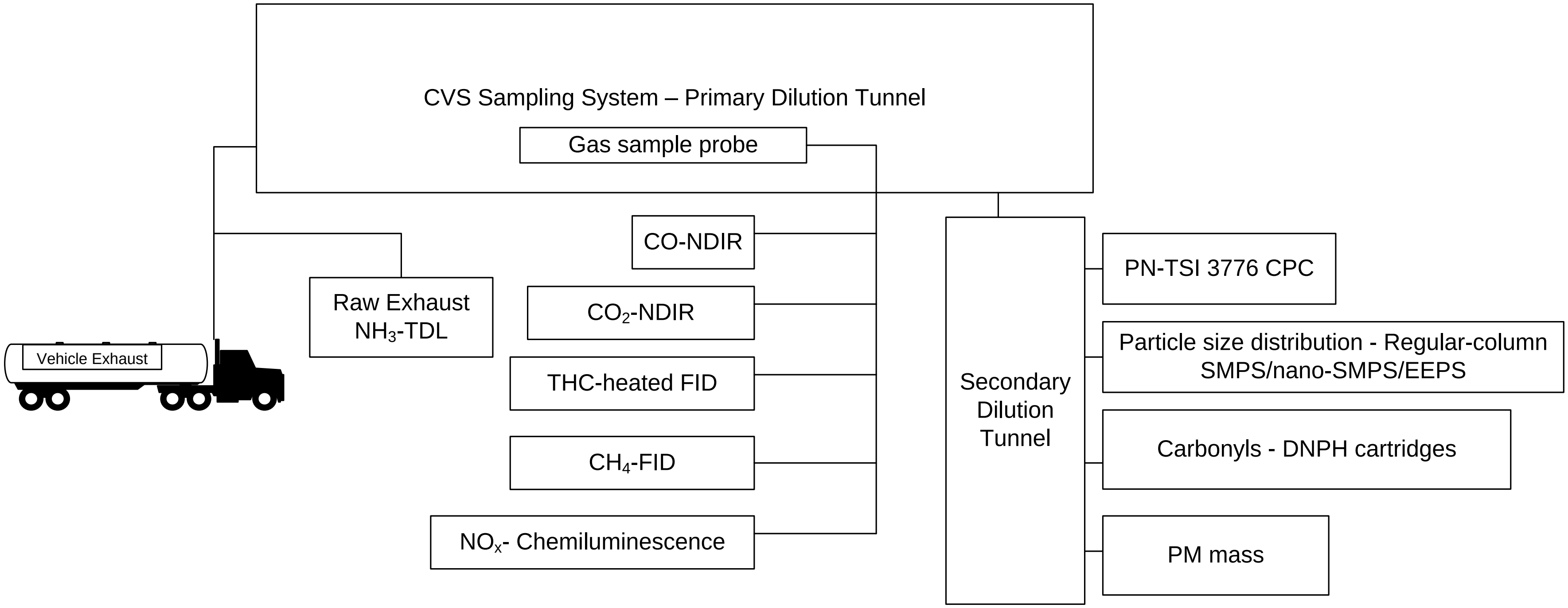
The sampling of carbonyls was done for 3 tests per test fuel/vehicle combination. Samples for carbonyl analysis were collected onto 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA). A critical flow orifice controls the flow to 1.0 liter per minute (LPM) through the cartridge. Sampled cartridges were extracted using 5 milliliter (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. 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 the cycle due to the low mass levels expected for these pollutants. As such, results for the individual segments of the Refuse Truck Cycle are not available for these pollutants. The FTIR $N_2O$ measurements were also made from bag samples that were collected cumulatively over the duration of the cycle. A schematic of the experimental setup is provided in Figure 2-3.

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


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) was used for measuring particle size distributions. The EEPS was used to obtain real-time second-by-second 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, which is considered to be high enough to minimize diffusional losses. They were then charged with a corona charger and sized based on their electrical mobility in an electrical field. Concentrations were determined through the use of multiple electrometers.

**Figure 2-3. Schematic of the Sampling Systems and Instruments**



# 3 Heavy-Duty Vehicle Chassis Dynamometer Testing Results

The emissions results are presented in the following section. The figures for each pollutant show the results for each vehicle/fuel/cycle combination based on the average of tests conducted on that particular test combination. The error bars on the figures are the standard deviation over all tests for each test combination. The average emissions test results with percentage differences between fuels and p-values for statistical analyses are provided in Appendix B. The statistical analyses were conducted using a 2-tailed, 2 sample equal variance t-test. For the statistical analyses, results are considered to be statistically significant for $p \leq 0.05$, or marginally statistically significant for $0.05 < p \leq 0.1$ for this study. Comparisons are also made with the results obtained for the NG waste hauler tested in Phase 1 throughout this section [28]. This provides information on the differences in fuel effects between the older lean burn engine tested previously and the newer technology stoichiometric engine. The waste hauler tested in Phase 1 was equipped with a 2002 C-Gas Plus lean burn NG engine.

## 3.1 $NO_x$ Emissions

Figure 3-1 (a-b) shows the emissions of $NO_x$ for the waste hauler for the transport and curbside segments of the Refuse Truck Cycle. Figure 3-2 shows the emissions of $NO_x$ for the waste hauler for the compaction segment of the Refuse Truck Cycle. For the compaction segment, the emissions are presented on 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.

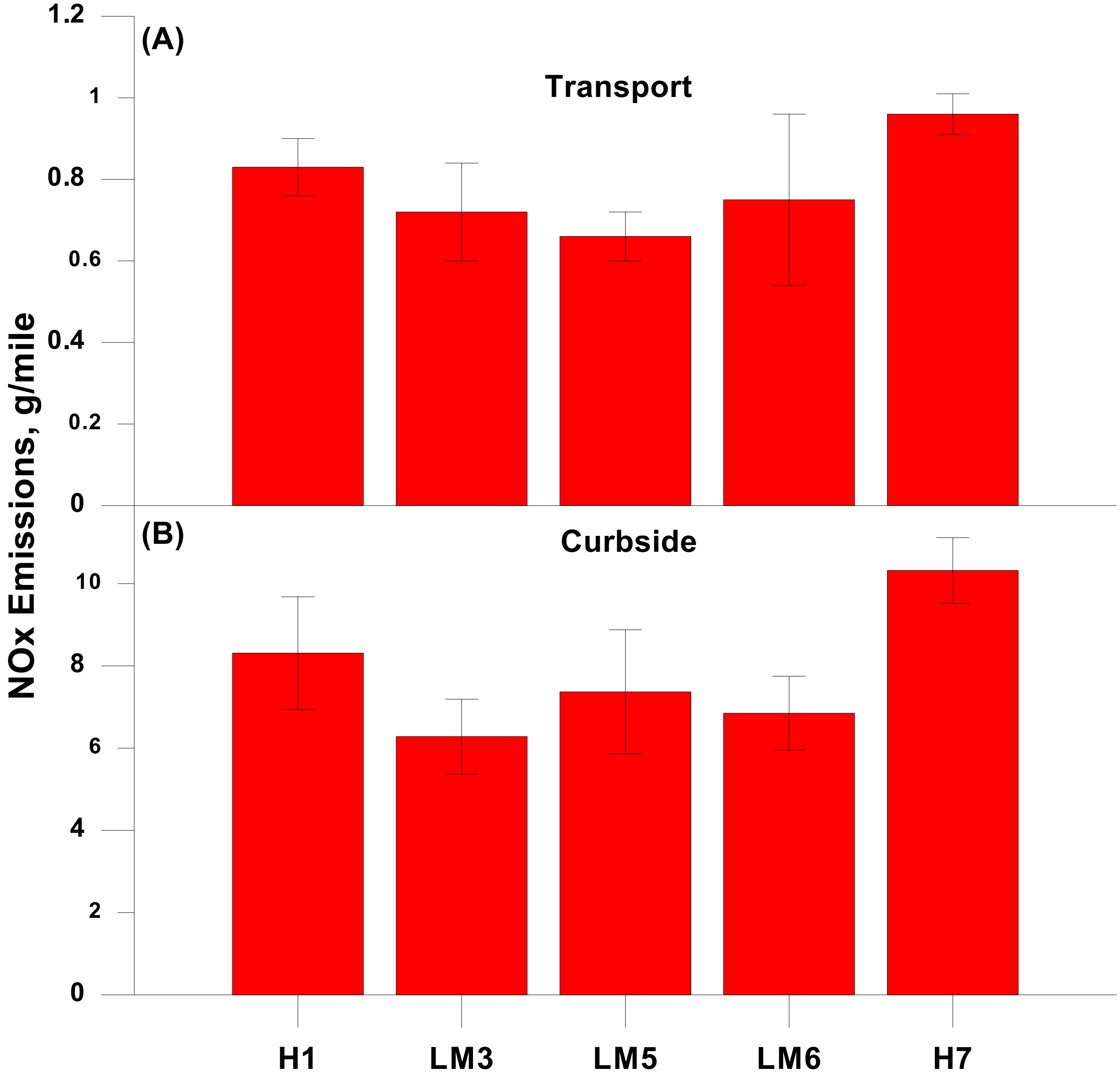
$NO_x$ emission levels for the Cummins Westport ISL-G waste hauler ranged from 0.66-0.96 g/mile for the transport phase, from 6.28-10.32 g/mile for the curbside phase, and from -0.0006-0.0086 g/bhp-hr for the compaction phase. The significantly higher $NO_x$ emissions for the curbside phase compared to the transport phase of the RTC can be attributed to the fact that the curbside segment is composed of short, low speed accelerations between periods of idle that cover a very short distance (0.36 miles). Such stop and go type of driving tends to create high emissions when evaluated on a per mile basis. For the transport cycle, LM3 and LM5 showed marginally statistically significant and statistically significant reductions in $NO_x$ emissions compared to H1 of 13% and 20.9%, respectively, while $NO_x$ emissions for H7 showed a statistically significant increase of 15.1% compared to H1. For the curbside cycle, LM3 and LM6 showed statistically significant reductions in $NO_x$ emissions compared to H1 of 24.3% and 17.4%, respectively, while $NO_x$ emissions for H7 showed a statistically significant increase of 24.2% compared to H1. $NO_x$ emissions for the compaction cycle were at very low levels and considerably below the 0.2 g/bhp-hr standard. Statistically significant increases in $NO_x$ emissions were seen for LM6 and H7 compared to H1 on the order of 1323% and 2086%, respectively, while LM5 showed a marginally statistically significant increase in $NO_x$ emissions of 779% compared to H1. Note that 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 $NO_x$ emission levels than those found in a similar study conducted by UCR's CE-CERT on a waste hauler equipped with a 2002 Cummins 8.3L C Gas Plus, lean burn, spark ignited engine using the same fuel blends and operated over the

RTC cycle. Several studies have shown that the majority of $NO_x$ reductions can be attributed to the TWC [29-30]. The newer stoichiometric engine tested in this study also has cooled EGR that introduces inert exhaust gases into the combustion cylinder, which reduces cylinder combustion temperature and results in lower $NO_x$ emissions.

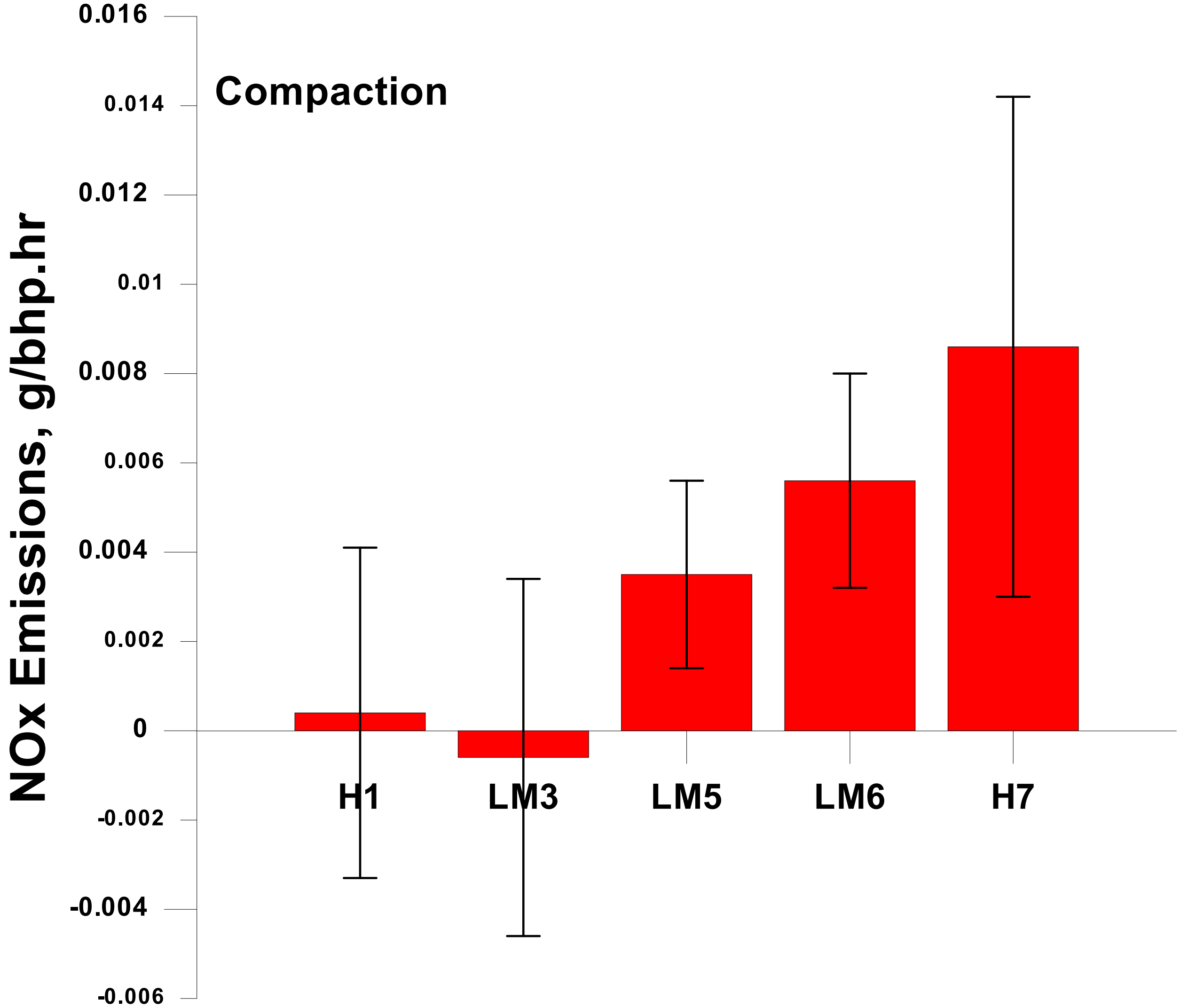
The slight decrease in NOx emissions observed for the low methane test fuels may be due to slightly richer air/fuel (A/F) ratios for combustion. The resultant decrease in oxygen may also lead to increased effectiveness in the TWC's ability to further reduce NOx emissions. Previously, lean burn engines have also been observed to operate with a slightly richer A/F ratio when running on low methane fuels [14]. In this case, the engines experienced increased NOx emissions, which had been attributed to higher flame speeds and adiabatic flame temperatures [14,28]. 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 3-1 (a-b). Average $NO_x$ Emissions for the Waste Hauler Transport and Curbside Segments**




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

**Figure 3-2. Average $NO_x$ Emissions for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis**

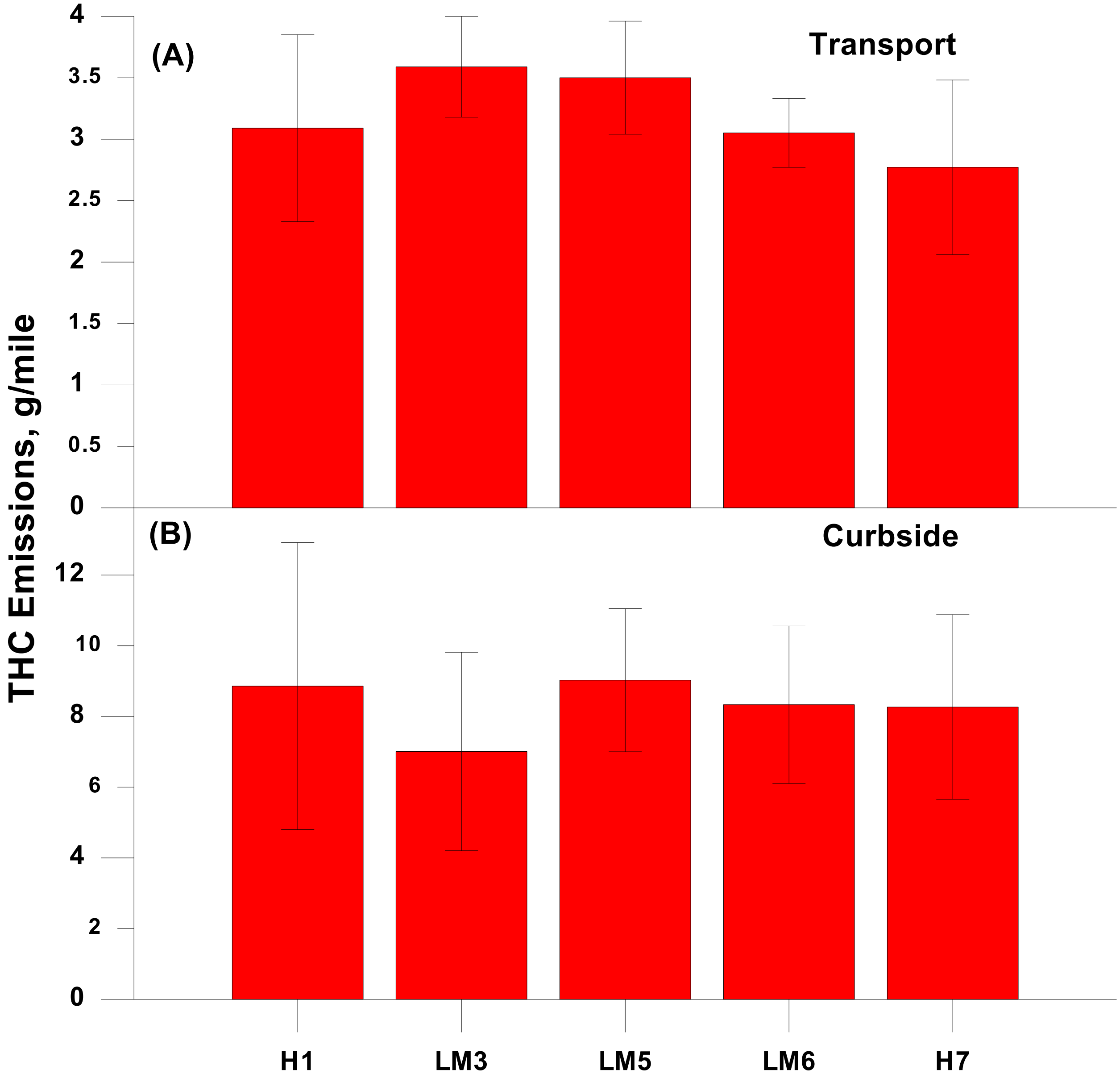



**H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)**

## 3.2 THC Emissions

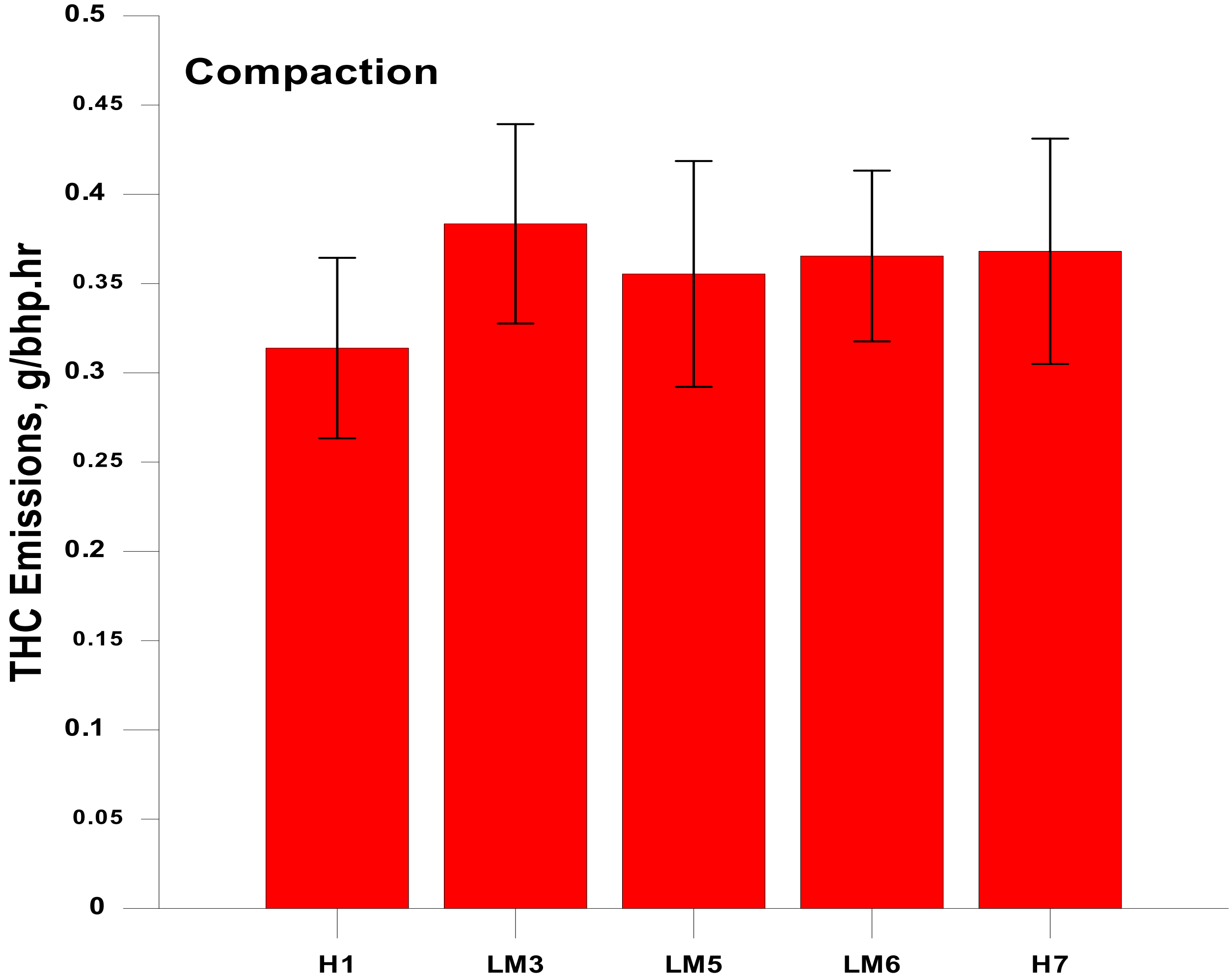
Figure 3-3 (a-b) shows the THC emissions for the waste hauler for the transport and curbside segments, while Figure 3-4 shows the THC emissions for the compaction segment on a bhp-hr basis. THC emissions were significantly lower than typically found for older lean burn NG engines equipped with oxidation catalysts (OCs) [28]. This can be attributed to the differences in the engine technology, since the older engines are all lean-burn engines with OCs designed to meet an earlier certification standard, and the ISL-G is a stoichiometric engine with a TWC that is designed to meet a more recent and stringent certification standard [31]. Overall, THC emissions did not show strong fuel trends. There were no statistically significant differences between fuels for the transport and curbside phases of the RTC cycle. The only statistically significant differences were seen for LM3 and LM5 compared to H7, which showed a statistically significant increase of THC emissions of 29% and a marginally statistically significant increase of 26%, respectively. For the compaction cycle, LM3 was higher (22.2%) than H1 at a statistically significant level, while LM6 was higher (16.4%) than H1 at a marginally statistically significant level. Although some trends toward higher THC emissions were observed for the low MN fuels over the compaction cycle, taken as a whole, there were no consistent fuel trends over the different phases of the RTC cycle. The results show that the effectiveness of the emissions control systems for THC is not impacted by differences in the hydrocarbon composition of the test fuels.

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




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

**Figure 3-4. Average THC Emissions for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis**

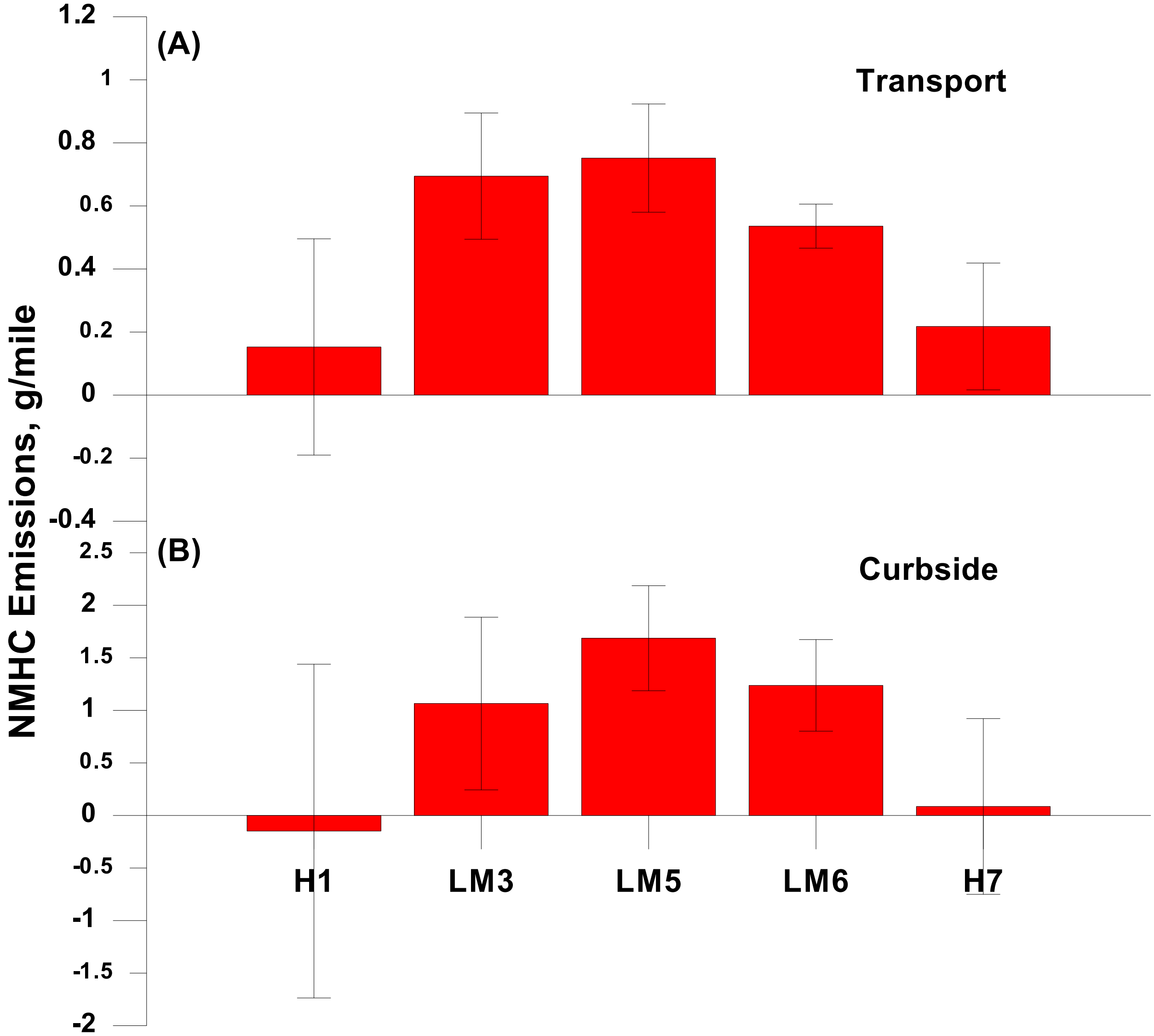



**H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)**

### 3.3 NMHC Emissions

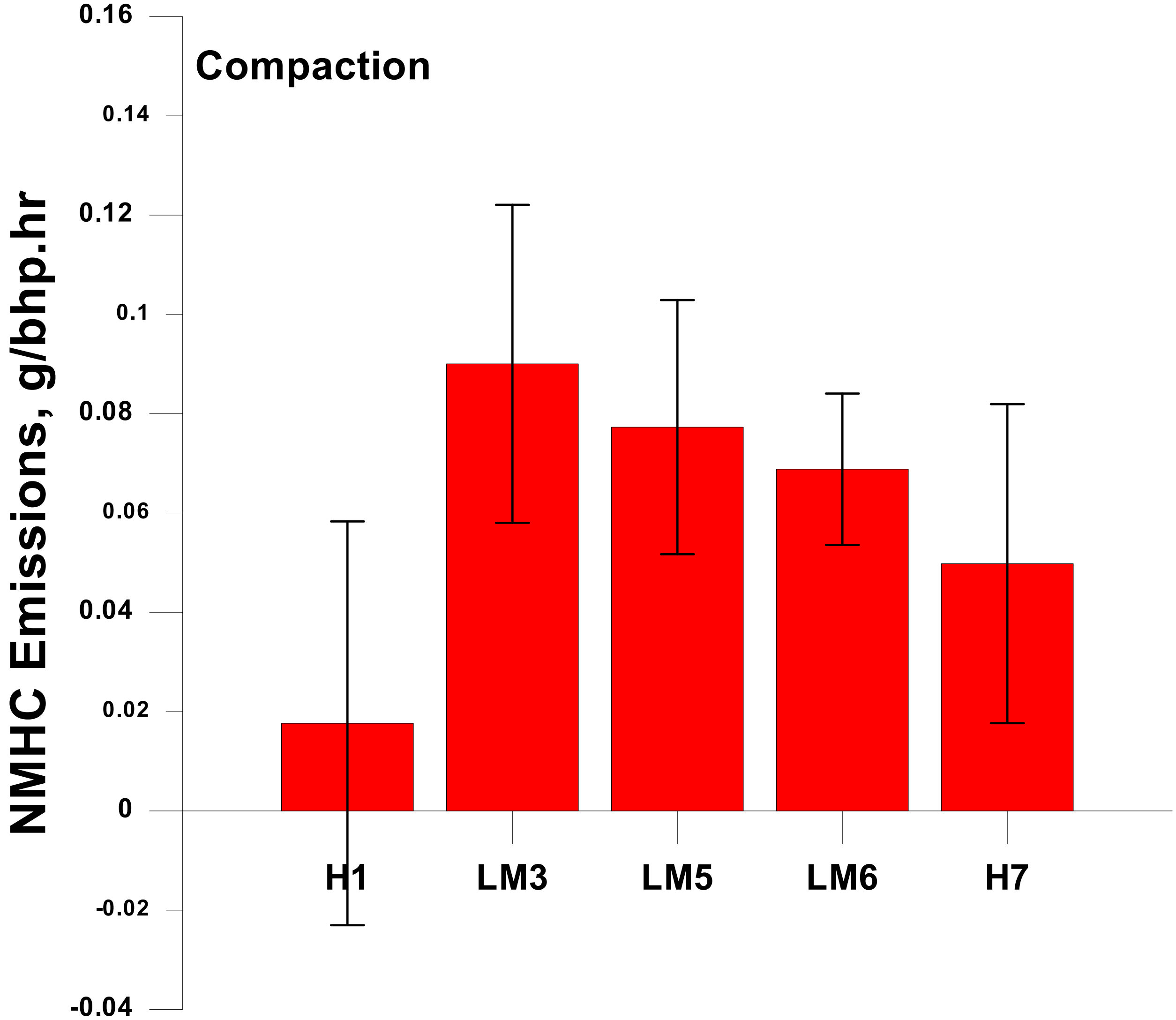
Figure 3-5 (a-b) shows the NMHC emissions for the waste hauler for the transport and curbside segments, while Figure 3-6 shows the NMHC emissions for the compaction segment on a bhp-hr basis. NMHC emissions showed a trend of higher emissions for the low methane fuels containing higher levels of NMHCs (i.e., ethane, propane, and butane, as shown in Table 2-1). This trend was seen for all three cycles. For both the transport and curbside cycles, NMHC emissions were 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 were 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 increased with low methane fuels [32-33]. THC emissions from natural gas engines are predominately unburned fuel, therefore, the non-methane hydrocarbon fraction of THC exhaust emission typically trends with the percentage of non-methane hydrocarbons in the test fuel. Previous studies conducted at CE-CERT for the stoichiometric Cummins ISL-G8.9 engine did 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 [28].

**Figure 3-5 (a-b). Average NMHC Emissions for Waste hauler Transport and Curbside Segments**




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

**Figure 3-6. Average NMHC emissions for Waste hauler for the Compaction Segment on an Engine bhp-hr Basis**

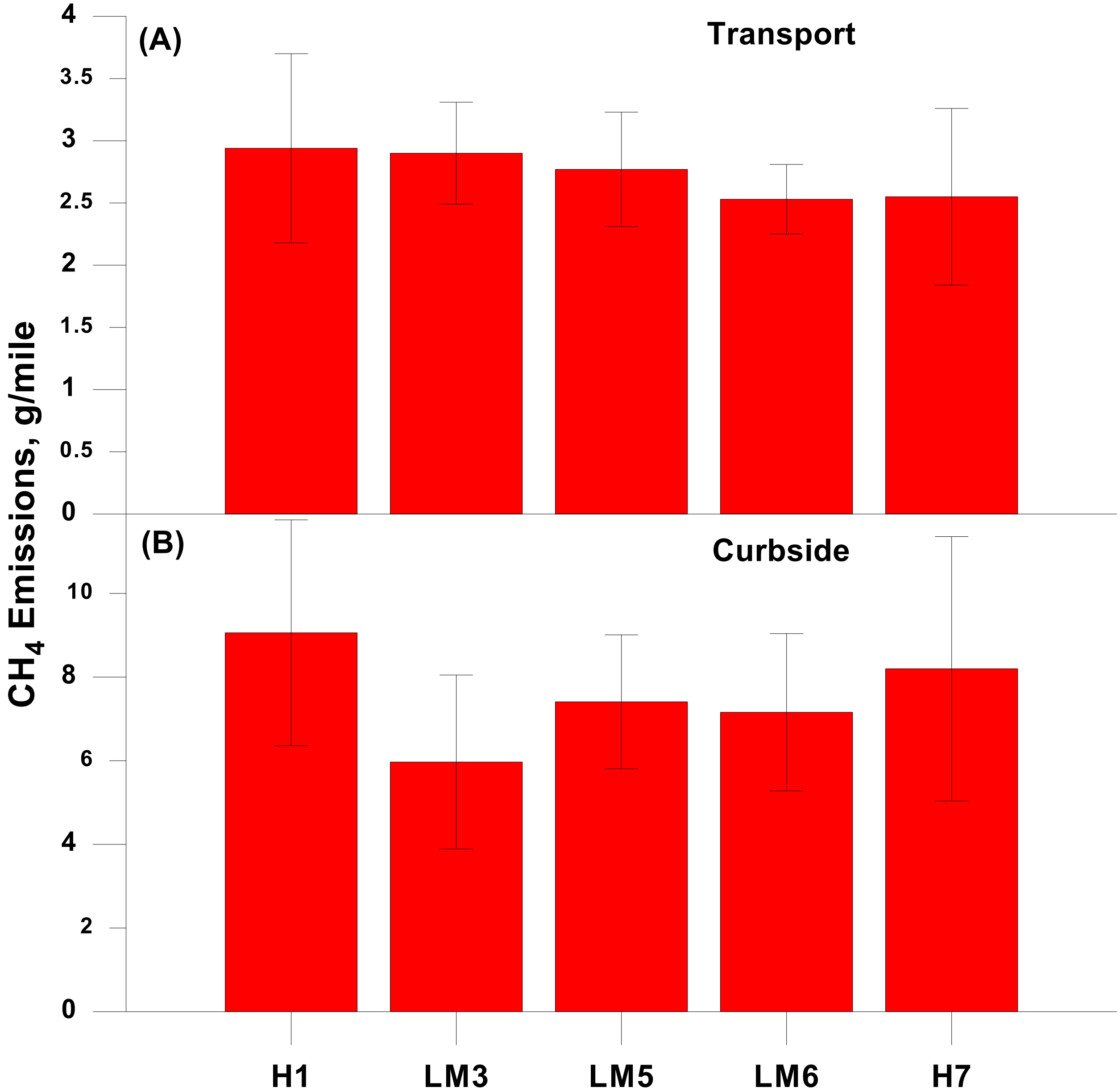



**H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)**

### 3.4 $CH_4$ Emissions

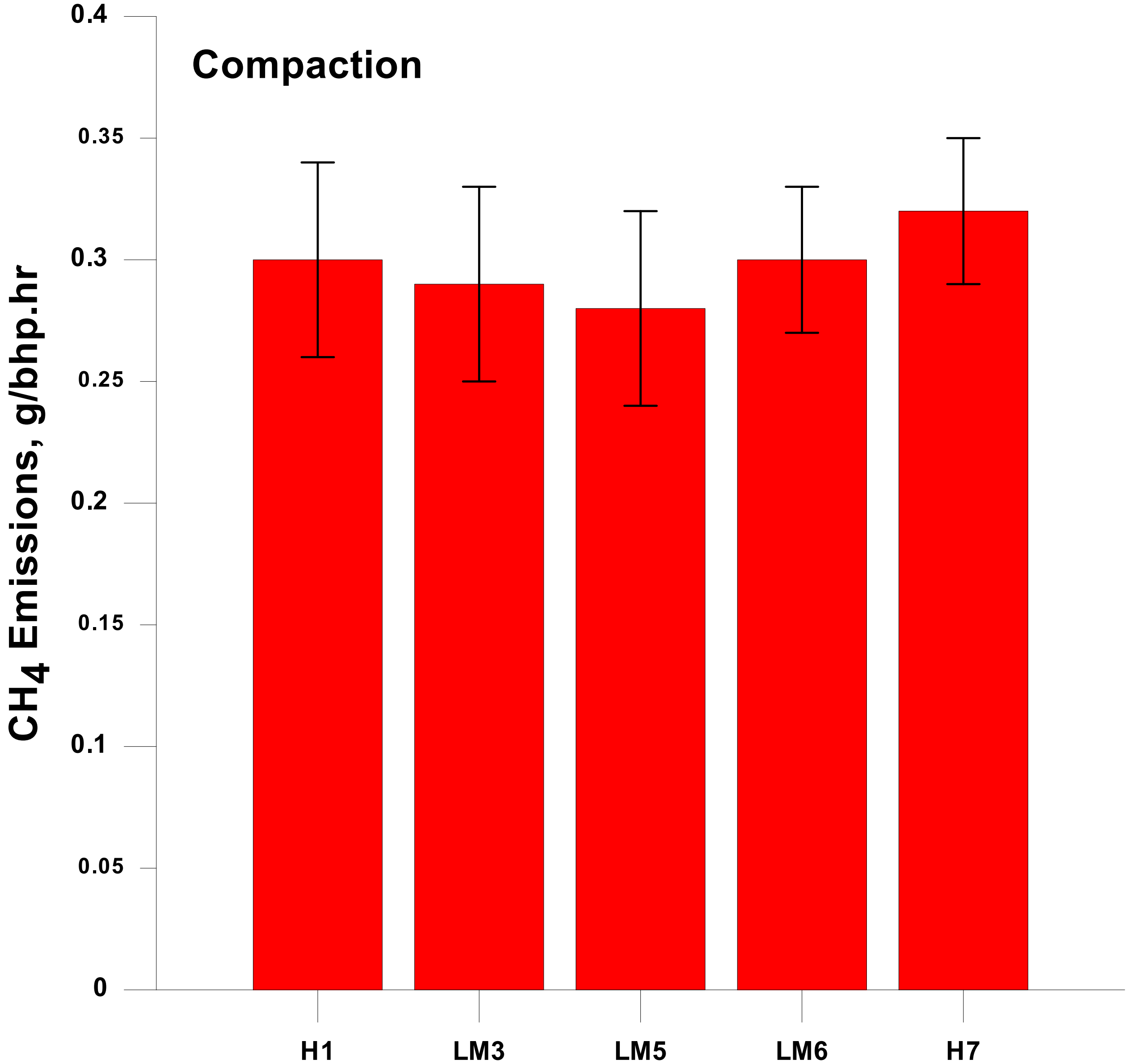
Figure 3-7 (a-b) shows the $CH_4$ emissions for the waste hauler for the transport and curbside segments, while Figure 3-8 shows the $CH_4$ emissions for the compaction segment on a bhp-hr basis. $CH_4$ emissions were significantly lower than typically found for older lean burn NG engines [28]. The $CH_4$ emissions are roughly comparable to the THC emissions, indicating that the THC emissions are predominantly $CH_4$. Similar to THC emissions, there were no strong fuel trends for $CH_4$ emissions. $CH_4$ emissions did not show any statistically significant differences between fuels for the transport cycle. For the curbside cycle, the only statistically significant decrease was seen for LM3 (34%) compared to H1. Although there are no strong 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. No statistically significant differences were found for $CH_4$ emissions over the compaction cycle.

**Figure 3-7 (a-b). Average $CH_4$ Emissions for Waste hauler Transport and Curbside Segments**




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

**Figure 3-8. Average $CH_4$ Emissions for Waste hauler for the Compaction Segment on an Engine bhp-hr Basis**



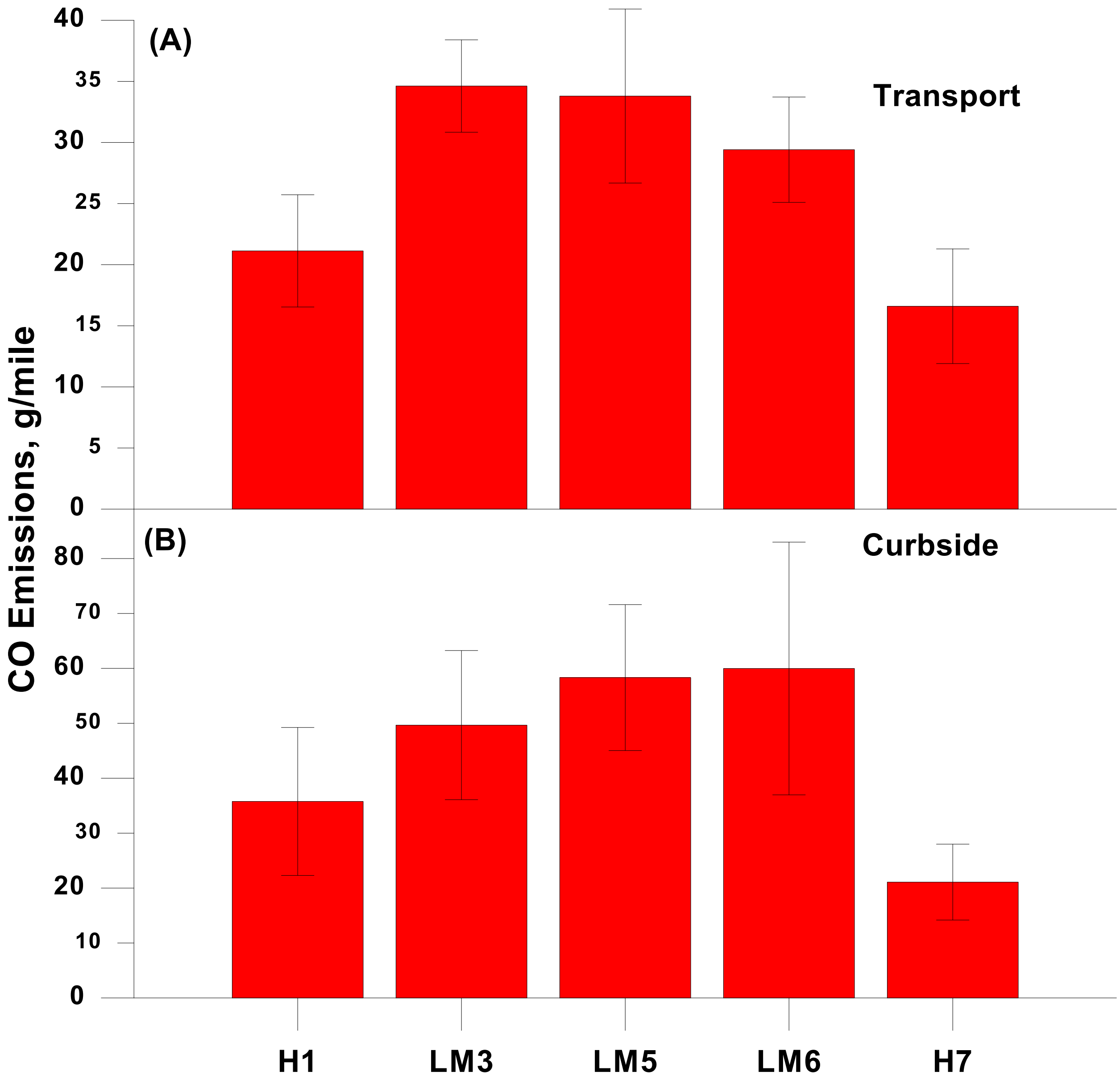

H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)

## 3.5 CO Emissions

Figure 3-9 (a-b) shows the CO emissions for the waste hauler for the transport and curbside segments, while Figure 3-10 shows the CO emissions for the compaction segment on a bhp-hr basis. The CO emissions for the stoichiometric Cummins Westport ISL-G engine tend to be higher compared to older lean-burn engines during combustion and across the catalyst. This observation has been seen in a number of other chassis dynamometer tests [34]. In these studies, the Cummins Westport ISL-G showed higher CO emissions compared to older lean burn engines. This can be attributed to the impact of richer operating conditions for the stoichiometric combustion compared to lean burn combustion. Specifically, richer operating conditions will lead to both increased engine-out CO as well as a reduction in the efficiency of removing CO over the catalyst [35].

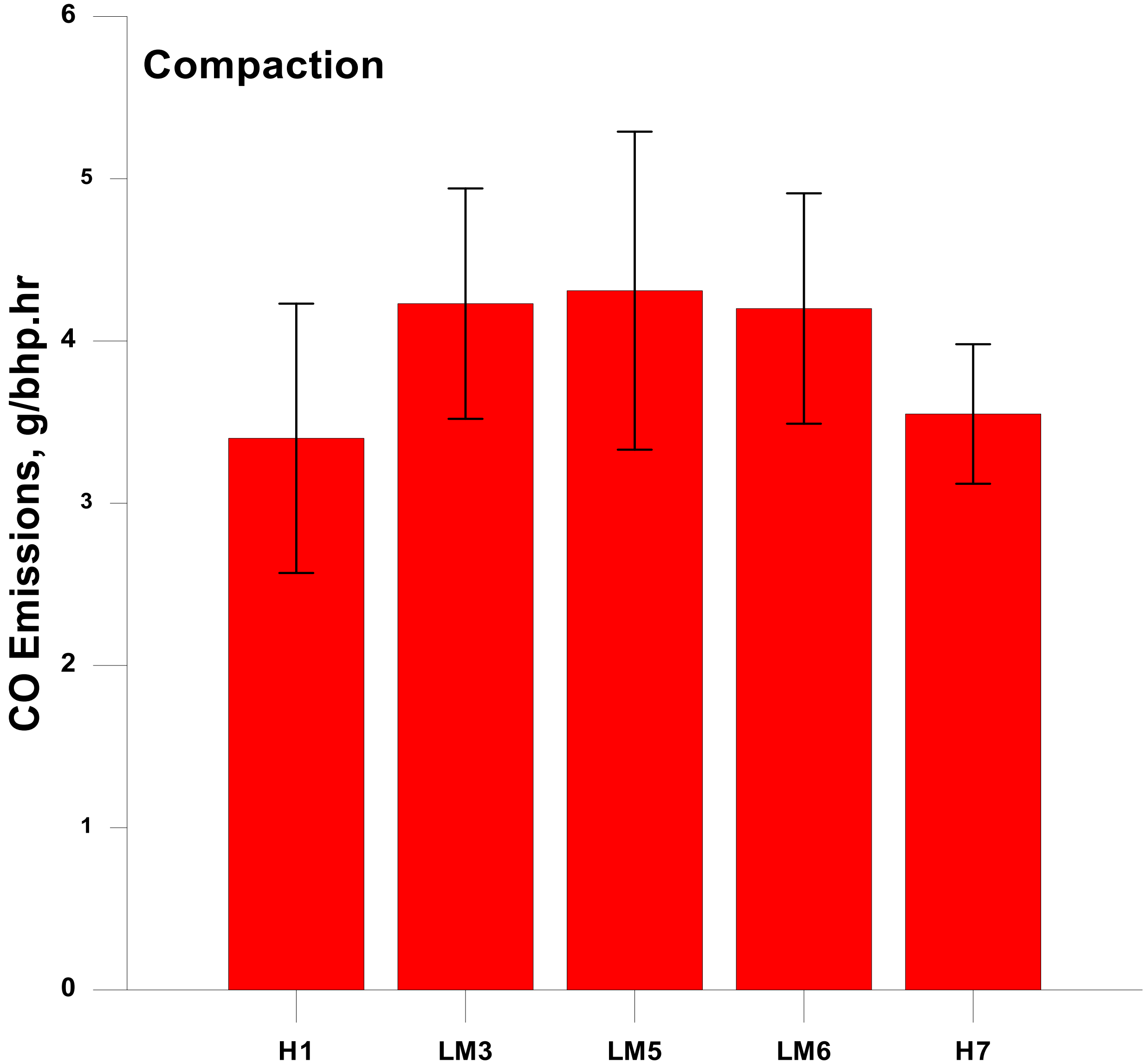
CO emissions showed a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. For the transport and curbside cycles, the increases in CO emissions LM3, LM5, and LM6 were statistically significant compared to both H1 and H7, with the comparison between H1 and LM3 being marginally statistically significant. For the compaction cycle, marginally statistically significant increases in CO emissions were seen for LM3, LM5, and LM6 compared to H1. Compared to H7, LM3 and LM6 also showed 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 [14,15], which could make oxidation of the CO slightly more difficult either during combustion or over the catalyst.

**Figure 3-9 (a-b). Average CO Emissions for Waste Hauler Transport and Curbside Segments**




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

**Figure 3-10. Average CO emissions for Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis**

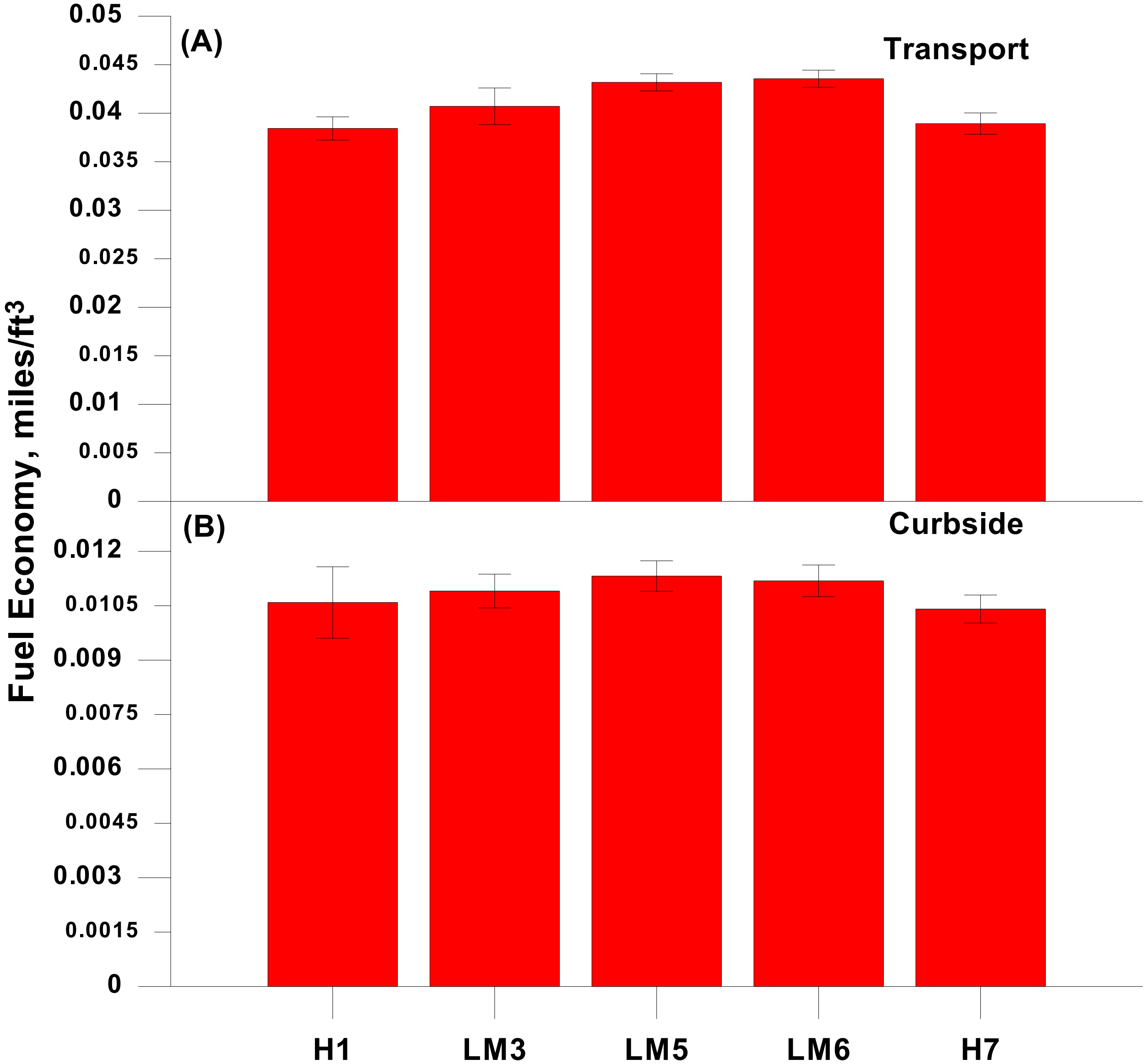



**H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)**

### 3.6 Fuel Economy/Consumption and $CO_2$ Emissions

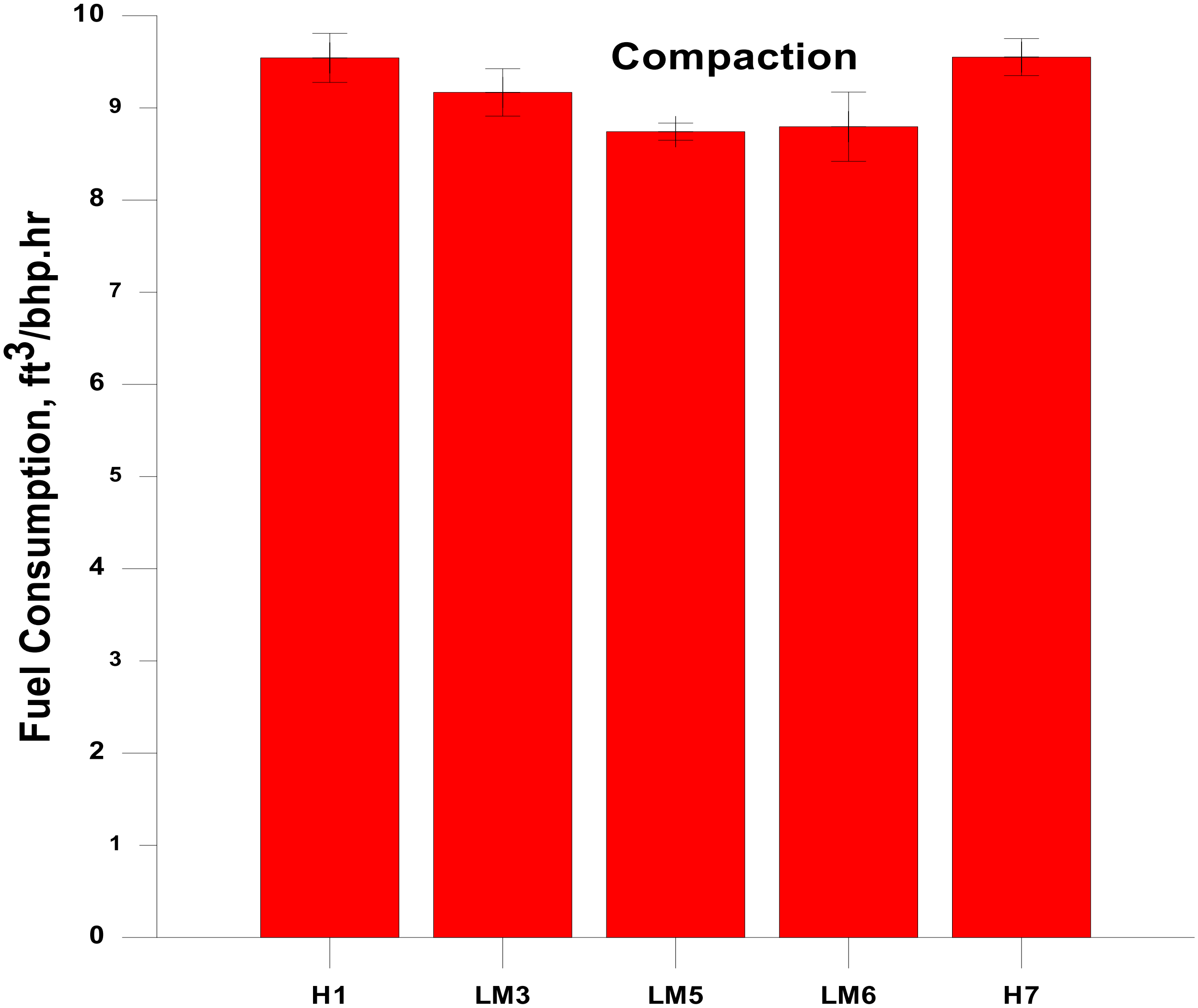
Figure 3-11 (a-b) show the average volumetric fuel economy, respectively, in miles/ft$^3$ for the waste hauler truck (the transport and curbside segments). Figure 3-12 shows the volumetric fuel consumption for the waste hauler on a ft$^3$/bhp-hr basis. The formulas used to calculate the volumetric fuel economy, as well as the energy equivalent fuel economy, as discussed below, are provided in Appendix C. Fuel economy was determined using the carbon balance method. This method uses the amount of carbon emitted in the exhaust based on THC, CO, and $CO_2$ emissions to determine the amount of fuel carbon, and by association the amount of fuel, that was used by the engine. As shown in Figure 3-11 (a-b) and Figure 3-12, when fuel economy/consumption is plotted on a volumetric basis, some differences between the fuel economies of the various test fuels can be seen. For the transport cycle, statistically significant differences were seen with higher fuel economy for LM3, LM5, and LM6 compared to H1, while LM5 and LM6 showed statistically significant and LM3 showed marginally statistically significant higher fuel economy compared to H7. The average fuel consumption for fuels LM3, LM5, and LM6 compared to H1 and H7 was 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, however, the only marginally statistically significant and statistically significant differences in fuel economy were higher fuel economy for LM3, LM5 and LM6 compared to H7. It is worth noting that the same trends were seen for the legacy waste hauler tested in Phase 1. For this vehicle, the low methane fuels showed higher volumetric fuel economy compared to H1, H2, and H7 over the transport and curbside phases of the RTC, while the volumetric fuel consumption was lower for the low methane fuels, consistent with the high energy contents of these fuels [28].

**Figure 3-11. (a-b). Average Volumetric Fuel Economy for the Waste Hauler Transport and Curbside Segments**




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

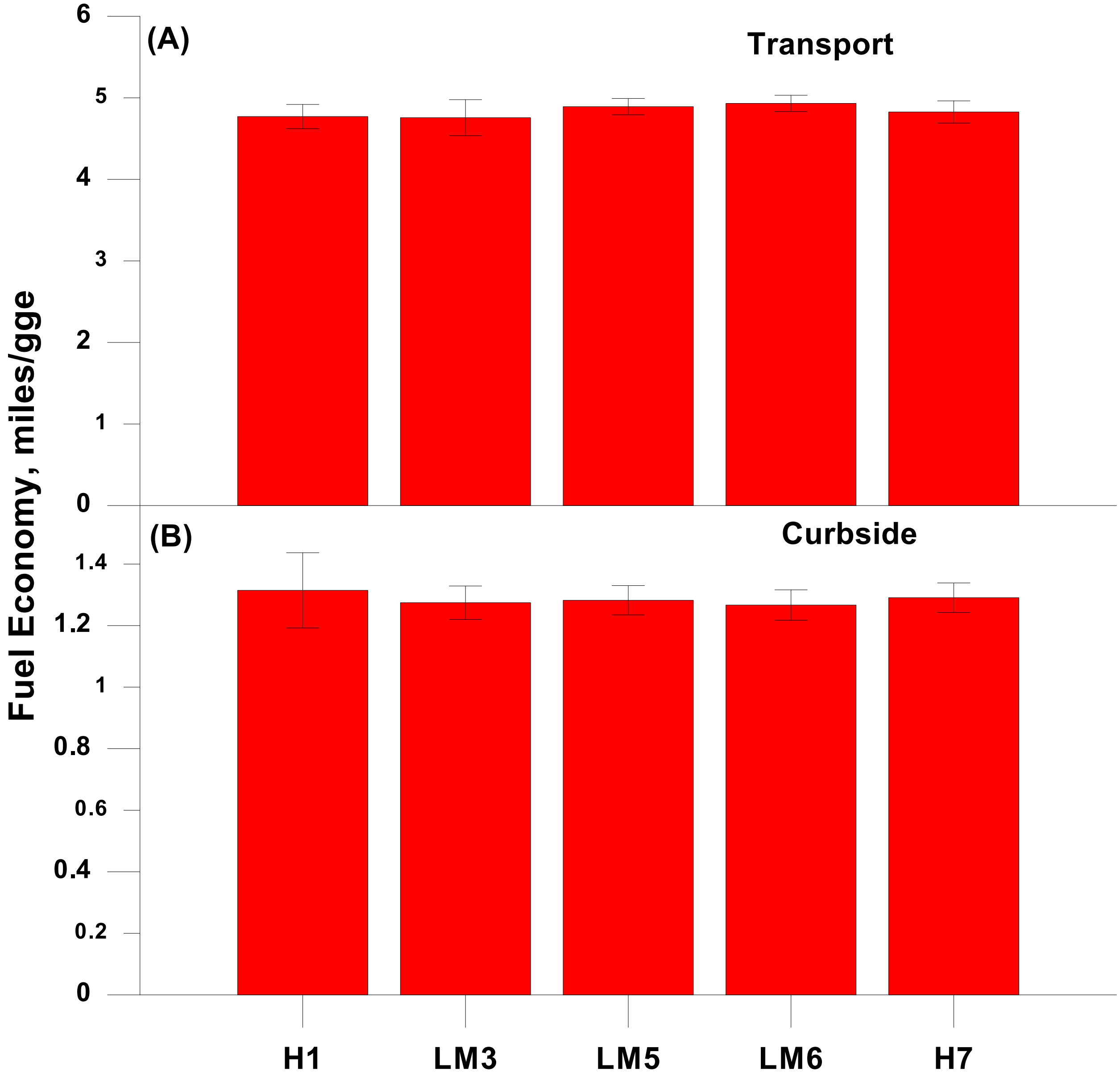
**Figure 3-12. Average Volumetric Fuel Consumption for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis**




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

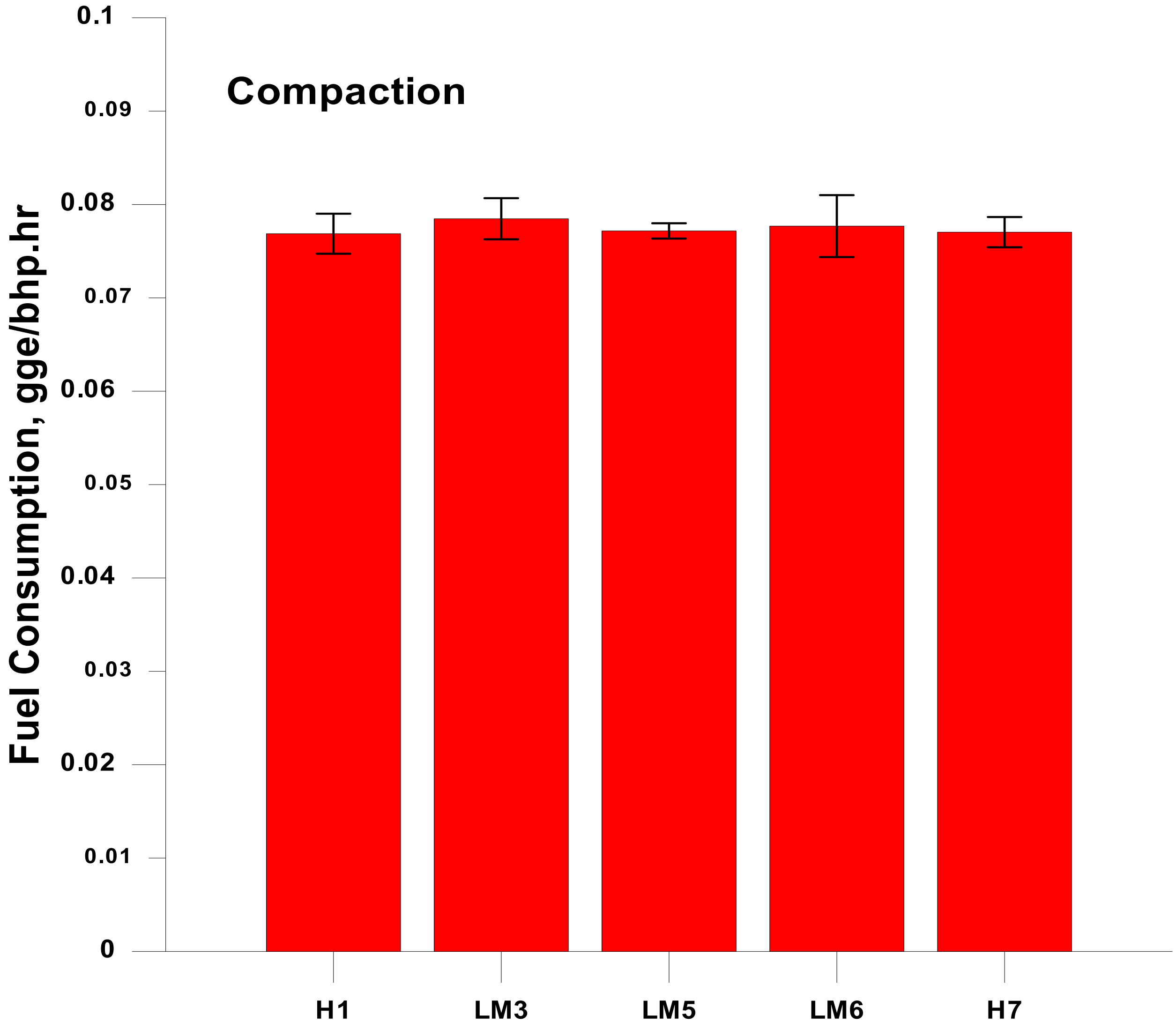
Fuel economy can also be examined on an energy equivalent basis. On this basis, the energy differences between the fuels are normalized. This provides an evaluation of fuel economy with the energy differences between fuels eliminated as a factor. For the transport and curbside segments fuel economy is shown in Figure 3-13 (a-b) on a gasoline gallon equivalent (GGE) energy basis. For the compaction segment, fuel consumption is shown in Figure 3-14 on a gasoline gallon equivalent energy per bhp-hr basis. The waste hauler did not show any statistically significant trends in fuel economy or fuel consumption on an energy equivalent basis, with the exception of LM6, which showed a statistically significant increase in fuel consumption relative to H1 for the transport phase. The Phase 1 testing on the legacy waste hauler showed stronger trends in fuel economy on an energy equivalent basis over the RTC [28], 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 3-13 (a-b). Average Energy Equivalent Fuel Economy for the Waste Hauler Transport and Curbside Segments**




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

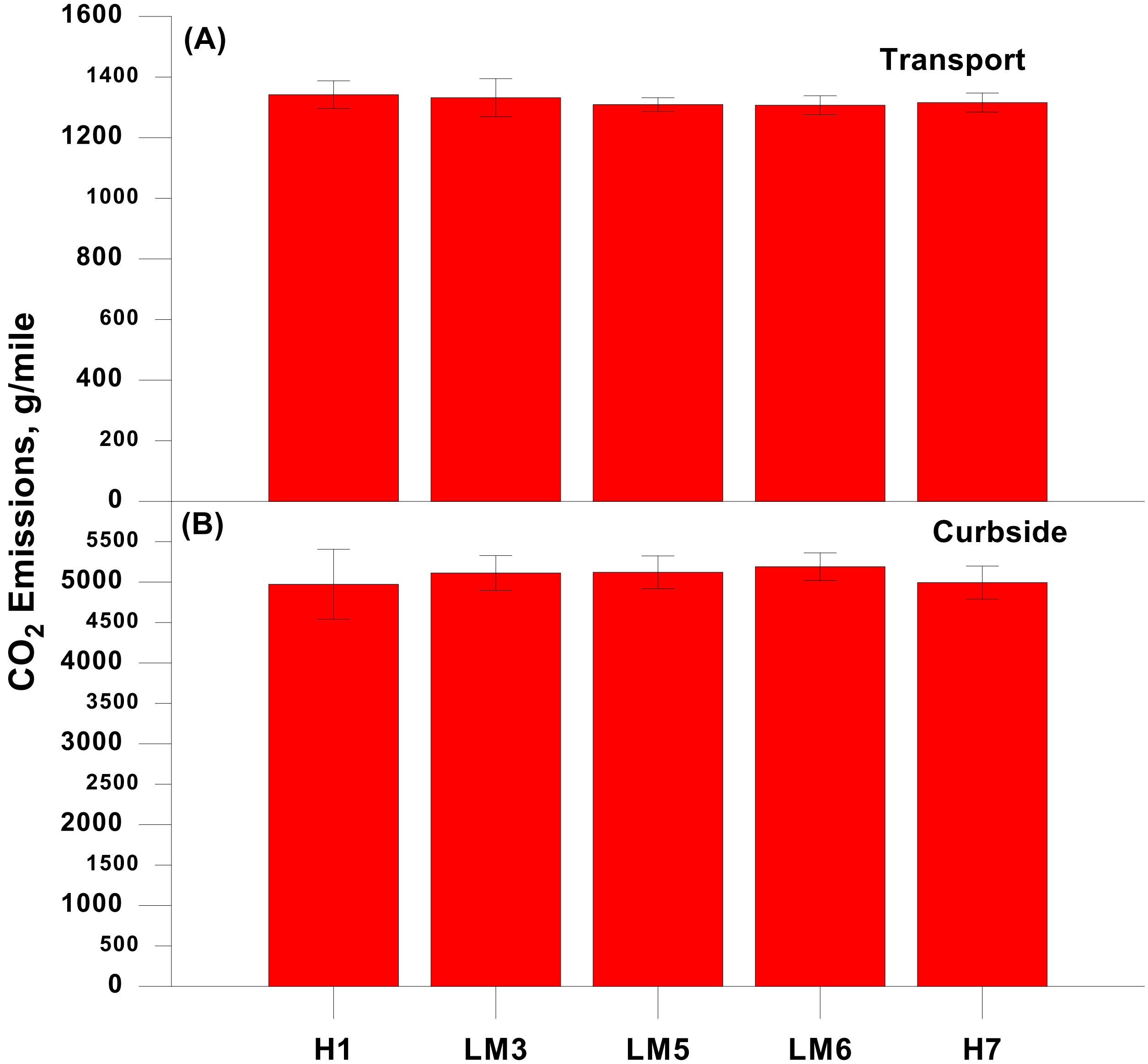
**Figure 3-14. Average Energy Equivalent Fuel Consumption for the Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis**




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

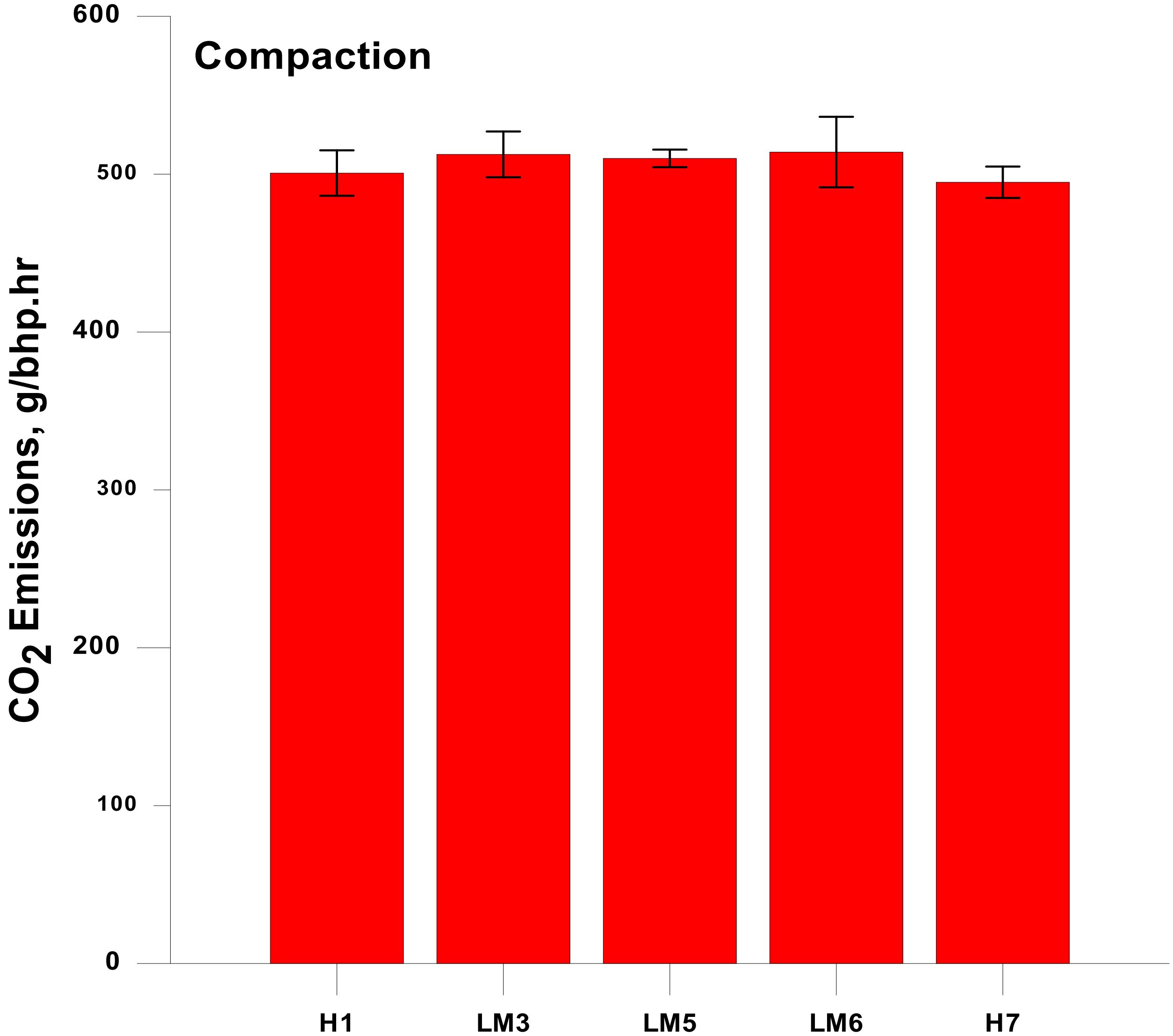
$CO_2$ emissions are shown in Figure 3-15 (a-b) for the transport and curbside segments. For the curbside segment, $CO_2$ emissions were higher than those for the transport segment on a per mile basis. No statistically significant fuel effects were found for either the transport or curbside cycles. $CO_2$ emissions are shown in Figure 3-16 for the compaction segment on a bhp-hr basis. There was a statistically significant reduction for H7 compared to LM3, LM5, and a marginally statistically significant reduction compared to LM6. H7 does have a higher 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 did not show any significant fuel trends. The results for this waste hauler were 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 [28]. The legacy vehicle showed stronger 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 3-15 (a-b). Average $CO_2$ Emissions for the Waste Hauler Transport and Curbside Segments**




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

**Figure 3-16. Average $CO_2$ Emissions for the Compaction Segment of the Waste Hauler on an Engine bhp-hr Basis**




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

### 3.7 PM Mass Emissions

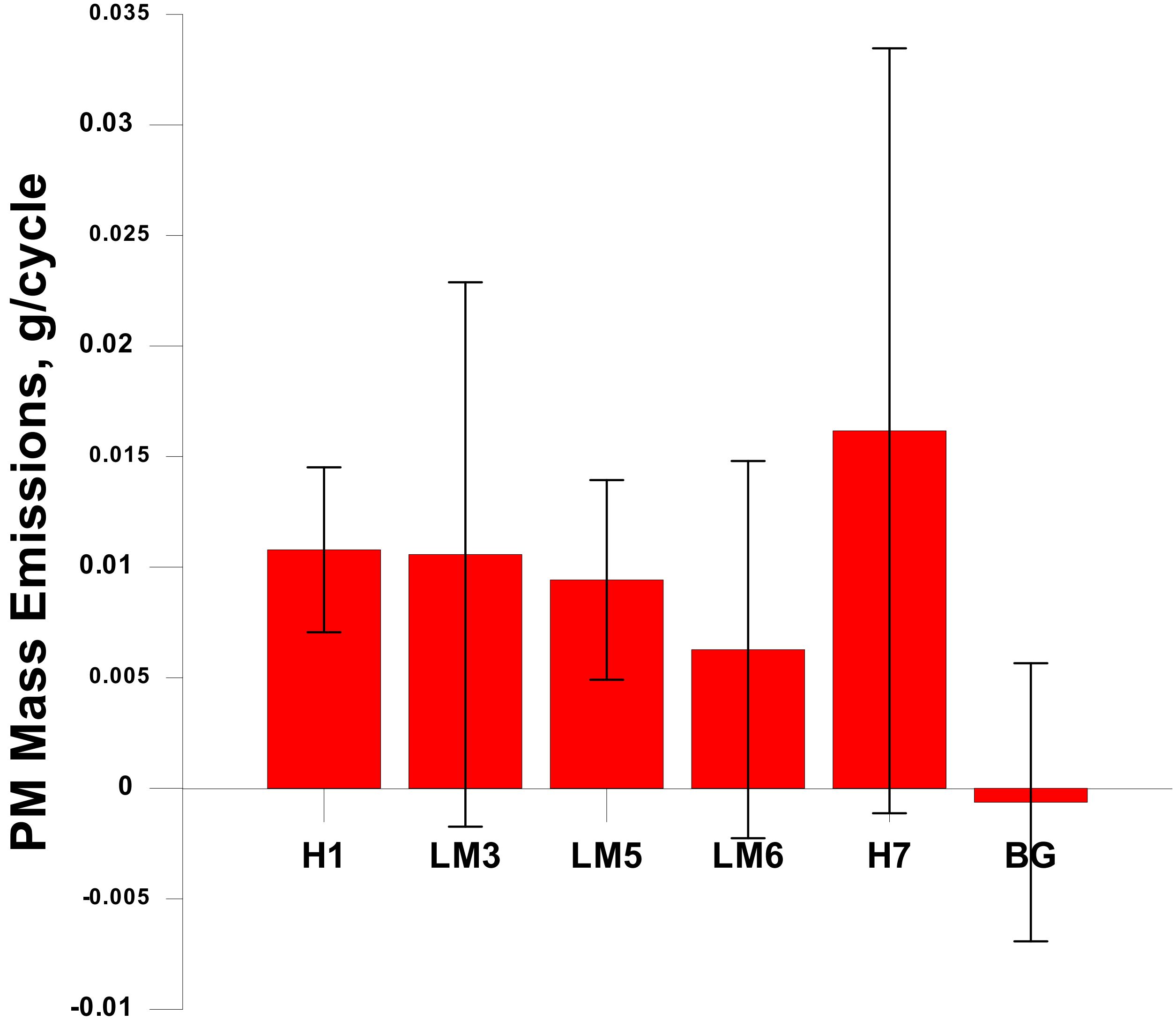
PM mass emissions for the waste hauler are shown in Figure 3-17 for the composite Refuse Truck Cycle. As explained in section 2.4, PM emissions were collected cumulatively over the entire duration of the RTC due to the expectation of low mass levels emitted. Therefore, separate emissions are not available for the curbside, transport, and compaction segments. Instead, PM emissions are shown in terms of g/cycle.

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. So, for this testing, 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 both the generation of low PM levels followed by its reduction in the exhaust. PM is generated from both the combustion of natural gas fuel and the leakage of the lubricant oil into the combustion chamber. Natural gas is primarily comprised of methane, which is the lowest molecular weight hydrocarbon and a simpler structure compared to diesel and gasoline fuels [11]. 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 [37]. The low levels of PM formed from the combustion process are reduced as the exhaust stream passes over the catalyst bed. The carbon particles in the exhaust carry adsorbed water soluble organic compounds of PM. Specifically, some of the soluble organic fraction (SOF) portion of PM is oxidized to $CO_2$ and water over the catalyst bed.

Testing on the legacy waste hauler in Phase 1 showed higher PM mass emission levels than those reported for the stoichiometric engine. 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 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 [28]. The PM levels for the stoichiometric engine, which are lower than those for the legacy engine, are near the limits of detection. At such levels, the experimental variability becomes greater on an absolute basis, making it more difficult to measure differences between fuels.

**Figure 3-17. Average PM Emissions for Waste Hauler**



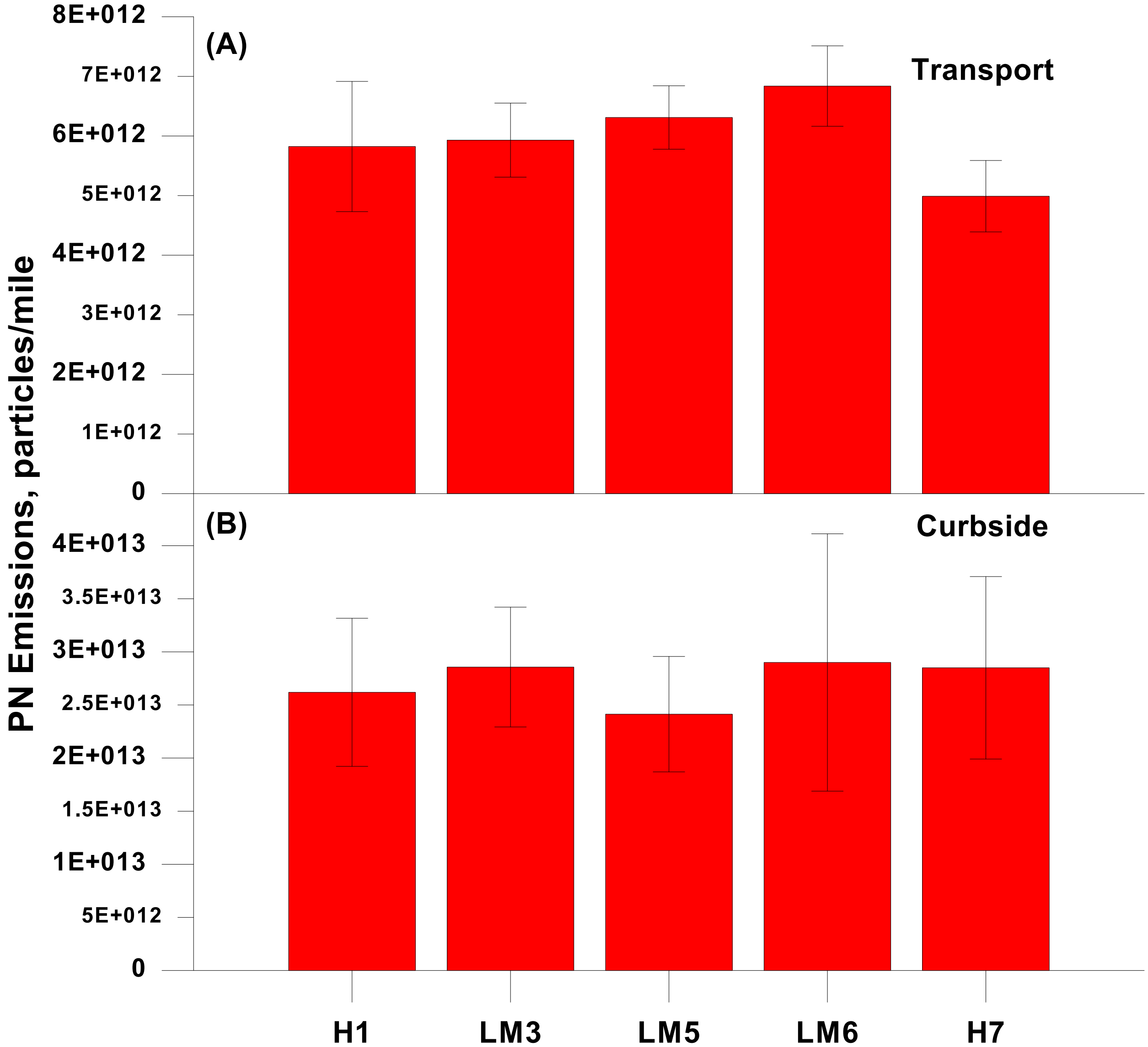

**H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)**

### 3.8 Particle Number Emissions

Particle number (PN) emissions are shown in Figure 3-18 (a-b) for the transport and curbside segment, and in Figure 3-19 (a-b) for the compaction segment on a bhp-hr basis. PN emissions did 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 were observed between fuels. PN emissions showed a marginally statistically significant increase of 17.4% for LM6 compared to H1. LM5 and LM6 showed statistically significant increases in PN emissions of 26.5% and 37%, respectively, while LM3 showed a marginally statistically significant increase of 18.8% compared to H7. It should be noted that PN emissions were approximately an order of magnitude higher for the curbside segment compared to the transport segment of the cycle, as the curbside 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 were no statistically significant differences between the test fuels.

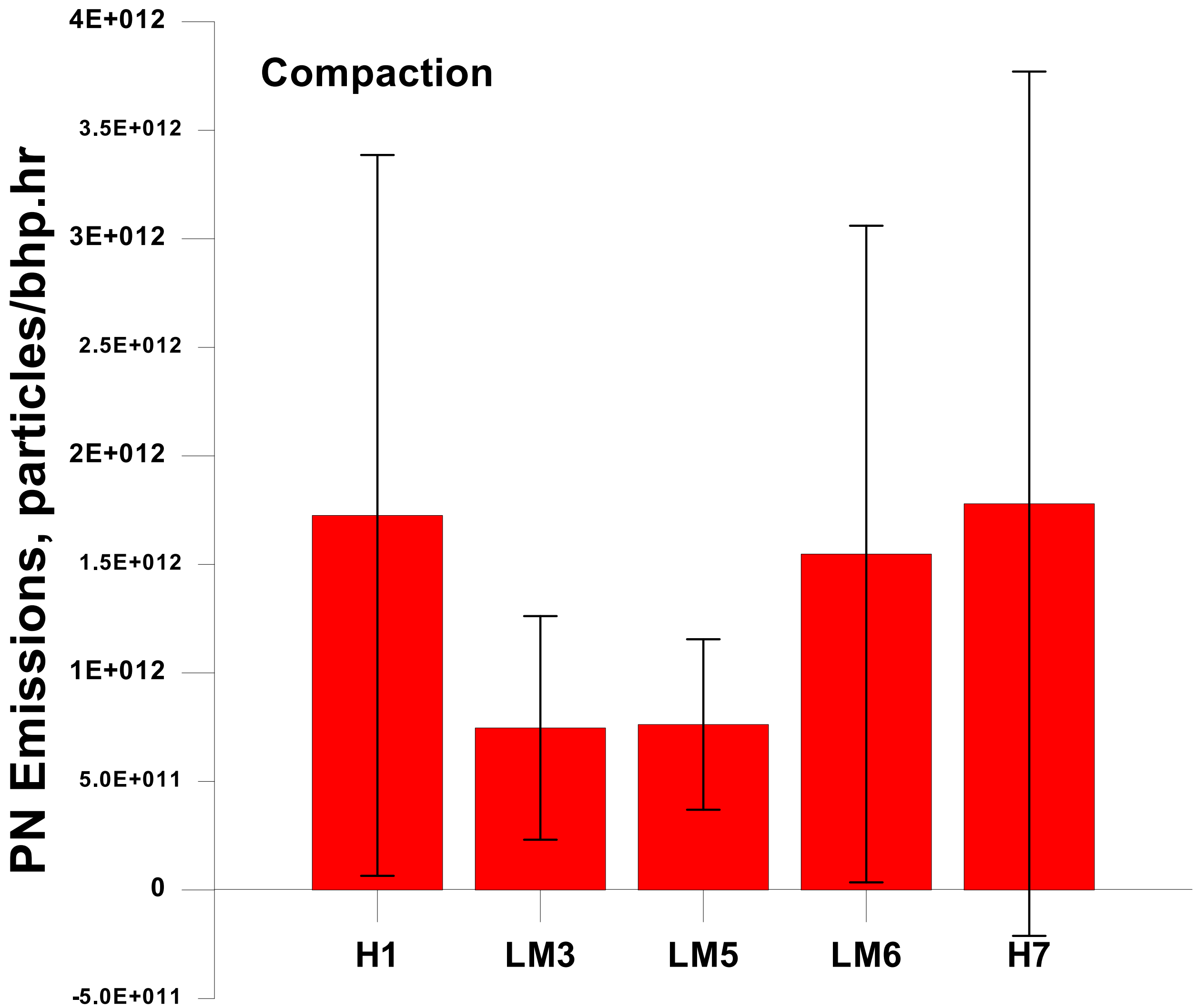
In comparing the results obtained from this study to previous work conducted by CE-CERT, the similarity in total PN emissions between older and newer technology natural gas engines suggests that PN emissions could largely be attributed to lubricant oil and are not significantly influenced by changes in the combustion of fuel and type of aftertreatment.

**Figure 3-18 (a-b). Average PN Emissions for Waste Hauler**




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

**Figure 3-19 (a-b). Average PN Emissions for Waste Hauler**




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

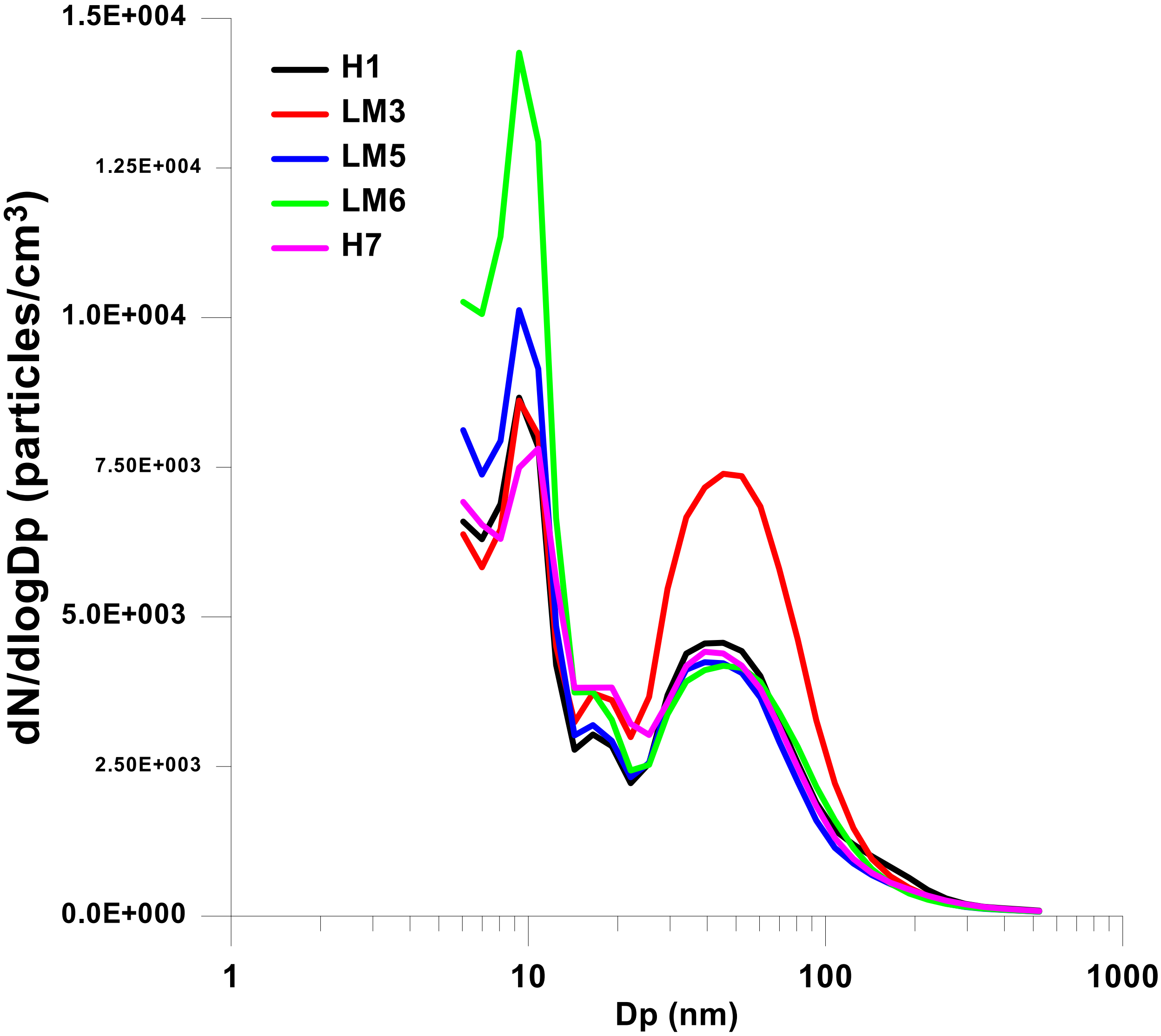
## 3.9 Particle Size Distributions

The average particle size distributions, as obtained with the Engine Exhaust Particle Sizer (EEPS) spectrometer, are shown in Figure 3-20. Exhaust stream particle size distributions for all test fuels showed a decidedly bimodal particle size distribution. The particle size distributions for most fuels showed particle concentrations in the nucleation mode between $8x10^3$ to $1x10^4$ particles/cm$^3$ for particle diameters centered from 9 to 11 nm size range. The exception was for LM6, which showed 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. It should be noted that particle concentrations in the accumulation mode were about an order of magnitude lower than particles in the nucleation mode. The findings of this study are in strong agreement with previous studies showing that the majority of particles from CNG heavy-duty vehicles were in the nucleation mode [8-9,36-37]. 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 were in the nucleation mode [28].

The observed particle concentrations for the nucleation mode somewhat corroborate with the transport mode PN trends. In both cases, the low methane fuels have higher PN emissions as well as higher concentrations of particles in the nucleation mode. Usually, nucleation mode particles consist mostly of semivolatile organic and sulfur compounds. However, our results showed that THC and NMHC were relatively low, and volatile organic compounds (VOCs) were close or below detection limits. Furthermore, lower chain VOCs do not typically participate in particle formation mechanisms. 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. [37] when they tested two 2007 CNG buses fitted with Cummins ISLG280 engines and TWCs.

The entry of lubricant oil in to the combustion chamber is dependent on engine load. Typically low-load operations, such as those applied during the RTC, result in insufficient sealing of the piston rings, which can contribute to the combustion of lubricant oil [37]. 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. This phenomenon has been explained by Khalek et al. [38] showing that lubricant oil additives do undergo volatilization when passing through the combustion chamber and a fraction of them renucleate to form nanoparticles.

**Figure 3-20. Average Particle Size Distributions for the Waste Hauler**




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

### 3.10 $NH_3$ Emissions

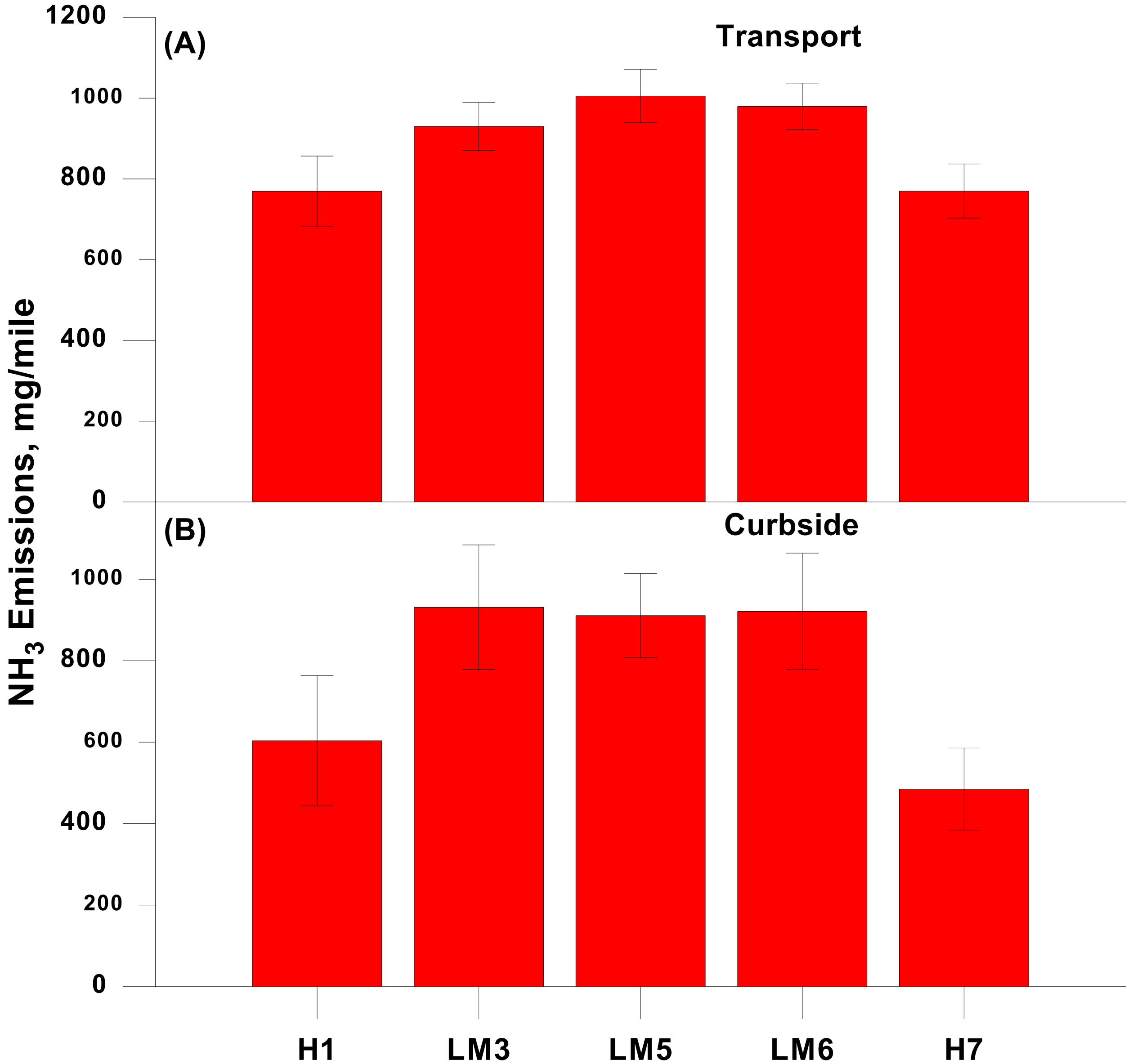
Road traffic is a major source of reactive nitrogen compounds such as $NH_3$. $NH_3$ is involved in the formation of secondary aerosols and also considered as toxic pollutant. Ammonia is formed de novo in noble metal-based TWCs and therefore has to be considered as a secondary pollutant of the catalytic process rather than a side product of the fuel combustion. NO and $H_2$, both formed during combustion, are the assumed precursor molecules [39-42].

Figure 3-21 shows the $NH_3$ emissions for the waste hauler for the transport and curbside segments, while Figure 3-22 shows the $NH_3$ emissions for the compaction segment on a bhp-hr basis. $NH_3$ 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 were 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 in turn are produced during periods of rich air-fuel mixtures. Hydrogen could be either formed due to a water gas shift reaction involving CO and water or steam reforming reactions involving $CH_4$ and water in the exhaust [40-42]. 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 appeared to play 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 [14]. It is also known that oxidation of methane with a standard platinum/palladium/rhodium TWC is somewhat more difficult to achieve than oxidation of the 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 could be a plausible explanation for the lower ammonia emissions observed for the higher methane fuels compared to LM3, LM5, and LM6. The presence of higher levels of CO also facilitates the formation of $NH_3$ 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 cycle resulting in higher $NH_3$ emissions.

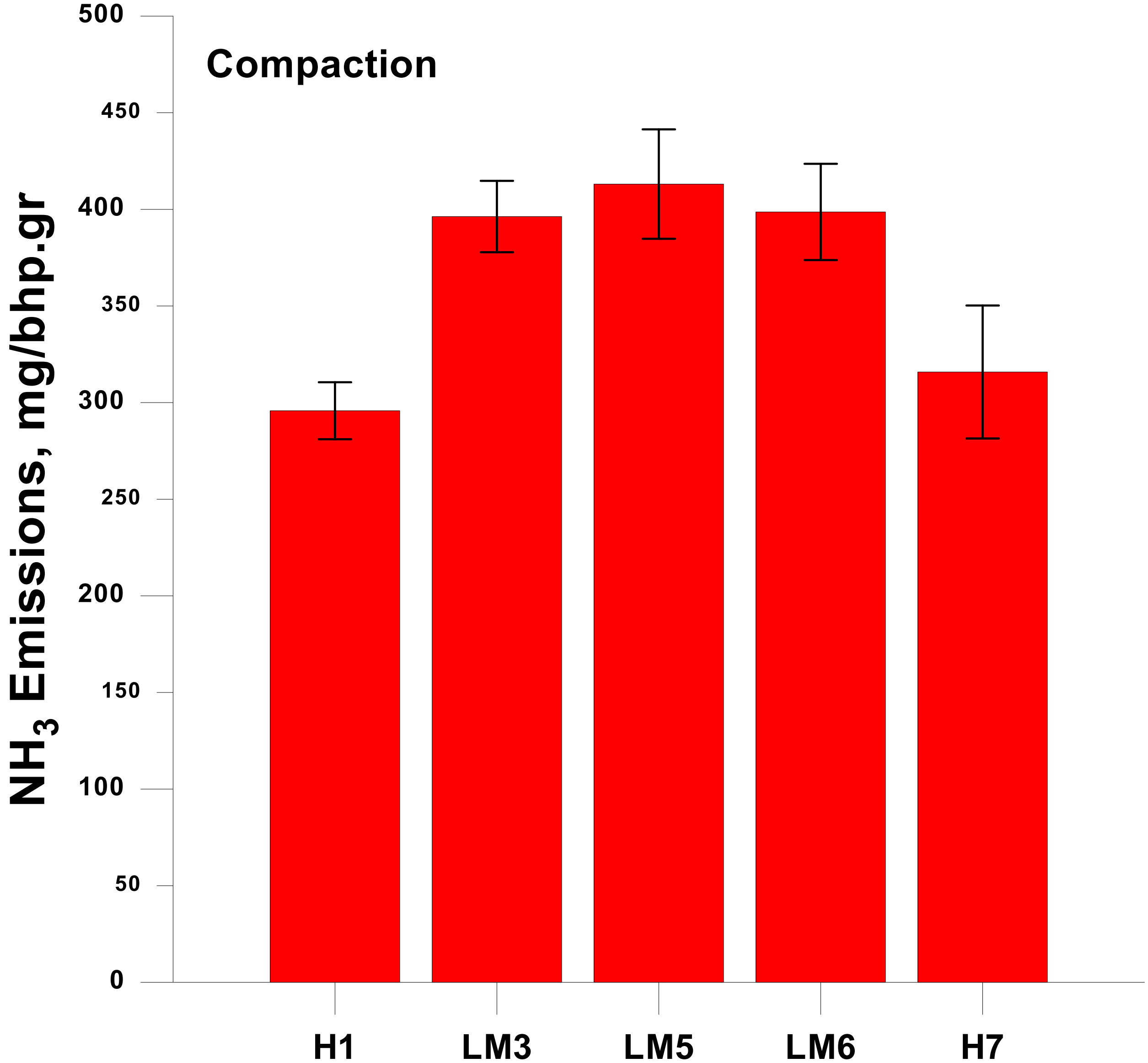
Our results show substantially higher $NH_3$ emissions for the stoichiometric ISL-G engine with TWC compared to the older technology Cummins 8.3L C Gas Plus lean burn engine with an oxidation catalyst that was previously tested at CE-CERT. Under the present test conditions, $NH_3$ emissions ranged from 769 mg/mile to 1005 mg/mile for the transport phase and from 485 mg/mile to 931 mg/mile for the curbside phase, whereas for the C Gas Plus lean burn engine $NH_3$ emissions 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. Similar findings were also observed in our previous studies for three natural gas buses over the CBD cycle. The stoichiometric Cummins Westport ISL-G bus produced significantly higher $NH_3$ emissions compared to the lean burn John Deere and Cummins C Gas Plus buses in the Phase 1 tests [28]. The higher $NH_3$ emissions for the stoichiometric engines is attributed to the presence of the TWC, which can catalyze the formation of $NH_3$ emissions through a complex series of reactions, including the water-gas shift reaction [41–42].

**Figure 3-21. (a-b). Average $NH_3$ Emissions for Waste Hauler Transport and Curbside Segments.**




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

**Figure 3-22. Average $NH_3$ Emissions for Waste Hauler for the Compaction Segment on an Engine bhp-hr Basis.**




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

### 3.11 $N_2O$ Emissions

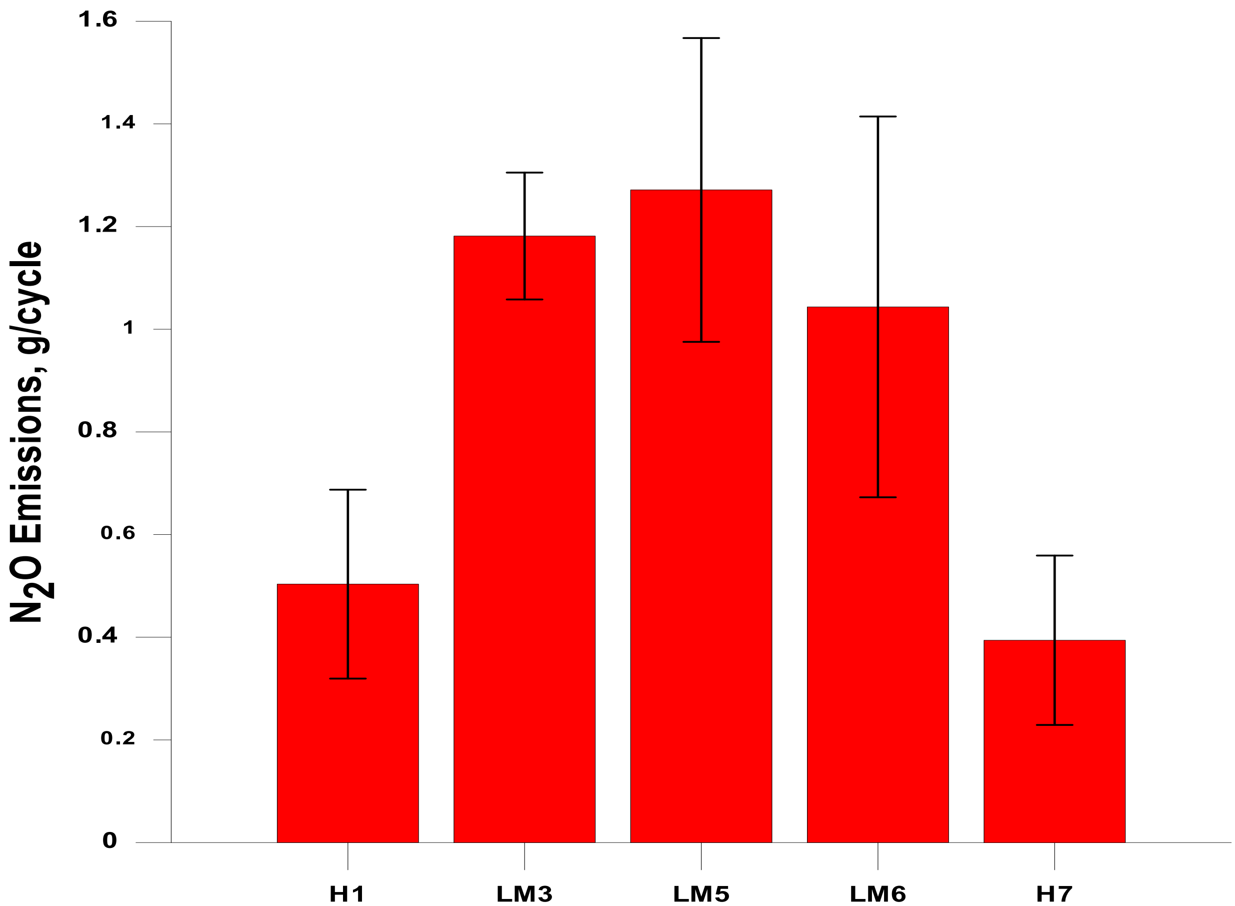
Nitrous oxide ($N_2O$) is considered both a toxic pollutant and a greenhouse gas. Although limited $N_2O$ is produced in aftertreatment systems, it was included in recent Greenhouse Gas regulations, which count $N_2O$ as $CO_2$ equivalents. This is because, according to the Fifth Assessment Report (AR5), $N_2O$ 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) [43]. Besides, $N_2O$ is the major source of $NO_x$ in the stratosphere and therefore an important natural regulator of stratospheric ozone. Figure 3-23 shows the composite $N_2O$ emissions over the RTC. Nitrous oxide emissions ranged from 0.39 g/cycle to 1.27 g/cycle. Our results show that selectivity towards $N_2O$ emissions is highly dependent on fuel composition. Low methane fuels resulted in higher emissions of $N_2O$ compared to high methane fuels. The fuels LM3, LM5, and LM6 showed statistically significant increases in $N_2O$ emissions of 134.7%, 152.5%, and 107% and 200%, 223%, and 165%, respectively, compared to H1 and H7. It was found that $N_2O$ emissions corroborate with $NH_3$ emissions and showed an inverse relation to $NO_x$ emissions for the transport and curbside segments.

$N_2O$ forms as an intermediate during the catalytic reduction of nitric oxide (NO) to molecular nitrogen ($N_2$). At high temperatures, NO is directly reduced to $N_2$; however, at lower temperatures, $N_2O$ is an intermediate product. Some of the reactions involved, which take place between species adsorbed on the surface of the TWC, are shown below [44-46]. Note that the richer conditions that give rise to higher levels of CO and hydrogen on the catalyst surface would 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.

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

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

**Figure 3-23. $N_2O$ Emissions for the Waste Hauler over the RTC**

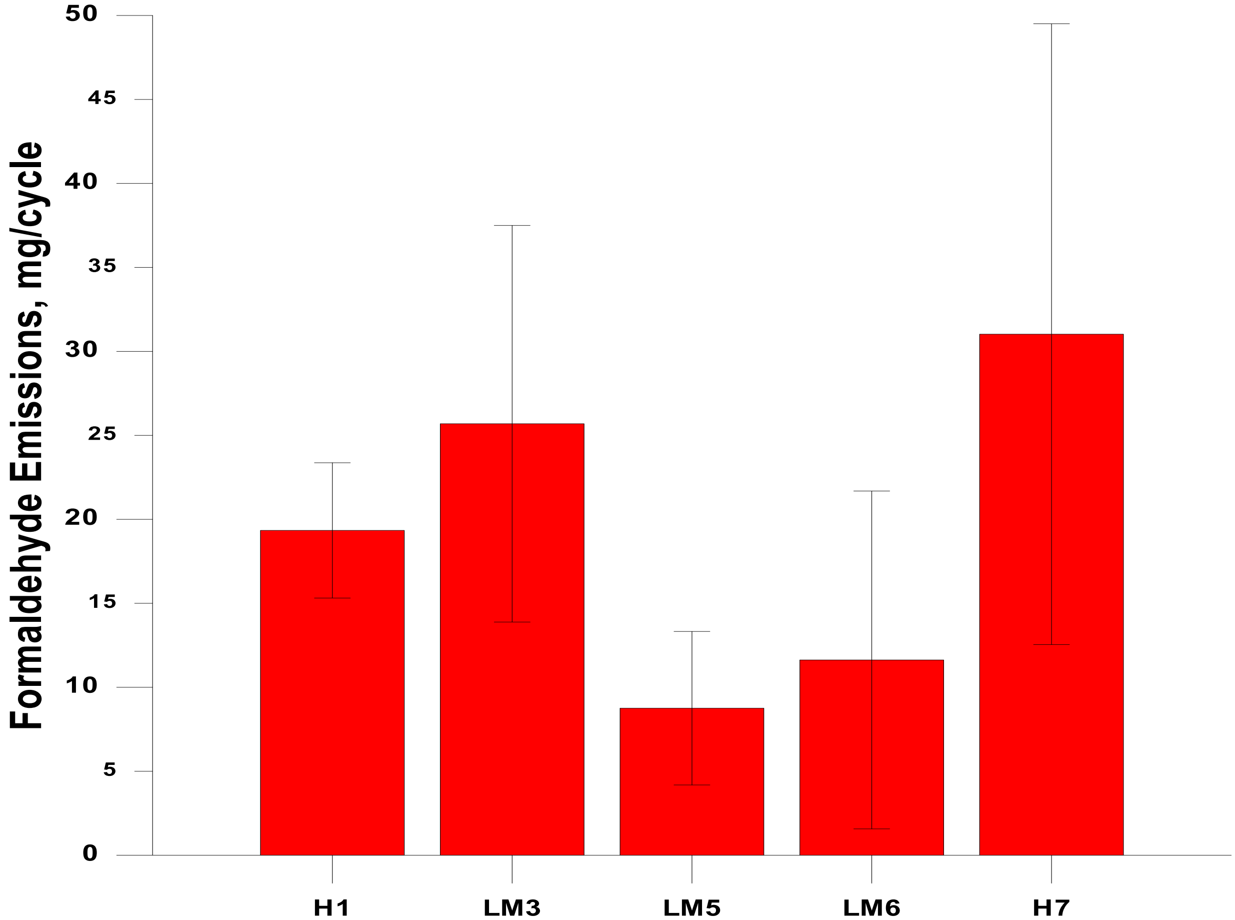



**H1-Texas (1339 WN), LM3Peruvian LNG (1385 WN), LM5-Hi Ethane (1385 WN), LM6-Hi Propane (1385 WN), H7 L-CNG (1370 WN)**

## 3.12 Carbonyl Emissions

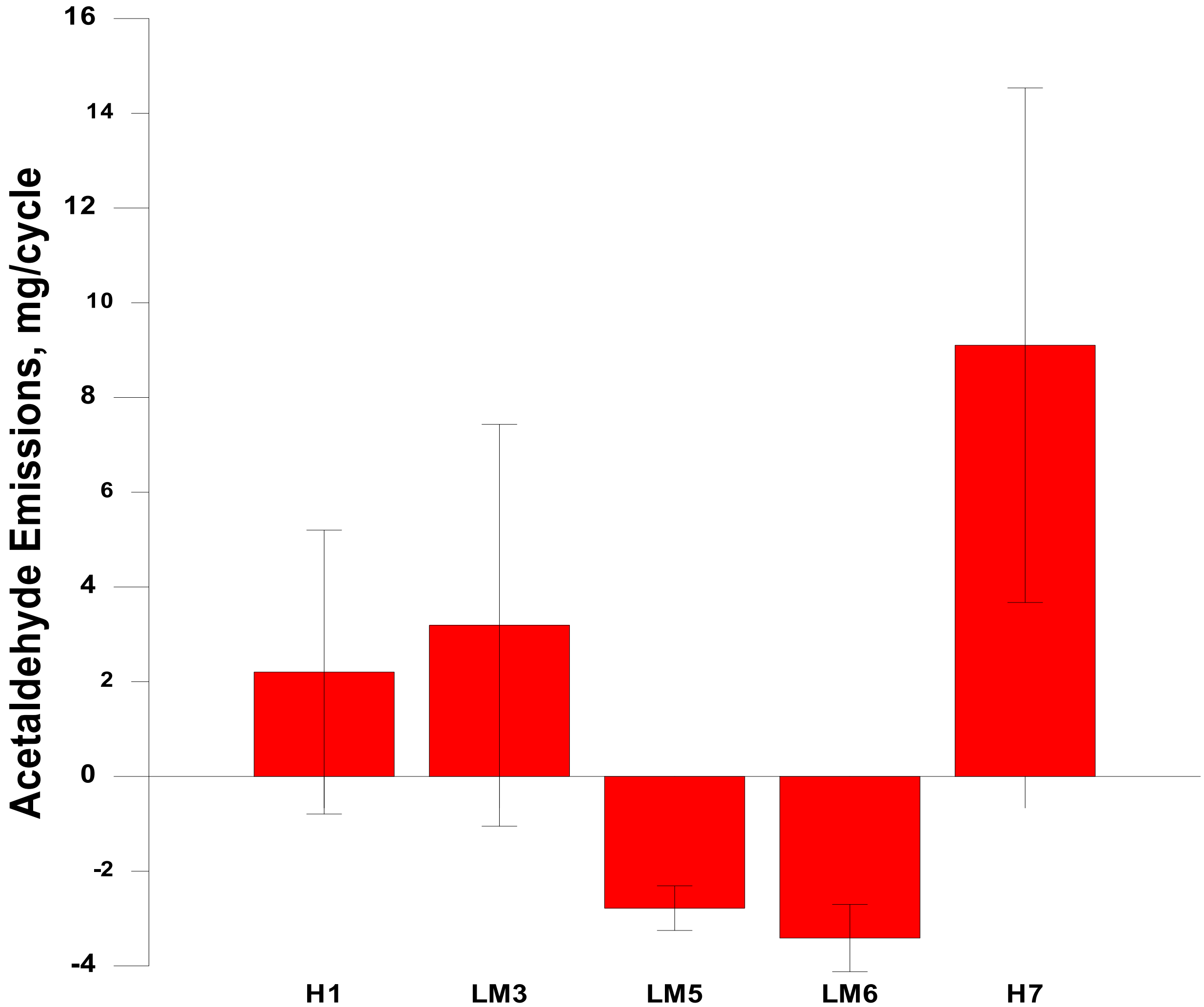
Figure 3-24 and Figure 3-25 show the average composite formaldehyde and acetaldehyde emissions, respectively, from the waste hauler truck. Note that similar to the PM emissions these are presented in terms of mg/cycle, since the emissions for the driving portions of the cycle (i.e., the curbside and transport segments) cannot be separated from the compaction segment, which is not an actual driving event. Formaldehyde and acetaldehyde emissions are typically the most prominent measured carbonyl emissions, with formaldehyde emissions being the highest. Note that formaldehyde and acetaldehyde are the lower molecular weight aldehydes, having one and two carbons, respectively. Our results are consistent with previous studies showing that the dominant carbonyl emissions from CNG vehicles come from the lowest molecular weight compounds [4-6, 28]. Formaldehyde emissions did not show any statistically significant fuel trends, with the exception of LM5 that showed a 54.7% decrease in formaldehyde emissions compared to H1 at a statistically significant level. Acetaldehyde emissions were 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 extend below zero. Acetaldehyde emissions showed a marginally statistically significant increase of 313% 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 [28]. 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 3-24. Average Formaldehyde Emissions for Waste Hauler.



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

**Figure 3-25. Average Acetaldehyde Emissions for Waste Hauler Truck.**




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

# 4 Summary and Conclusions

As the demand for NG in California and the production of NG throughout the U.S. both expand, there is potential for a wider range of natural gas compositions to be used in NGVs. It is important to evaluate whether changing compositions of NG will have adverse impacts on the emissions or performance of NGVs. Previous studies of small stationary source engines, such as compressors, heavy-duty engines, and heavy-duty vehicles [12–22,28] have shown that NG composition can have an impact on emissions. Some of these studies have shown that these impacts may be less pronounced for the latest generation of heavy-duty NGV with the more advanced emission control systems, however. The current study was designed to evaluate the impact of changing NG composition on emissions in the latest generation NG refuse hauler. These results may also be used in CARB's ongoing process to amend the California NG fuel standards for motor vehicles.

In this study, five blends of natural gas with different fuel compositions were tested. The test fuels included fuels representative of Texas Pipeline gas; a fuel representing Peruvian LNG modified to 1385 WN; 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. Emissions testing was performed on a waste hauler equipped with a stoichiometric spark ignited Cummins Westport ISL-G engine with EGR and a TWC. The vehicle was tested over a refuse truck cycle that included transport, compaction, and curbside segments. The testing included measurements of regulated emissions and fuel economy/consumption, as well as measurements of $NH_3$, $N_2O$, carbonyls, and particle number (PN) and particle size distributions.

The results of the test program did show some emissions impacts with the changing fuel compositions, although the emissions impacts were generally less than those seen for older engine technologies. The results of this study are summarized below. Results are generally statistically significant, except as noted.

- THC, NMHC, $CH_4$, $NO_x$, formaldehyde, acetaldehyde emissions for the Westport ISL-G waste hauler were considerably lower than these emissions from previous studies of lean burn technology engines.
- The Cummins Westport ISL-G waste hauler did, however, show higher CO and $NH_3$ emissions compared to older lean burn engines. This could be attributed to the richer operation for the stoichiometric engine compared to the lean burn engines, as well as the TWC for the $NH_3$ emissions.
- The results showed reductions in $NO_x$ emissions for the low methane fuels for the transport and curbside cycles. This could be due to richer combustion with these fuels, which would promote greater reduction of $NO_x$ emissions over the TWC. $NO_x$ emissions for the compaction cycle were very low, and were either at the background levels or were considerably below the 0.2 g/bhp-hr standard.
- THC and $CH_4$ emissions did not show any consistent fuel trends. $CH_4$ comprised a majority of the THC emissions, with NMHC emissions representing a smaller fraction of the THC. NMHC emissions showed a trend of higher emissions for the low methane fuels containing higher levels of NMHCs (i.e., ethane, propane, and butane). This trend was seen for all three cycles.
- CO emissions showed a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. The higher CO emissions could be due to slightly richer combustion for

the low methane fuels, which could make oxidation of the CO slightly more difficult either during combustion or over the catalyst.

- Fuel economy/consumption on a volumetric basis showed some differences between the various test fuels. Specifically, LM3, LM5, and LM6 generally showed higher fuel economy on a volumetric basis compared to H1 and H7. These trends are consistent with the low methane fuels providing higher fuel economy and lower fuel consumption. Fuel economy/consumption on an energy equivalent basis did not show any statistically significant trends. $CO_2$ emissions did not show any statistically significant trends for either the transport or curbside cycles, but did show some statistically significant reductions for H7 compared to LM3 and LM5 and some marginally statistically significant reductions for H7 compared to LM6 for the compaction cycle.
- PM mass emissions were very low for refuse truck on an absolute level, and are at the same levels as the tunnel background. There were no statistically significant differences between test fuels for PM emissions.
- PN emissions did not show strong fuel trends for the different RTC segments. PN emission levels were similar to those found for older heavy-duty NGVs, suggesting a strong contribution from the lubricant oil.
- The particle size distributions showed bimodal distributions, with a majority of the particles in the nucleation mode with particle diameters centered from 9 to 11 nm size range.
- $NH_3$ emissions were found for the stoichiometric Cummins Westport ISL-G at levels higher than those seen for older lean burn engines. $NH_3$ emissions showed a trend of higher emissions for the low methane fuels, i.e., LM3, LM5, and LM6. The increases in $NH_3$ emissions LM3, LM5, and LM6 were statistically significant compared to both H1 and H7 for all three of the test cycles. The higher $NH_3$ emissions could be due to slightly richer combustion for the low methane fuels, which could make oxidation of the $NH_3$ slightly more difficult either during combustion or over the catalyst.
- $N_2O$ emissions were highly dependent on fuel composition, with low methane fuels showing higher emissions of $N_2O$ compared to high methane fuels. Overall, $N_2O$ emissions corroborate with $NH_3$ emissions and showed an inverse relation to $NO_x$ emissions for the transport and curbside segments.
- Formaldehyde emissions did not show any statistically significant fuel trends, with the exception of LM5 that showed a 54.7% decrease in formaldehyde emissions compared to H1. Acetaldehyde emissions were at or below the background levels for all of the test fuels with the exception of H7.

# 5 References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## Appendix A.

### *2011 Cummins Westport 8.9L C-Gas Plus 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.).

| in g/bhp-hr [4] | 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**

## Appendix B. Emissions Test Results

### a) Averages, percentage differences, and P-values

*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 |

| | | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/$ft^3$ | PN #/mile |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage difference | vs. H1 | | | | | | | | | | |
| Transport | LM3 | 16.16% | -1.35% | 354.88% | 63.85% | -13.03% | 20.81% | -0.73% | -0.29% | 5.94% | 1.84% |
| | LM5 | 13.29% | -5.86% | 392.33% | 59.97% | -20.92% | 30.62% | -2.44% | 2.55% | 12.37% | 8.36% |
| | LM6 | -1.25% | -13.81% | 251.01% | 39.16% | -10.00% | 27.26% | -2.58% | 3.38% | 13.35% | 17.42% |
| | H7 | -10.30% | -13.37% | 42.60% | -21.44% | 15.14% | 0.04% | -1.93% | 1.17% | 1.30% | -14.31% |
| Percentage difference | | | | | | | | | | | |
| Curbside pick up | vs. H1 | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/$ft^3$ | PN #/mile |
| | LM3 | -20.87% | -34.04% | 817.34% | 38.83% | -24.34% | 54.30% | 2.82% | -3.06% | 3.00% | 9.07% |
| | LM5 | 1.89% | -18.22% | 1235.87% | 63.02% | -11.23% | 50.89% | 2.99% | -2.45% | 6.90% | -7.86% |
| | LM6 | -5.95% | -20.89% | 933.58% | 67.67% | -17.49% | 52.61% | 4.37% | -3.63% | 5.65% | 10.72% |
| | H7 | -6.67% | -9.49% | 157.80% | -41.04% | 24.26% | -19.66% | 0.42% | -1.82% | -1.69% | 8.80% |
| Percentage difference | vs. H1 | | | | | | | | | | |
| Compaction | | THC g/bhp.hr | $CH_4$ g/bhp.hr | NMHC g/bhp.hr | CO g/bhp.hr | $NO_x$ g/bhp.hr | $NH_3$ mg/bhp.hr | $CO_2$ g/bhp.hr | GGE/bhp.hr | $ft^3$/bhp.hr | PN #/bhp.hr |
| | LM3 | 22.18% | -1.10% | 410.55% | 24.34% | -247.13% | 33.98% | 2.36% | 2.09% | -3.92% | -56.73% |
| | LM5 | 13.23% | -5.55% | 338.24% | 26.72% | 779.28% | 39.66% | 1.85% | 0.39% | -8.39% | -55.82% |
| | LM6 | 16.43% | 0.72% | 290.16% | 23.42% | 1323.28% | 34.78% | 2.66% | 1.06% | -7.82% | -10.31% |
| | H7 | 17.27% | 6.66% | 182.33% | 4.18% | 2085.96% | 6.78% | -1.16% | 0.22% | 0.09% | 3.12% |

Note that the units in the header represent the units for the average values that are being compared. The percent values themselves are unitless.

| | | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/$ft^3$ | PN #/mile |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage difference | vs. H7 | | | | | | | | | | |
| Transport | H1 | 11.48% | 15.43% | -29.87% | 27.29% | -13.15% | -0.04% | 1.97% | -1.16% | -1.28% | 16.70% |
| | LM3 | 29.49% | 13.87% | 218.99% | 108.57% | -24.47% | 20.76% | 1.22% | -1.44% | 4.58% | 18.85% |
| | LM5 | 26.30% | 8.67% | 245.25% | 103.63% | -31.31% | 30.56% | -0.52% | 1.36% | 10.93% | 26.46% |
| | LM6 | 10.09% | -0.51% | 146.15% | 77.15% | -21.83% | 27.20% | -0.66% | 2.19% | 11.89% | 37.03% |
| Percentage difference | vs. H7 | | | | | | | | | | |
| Curbside pick up | | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/$ft^3$ | PN #/mile |
| | H1 | 7.15% | 10.49% | -273.02% | 69.61% | -19.52% | 24.48% | -0.42% | 1.85% | 1.72% | -8.09% |
| | LM3 | -15.22% | -27.12% | 1141.11% | 135.47% | -39.11% | 92.07% | 2.38% | -1.26% | 4.78% | 0.25% |
| | LM5 | 9.17% | -9.64% | 1865.25% | 176.49% | -28.57% | 87.83% | 2.56% | -0.64% | 8.74% | -15.31% |
| | LM6 | 0.78% | -12.60% | 1342.24% | 184.37% | -33.60% | 89.97% | 3.93% | -1.85% | 7.47% | 1.76% |
| Percentage difference | vs. H7 | | | | | | | | | | |
| Compaction | | THC g/bhp.hr | $CH_4$ g/bhp.hr | NMHC g/bhp.hr | CO g/bhp.hr | $NO_x$ g/bhp.hr | $NH_3$ mg/bhp.hr | $CO_2$ g/bhp.hr | GGE/bhp.hr | $ft^3$/bhp.hr | PN #/bhp.hr |
| | H1 | -14.73% | -6.24% | -64.58% | -4.01% | -95.43% | -6.35% | 1.18% | -0.22% | -0.09% | -3.03% |
| | LM3 | 4.18% | -7.27% | 80.83% | 19.35% | -106.73% | 25.47% | 3.57% | 1.86% | -4.01% | -58.04% |
| | LM5 | -3.45% | -11.44% | 55.22% | 21.63% | -59.78% | 30.79% | 3.05% | 0.17% | -8.47% | -57.16% |
| | LM6 | -0.72% | -5.57% | 38.19% | 18.46% | -34.89% | 26.22% | 3.86% | 0.84% | -7.90% | -13.03% |

Note that the units in the header represent the units for the average values that are being compared. The percent values themselves are unitless.

| | | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/ft$^3$ | PN #/mile |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P-value | | | | | | | | | | | |
| Transport | Vs. H1 | | | | | | | | | | |
| | LM3 | 0.315 | 0.912 | 0.006 | 0.000 | 0.073 | 0.003 | 0.750 | 0.896 | 0.023 | 0.850 |
| | LM5 | 0.409 | 0.640 | 0.003 | 0.003 | 0.001 | 0.000 | 0.140 | 0.118 | 0.000 | 0.349 |
| | LM6 | 0.931 | 0.245 | 0.022 | 0.007 | 0.348 | 0.000 | 0.145 | 0.046 | 0.000 | 0.082 |
| | H7 | 0.524 | 0.360 | 0.692 | 0.107 | 0.003 | 0.994 | 0.266 | 0.497 | 0.452 | 0.267 |
| P-value | Vs. H1 | | | | | | | | | | |
| Curbside | | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/ft$^3$ | PN #/mile |
| | LM3 | 0.368 | 0.044 | 0.121 | 0.092 | 0.011 | 0.003 | 0.488 | 0.474 | 0.485 | 0.531 |
| | LM5 | 0.929 | 0.217 | 0.021 | 0.012 | 0.268 | 0.002 | 0.457 | 0.558 | 0.121 | 0.581 |
| | LM6 | 0.783 | 0.178 | 0.064 | 0.038 | 0.050 | 0.003 | 0.274 | 0.391 | 0.197 | 0.633 |
| | H7 | 0.766 | 0.607 | 0.752 | 0.035 | 0.009 | 0.146 | 0.915 | 0.663 | 0.685 | 0.676 |
| P-value | Vs. H1 | | | | | | | | | | |
| Compaction | | THC g/bhp.hr | $CH_4$ g/bhp.hr | NMHC g/bhp.hr | CO g/bhp.hr | $NO_x$ g/bhp.hr | $NH_3$ mg/bhp.hr | $CO_2$ g/bhp.hr | GGE/bhp.hr | ft$^3$/bhp.hr | PN #/bhp.hr |
| | LM3 | 0.038 | 0.882 | 0.005 | 0.082 | 0.654 | 0.000 | 0.169 | 0.211 | 0.026 | 0.198 |
| | LM5 | 0.215 | 0.495 | 0.010 | 0.098 | 0.097 | 0.000 | 0.167 | 0.754 | 0.000 | 0.197 |
| | LM6 | 0.087 | 0.919 | 0.014 | 0.093 | 0.012 | 0.000 | 0.222 | 0.603 | 0.002 | 0.850 |
| | H7 | 0.113 | 0.349 | 0.147 | 0.715 | 0.009 | 0.187 | 0.422 | 0.878 | 0.950 | 0.967 |

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1); bhp-hr = brake horsepower-hour basis from engine control module (ECM); Note that the units in the header represent the units for the average values that are being compared. The p-values themselves are unitless.

| | | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/$ft^3$ | PN #/mile |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P-value | | | | | | | | | | | |
| Transport | Vs. H7 | | | | | | | | | | |
| | H1 | 0.524 | 0.360 | 0.692 | 0.107 | 0.003 | 0.994 | 0.266 | 0.497 | 0.452 | 0.267 |
| | LM3 | 0.047 | 0.318 | 0.002 | 0.000 | 0.002 | 0.001 | 0.586 | 0.526 | 0.073 | 0.081 |
| | LM5 | 0.076 | 0.539 | 0.001 | 0.001 | 0.000 | 0.000 | 0.675 | 0.364 | 0.000 | 0.012 |
| | LM6 | 0.375 | 0.968 | 0.004 | 0.001 | 0.042 | 0.000 | 0.640 | 0.157 | 0.000 | 0.005 |
| P-value | | | | | | | | | | | |
| Curbside | Vs. H7 | THC g/mile | $CH_4$ g/mile | NMHC g/mile | CO g/mile | $NO_x$ g/mile | $NH_3$ mg/mile | $CO_2$ g/mile | miles/GGE | miles/$ft^3$ | PN #/mile |
| | H1 | 0.766 | 0.607 | 0.752 | 0.035 | 0.009 | 0.146 | 0.915 | 0.663 | 0.685 | 0.676 |
| | LM3 | 0.440 | 0.181 | 0.068 | 0.001 | 0.000 | 0.000 | 0.349 | 0.594 | 0.072 | 0.988 |
| | LM5 | 0.586 | 0.597 | 0.002 | 0.000 | 0.002 | 0.000 | 0.302 | 0.770 | 0.003 | 0.374 |
| | LM6 | 0.964 | 0.507 | 0.014 | 0.003 | 0.000 | 0.000 | 0.101 | 0.415 | 0.008 | 0.951 |
| P-value | | | | | | | | | | | |
| Compaction | Vs. H7 | THC g/bhp.hr | $CH_4$ g/bhp.hr | NMHC g/bhp.hr | CO g/bhp.hr | $NO_x$ g/bhp.hr | $NH_3$ mg/bhp.hr | $CO_2$ g/bhp.hr | GGE/bhp.hr | $ft^3$/bhp.hr | PN #/bhp.hr |
| | H1 | 0.113 | 0.349 | 0.147 | 0.715 | 0.009 | 0.187 | 0.422 | 0.878 | 0.950 | 0.967 |
| | LM3 | 0.664 | 0.281 | 0.055 | 0.070 | 0.008 | 0.001 | 0.034 | 0.227 | 0.017 | 0.245 |
| | LM5 | 0.735 | 0.141 | 0.132 | 0.111 | 0.061 | 0.000 | 0.009 | 0.862 | 0.000 | 0.238 |
| | LM6 | 0.936 | 0.379 | 0.219 | 0.083 | 0.254 | 0.001 | 0.085 | 0.676 | 0.001 | 0.849 |

Yellow highlight: Statistically significant (p-value ≤ 0.05) or Marginally statistically significant (0.05<p-value≤0.1) bhp-hr = brake horsepower-hour basis from engine control module (ECM); Note that the units in the header represent the units for the average values that are being compared. The p-values themselves are unitless.

| | PM g/cycle | Formaldehyde (mg/cycle) | Acetaldehyde (mg/cycle) | $N_2O$ g/cycle |
|---|---|---|---|---|
| | **Average** | | | |
| H1 | 0.0108 | 19.34 | 2.20 | 0.503 |
| LM3 | 0.0106 | 25.69 | 3.19 | 1.182 |
| LM5 | 0.0094 | 8.76 | -2.78 | 1.271 |
| LM6 | 0.0063 | 11.63 | -3.41 | 1.044 |
| H7 | 0.0162 | 31.03 | 9.10 | 0.394 |
| **Vs. H1** | **Percentage difference** | | | |
| LM3 | -1.96% | 32.8% | 44.8% | 134.70% |
| LM5 | -12.64% | -54.7% | -226.2% | 152.52% |
| LM6 | -41.86% | -39.9% | -254.9% | 107.27% |
| H7 | 49.90% | 60.4% | 313.2% | -21.71% |
| **Vs. H1** | **P-value** | | | |
| LM3 | 0.969 | 0.351 | 0.600 | 0.000 |
| LM5 | 0.581 | 0.022 | 0.039 | 0.000 |
| LM6 | 0.262 | 0.213 | 0.027 | 0.010 |
| H7 | 0.473 | 0.262 | 0.081 | 0.304 |
| **Vs. H7** | **Percentage difference** | | | |
| H1 | -33.29% | -37.7% | -75.8% | 27.74% |
| LM3 | -34.60% | -17.2% | -64.9% | 199.79% |
| LM5 | -41.72% | -71.8% | -130.5% | 222.56% |
| LM6 | -61.22% | -62.5% | -137.5% | 164.76% |
| **Vs. H7** | **P-value** | | | |
| H1 | 0.473 | 0.262 | 0.081 | 0.304 |
| LM3 | 0.533 | 0.695 | 0.211 | 0.000 |
| LM5 | 0.377 | 0.113 | 0.020 | 0.000 |
| LM6 | 0.237 | 0.186 | 0.017 | 0.003 |

Yellow highlight: Statistically significant ($p\text{-value} \leq 0.05$) or marginally statistically significant ($0.05 < p\text{-value} \leq 0.1$); Note that the units in the header represent the units for the average values that are being compared. The p-values themselves are unitless.

## b) Individual Test results

### *2011 Cummins Westport 8.9L C-Gas Plus Waste Hauler*

| Test Name*** | Test Segment | Fuel | THC | CH4 | NMHC | CO | NOx | NH3 | CO2 | PM | N2O | Fuel E/C | Volumetric E/C | Formaldehyde mg/cycle | Acetaldehyde mg/cycle | Particle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 201406061221 | Transport | H1 | 2.411 | 2.385 | 0.033 | 16.634 | 0.815 | 789.149 | 1317.897 | 0.0135 | 0.162 | 4.883 | 0.039 | 20.708 | 5.385 | ** |
| 201406061221 | Curbside | H1 | 6.510 | 7.080 | -0.509 | 38.780 | 9.035 | 521.297 | 4721.656 | | | 1.374 | 0.011 | | | ** |
| 201406061221 | Compaction | H1 | 0.381 | 0.350 | 0.031 | 3.709 | 0.003 | 299.363 | 504.191 | | | 0.077 | 9.620 | | | ** |
| 201406061310 | Transport | H1 | 3.010 | 3.002 | 0.020 | 18.855 | 0.878 | 812.902 | 1325.157 | 0.0109 | 0.466 | 4.838 | 0.039 | 22.360 | 4.054 | 5.27E+12 |
| 201406061310 | Curbside | H1 | 7.623 | 8.501 | -0.792 | 30.104 | 10.704 | 546.591 | 4937.151 | | | 1.318 | 0.011 | | | 2.49E+13 |
| 201406061310 | Compaction | H1 | 0.344 | 0.328 | 0.016 | 5.035 | 0.005 | 313.261 | 483.810 | | | 0.075 | 9.274 | | | 3.48E+11 |
| 201406061404 | Transport | H1 | 1.480 | 1.553 | -0.062 | 16.090 | 0.807 | 797.925 | 1432.373 | 0.0037 | 0.498 | 4.512 | 0.036 | 20.897 | -0.917 | 7.90E+12 |
| 201406061404 | Curbside | H1 | 4.071 | 5.250 | -1.090 | 17.584 | 8.209 | 450.913 | 4269.732 | | | 1.531 | 0.012 | | | 1.73E+13 |
| 201406061404 | Compaction | H1 | 0.310 | 0.330 | -0.017 | 3.602 | -0.002 | 318.009 | 528.967 | | | 0.081 | 10.080 | | | 1.77E+11 |
| 201406090743 | Transport | H1 | 3.231 | 3.228 | 0.015 | 21.957 | 0.846 | 855.840 | 1284.456 | * | 0.597 | 4.966 | 0.040 | ** | ** | 6.07E+12 |
| 201406090743 | Curbside | H1 | 8.168 | 9.292 | -1.022 | 25.199 | 7.097 | 549.451 | 4856.243 | | | 1.341 | 0.011 | | | 3.80E+13 |
| 201406090743 | Compaction | H1 | 0.281 | 0.280 | 0.002 | 2.994 | -0.001 | 288.711 | 491.756 | | | 0.075 | 9.360 | | | 3.56E+12 |
| 201406090835 | Transport | H1 | 3.061 | 3.015 | 0.055 | 22.276 | 0.720 | 823.326 | 1334.066 | 0.0142 | 0.662 | 4.787 | 0.039 | 13.406 | 0.292 | 5.09E+12 |
| 201406090835 | Curbside | H1 | 11.491 | 11.981 | -0.414 | 55.021 | 7.003 | 728.928 | 5222.982 | | | 1.235 | 0.010 | | | 2.38E+13 |
| 201406090835 | Compaction | H1 | 0.243 | 0.252 | -0.008 | 2.447 | 0.002 | 285.827 | 504.266 | | | 0.077 | 9.577 | | | 1.63E+12 |
| 201406090925 | Transport | H1 | 3.697 | 3.624 | 0.083 | 29.611 | 0.943 | 705.928 | 1348.971 | 0.0110 | ** | 4.691 | 0.038 | ** | ** | 5.00E+12 |
| 201406090925 | Curbside | H1 | 7.568 | 8.260 | -0.620 | 32.921 | 7.108 | 517.986 | 5156.371 | | | 1.261 | 0.010 | | | 2.38E+13 |
| 201406090925 | Compaction | H1 | 0.277 | 0.281 | -0.003 | 3.054 | 0.001 | 282.490 | 498.455 | | | 0.076 | 9.487 | | | 3.97E+12 |
| 201406091029 | Transport | H1 | 4.741 | 3.776 | 0.924 | 22.500 | 0.811 | 602.650 | 1350.167 | 0.0114 | 0.635 | 4.715 | 0.038 | ** | ** | 5.61E+12 |
| 201406091029 | Curbside | H1 | 16.586 | 13.023 | 3.407 | 50.808 | 8.980 | 910.803 | 5645.704 | | | 1.143 | 0.009 | | | 2.95E+13 |
| 201406091029 | Compaction | H1 | 0.362 | 0.254 | 0.102 | 2.990 | -0.006 | 282.862 | 493.578 | | | 0.076 | 9.398 | | | 6.74E+11 |
| 201406091201 | Transport | LM3 | 3.549 | 2.761 | 0.788 | 28.401 | 0.626 | 999.655 | 1289.125 | 0.0053 | 0.986 | 4.934 | 0.042 | 38.948 | 8.079 | 6.66E+12 |
| 201406091201 | Curbside | LM3 | 8.401 | 6.542 | 1.860 | 42.564 | 5.919 | 811.606 | 4729.382 | | | 1.376 | 0.012 | | | 2.20E+13 |
| 201406091201 | Compaction | LM3 | 0.359 | 0.269 | 0.090 | 4.667 | -0.008 | 412.685 | 507.441 | | | 0.078 | 9.089 | | | 5.66E+11 |
| 201406091254 | Transport | LM3 | 3.634 | 2.934 | 0.706 | 33.010 | 0.797 | 832.835 | 1304.236 | -0.0007 | 1.110 | 4.853 | 0.042 | 16.312 | 1.017 | 5.87E+12 |
| 201406091254 | Curbside | LM3 | 7.357 | 6.030 | 1.344 | 51.709 | 6.394 | 939.087 | 5023.163 | | | 1.294 | 0.011 | | | 2.73E+13 |

| Test Name*** | Test Segment | Fuel | THC | CH4 | NMHC | CO | NOx | NH3 | CO2 | PM | N2O | Fuel E/C | Volumetric E/C | Formaldehyde mg/cycle | Acetaldehyde mg/cycle | Particle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 201406091254 | Compaction | LM3 | 0.460 | 0.341 | 0.118 | 5.131 | -0.002 | 381.245 | 528.352 | | | 0.081 | 9.475 | | | 7.21E+11 |
| 201406091344 | Transport | LM3 | 4.495 | 3.500 | 0.995 | 38.795 | 0.879 | 918.607 | 1385.576 | 0.0245 | 1.218 | 4.544 | 0.039 | 21.817 | 0.477 | 6.45E+12 |
| 201406091344 | Curbside | LM3 | 7.315 | 5.945 | 1.384 | 46.040 | 6.923 | 925.340 | 5263.159 | | | 1.238 | 0.011 | | | 2.41E+13 |
| 201406091344 | Compaction | LM3 | 0.420 | 0.279 | 0.138 | 3.439 | 0.003 | 366.146 | 532.622 | | | 0.081 | 9.502 | | | 4.97E+11 |
| 201406100736 | Transport | LM3 | 2.600 | 2.228 | 0.383 | 38.044 | 0.606 | 940.780 | 1430.841 | 0.0011 | 1.163 | 4.426 | 0.038 | ** | ** | * |
| 201406100736 | Curbside | LM3 | 1.477 | 2.050 | -0.524 | 31.050 | 4.613 | 1203.747 | 5326.957 | | | 1.232 | 0.011 | | | 3.81E+13 |
| 201406100736 | Compaction | LM3 | 0.335 | 0.271 | 0.064 | 4.312 | 0.002 | 407.238 | 496.505 | | | 0.076 | 8.885 | | | 1.77E+12 |
| 201406100830 | Transport | LM3 | 3.606 | 2.972 | 0.643 | 35.403 | 0.604 | 980.818 | 1268.120 | 0.0056 | 1.321 | 4.971 | 0.043 | ** | ** | 5.26E+12 |
| 201406100830 | Curbside | LM3 | 9.269 | 8.054 | 1.261 | 71.521 | 6.989 | 763.681 | 5189.863 | | | 1.244 | 0.011 | | | 3.05E+13 |
| 201406100830 | Compaction | LM3 | 0.315 | 0.259 | 0.057 | 3.344 | 0.002 | 401.839 | 506.907 | | | 0.077 | 9.041 | | | 3.48E+11 |
| 201406100924 | Transport | LM3 | 3.653 | 3.009 | 0.652 | 34.089 | 0.827 | 906.382 | 1314.396 | 0.0277 | 1.291 | 4.811 | 0.041 | ** | ** | 5.41E+12 |
| 201406100924 | Curbside | LM3 | 8.242 | 7.219 | 1.067 | 55.111 | 6.865 | 945.773 | 5145.011 | | | 1.262 | 0.011 | | | 2.94E+13 |
| 201406100924 | Compaction | LM3 | 0.412 | 0.340 | 0.073 | 4.506 | 0.000 | 408.566 | 503.507 | | | 0.077 | 9.018 | | | 5.80E+11 |
| 201406101018 | Transport | LM5 | 4.016 | 3.212 | 0.828 | 41.066 | 0.724 | 989.795 | 1327.328 | 0.0077 | 1.554 | 4.782 | 0.042 | 3.708 | -2.459 | 5.75E+12 |
| 201406101018 | Curbside | LM5 | 9.110 | 7.867 | 1.332 | 37.373 | 6.988 | 916.800 | 5397.477 | | | 1.224 | 0.011 | | | 2.67E+13 |
| 201406101018 | Compaction | LM5 | 0.404 | 0.340 | 0.068 | 6.247 | 0.005 | 452.877 | 508.340 | | | 0.077 | 8.767 | | | 4.37E+11 |
| 201406101208 | Transport | LM5 | 3.115 | 2.498 | 0.636 | 26.568 | 0.574 | 1079.188 | 1309.202 | 0.0179 | 1.155 | 4.935 | 0.044 | 12.611 | -3.321 | 7.26E+12 |
| 201406101208 | Curbside | LM5 | 8.904 | 7.355 | 1.617 | 71.932 | 8.204 | 932.191 | 5029.816 | | | 1.298 | 0.011 | | | 3.30E+13 |
| 201406101208 | Compaction | LM5 | 0.402 | 0.310 | 0.094 | 4.415 | 0.004 | 426.672 | 506.090 | | | 0.077 | 8.681 | | | 1.19E+12 |
| 201406101301 | Transport | LM5 | 3.743 | 2.904 | 0.856 | 36.351 | 0.681 | 914.389 | 1301.103 | 0.0086 | 1.325 | 4.902 | 0.043 | 9.951 | -2.561 | 5.92E+12 |
| 201406101301 | Curbside | LM5 | 8.550 | 6.726 | 1.869 | 64.084 | 9.828 | 707.397 | 5213.676 | | | 1.257 | 0.011 | | | 2.48E+13 |
| 201406101301 | Compaction | LM5 | 0.430 | 0.309 | 0.122 | 3.727 | 0.004 | 374.032 | 520.849 | | | 0.079 | 8.913 | | | 4.37E+11 |
| 201406110807 | Transport | LM5 | 2.428 | 1.971 | 0.473 | 23.489 | 0.684 | 946.840 | 1309.931 | 0.0075 | 0.735 | 4.957 | 0.044 | ** | ** | 6.42E+12 |
| 201406110807 | Curbside | LM5 | 5.551 | 4.673 | 0.925 | 49.374 | 6.107 | 964.912 | 4909.612 | | | 1.341 | 0.012 | | | 1.73E+13 |
| 201406110807 | Compaction | LM5 | 0.307 | 0.247 | 0.061 | 3.658 | 0.006 | 397.625 | 506.314 | | | 0.076 | 8.660 | | | 1.32E+12 |
| 201406110943 | Transport | LM5 | 3.636 | 2.891 | 0.766 | 36.063 | 0.586 | 1037.432 | 1271.312 | 0.0047 | 1.386 | 5.014 | 0.044 | ** | ** | 6.35E+12 |
| 201406110943 | Curbside | LM5 | 10.729 | 8.615 | 2.181 | 70.310 | 5.671 | 990.996 | 4909.519 | | | 1.329 | 0.012 | | | 2.11E+13 |
| 201406110943 | Compaction | LM5 | 0.288 | 0.234 | 0.056 | 3.876 | 0.001 | 429.115 | 510.826 | | | 0.077 | 8.741 | | | 5.81E+11 |
| 201406111038 | Transport | LM5 | 4.067 | 3.134 | 0.950 | 39.290 | 0.696 | 1064.480 | 1335.975 | 0.0101 | 1.472 | 4.762 | 0.042 | ** | ** | 6.16E+12 |

| Test Name*** | Test Segment | Fuel | THC | CH4 | NMHC | CO | NOx | NH3 | CO2 | PM | N2O | Fuel E/C | Volumetric E/C | Formaldehyde mg/cycle | Acetaldehyde mg/cycle | Particle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 201406111038 | Curbside | LM5 | 11.317 | 9.197 | 2.196 | 56.835 | 7.434 | 953.492 | 5269.797 | | | 1.245 | 0.011 | | | 2.19E+13 |
| 201406111038 | Compaction | LM5 | 0.301 | 0.240 | 0.063 | 3.960 | 0.001 | 398.205 | 507.590 | | | 0.077 | 8.689 | | | 6.02E+11 |
| 201406111251 | Transport | LM6 | 3.282 | 2.697 | 0.604 | 31.448 | 0.841 | 993.964 | 1321.556 | 0.0146 | 1.049 | 4.865 | 0.043 | 11.186 | -3.606 | 7.75E+12 |
| 201406111251 | Curbside | LM6 | 7.862 | 6.629 | 1.289 | 36.507 | 5.369 | 1115.150 | 5026.235 | | | 1.315 | 0.012 | | | 3.11E+13 |
| 201406111251 | Compaction | LM6 | 0.351 | 0.295 | 0.059 | 4.400 | 0.008 | 415.671 | 512.431 | | | 0.077 | 8.774 | | | 4.50E+12 |
| 201406111348 | Transport | LM6 | 2.393 | 1.987 | 0.421 | 25.467 | 0.745 | 923.056 | 1332.491 | 0.0014 | 0.715 | 4.869 | 0.043 | 1.800 | -4.006 | 6.91E+12 |
| 201406111348 | Curbside | LM6 | 4.425 | 3.963 | 0.510 | 39.249 | 7.793 | 871.877 | 4972.875 | | | 1.330 | 0.012 | | | 2.64E+13 |
| 201406111348 | Compaction | LM6 | 0.427 | 0.339 | 0.089 | 4.554 | 0.007 | 430.521 | 531.931 | | | 0.080 | 9.110 | | | 4.07E+11 |
| 201406111445 | Transport | LM6 | 3.330 | 2.766 | 0.584 | 22.797 | 1.128 | 1085.516 | 1335.847 | 0.0057 | 0.482 | 4.862 | 0.043 | 21.899 | -2.625 | 6.15E+12 |
| 201406111445 | Curbside | LM6 | 8.497 | 6.943 | 1.599 | 42.701 | 7.722 | 1076.758 | 5195.382 | | | 1.270 | 0.011 | | | 5.23E+13 |
| 201406111445 | Compaction | LM6 | 0.385 | 0.319 | 0.068 | 3.294 | 0.008 | 365.239 | 547.429 | | | 0.082 | 9.336 | | | 1.73E+12 |
| 201406120745 | Transport | LM6 | 3.215 | 2.660 | 0.575 | 33.198 | 0.587 | 939.678 | 1267.028 | -0.0052 | 1.388 | 5.055 | 0.045 | ** | ** | 7.53E+12 |
| 201406120745 | Curbside | LM6 | 10.652 | 9.256 | 1.491 | 85.373 | 6.594 | 882.833 | 5231.925 | | | 1.244 | 0.011 | | | 2.24E+13 |
| 201406120745 | Compaction | LM6 | 0.311 | 0.260 | 0.053 | 3.880 | 0.006 | 400.442 | 499.049 | | | 0.075 | 8.533 | | | 1.04E+12 |
| 201406120840 | Transport | LM6 | 3.116 | 2.588 | 0.547 | 30.366 | 0.627 | 977.952 | 1269.059 | 0.0177 | 1.336 | 5.066 | 0.045 | ** | ** | 6.35E+12 |
| 201406120840 | Curbside | LM6 | 10.296 | 8.775 | 1.600 | 83.981 | 7.101 | 755.071 | 5441.114 | | | 1.199 | 0.011 | | | 2.22E+13 |
| 201406120840 | Compaction | LM6 | 0.315 | 0.257 | 0.059 | 3.763 | 0.001 | 373.791 | 485.913 | | | 0.073 | 8.308 | | | 9.04E+11 |
| 201406120934 | Transport | LM6 | 2.972 | 2.508 | 0.486 | 33.172 | 0.562 | 956.616 | 1317.475 | 0.0035 | 1.291 | 4.873 | 0.043 | ** | ** | 6.34E+12 |
| 201406120934 | Curbside | LM6 | 8.264 | 7.416 | 0.938 | 72.073 | 6.538 | 826.319 | 5272.847 | | | 1.241 | 0.011 | | | 1.96E+13 |
| 201406120934 | Compaction | LM6 | 0.404 | 0.320 | 0.085 | 5.318 | 0.004 | 406.321 | 507.333 | | | 0.077 | 8.715 | | | 7.00E+11 |
| 201406060854 | Transport | H7 | 3.824 | 3.700 | 0.125 | 22.560 | 0.904 | 783.127 | 1335.373 | 0.0280 | 0.549 | 4.712 | 0.038 | 33.913 | 8.745 | ** |
| 201406060854 | Curbside | H7 | 7.954 | 8.395 | -0.399 | 16.844 | 11.428 | 377.732 | 4994.844 | | | 1.291 | 0.010 | | | ** |
| 201406060854 | Compaction | H7 | 0.316 | 0.280 | 0.034 | 3.209 | 0.006 | 275.436 | 491.900 | | | 0.076 | 9.481 | | | ** |
| 201406060948 | Transport | H7 | 2.809 | 2.789 | 0.026 | 21.235 | 0.990 | 683.216 | 1334.526 | 0.0056 | 0.579 | 4.732 | 0.038 | 47.893 | 14.706 | ** |
| 201406060948 | Curbside | H7 | 6.543 | 7.128 | -0.539 | 22.452 | 9.247 | 432.624 | 4827.005 | | | 1.334 | 0.011 | | | ** |
| 201406060948 | Compaction | H7 | 0.289 | 0.282 | 0.007 | 3.230 | 0.003 | 294.775 | 495.200 | | | 0.077 | 9.543 | | | ** |
| 201406061039 | Transport | H7 | 2.674 | 2.660 | 0.019 | 16.244 | 0.916 | 739.637 | 1337.453 | 0.0460 | 0.478 | 4.750 | 0.038 | 11.271 | 3.861 | ** |
| 201406061039 | Curbside | H7 | 13.099 | 14.192 | -1.004 | 32.592 | 9.657 | 450.648 | 4786.349 | | | 1.336 | 0.011 | | | ** |
| 201406061039 | Compaction | H7 | 0.356 | 0.325 | 0.030 | 3.683 | 0.008 | 294.192 | 496.921 | | | 0.077 | 9.593 | | | ** |

| Test Name*** | Test Segment | Fuel | THC | CH4 | NMHC | CO | NOx | NH3 | CO2 | PM | N2O | Fuel E/C | Volumetric E/C | Formaldehyde mg/cycle | Acetaldehyde mg/cycle | Particle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 201406121142 | Transport | H7 | 1.843 | 1.591 | 0.242 | 14.824 | 0.970 | 886.083 | 1258.835 | 0.0014 | 0.324 | 5.057 | 0.041 | ** | ** | 5.57E+12 |
| 201406121142 | Curbside | H7 | 9.092 | 8.084 | 0.971 | 24.252 | 10.543 | 519.788 | 4916.639 | | | 1.307 | 0.011 | | | 1.86E+13 |
| 201406121142 | Compaction | H7 | 0.369 | 0.311 | 0.055 | 3.179 | 0.004 | 324.667 | 477.201 | | | 0.074 | 9.203 | | | 4.07E+12 |
| 201406121235 | Transport | H7 | 2.479 | 2.088 | 0.374 | 9.749 | 0.930 | 752.268 | 1299.543 | 0.0071 | 0.177 | 4.925 | 0.040 | ** | ** | 5.03E+12 |
| 201406121235 | Curbside | H7 | 5.987 | 5.356 | 0.608 | 13.293 | 10.869 | 461.129 | 5097.265 | | | 1.268 | 0.010 | | | 3.42E+13 |
| 201406121235 | Compaction | H7 | 0.455 | 0.365 | 0.086 | 4.292 | 0.017 | 336.710 | 504.042 | | | 0.079 | 9.752 | | | 4.51E+11 |
| 201406121329 | Transport | H7 | 3.002 | 2.457 | 0.521 | 14.993 | 1.033 | 775.772 | 1329.913 | 0.0090 | 0.257 | 4.780 | 0.039 | ** | ** | 4.37E+12 |
| 201406121329 | Curbside | H7 | 6.935 | 6.021 | 0.877 | 17.121 | 10.176 | 668.032 | 5341.675 | | | 1.208 | 0.010 | | | 3.27E+13 |
| 201406121329 | Compaction | H7 | 0.425 | 0.334 | 0.087 | 3.687 | 0.014 | 369.318 | 504.068 | | | 0.079 | 9.733 | | | 8.19E+11 |

*Outlier tests that were eliminated from the averages,
** No data collected
*** Note the test name is indicative of the data and time of the test, with the test number including the year-month-day-time of the test. For example, 201406091221 identifies the test as being run in 2014, in the month of June (06), on the 9th day of June (09), and at 12:21 PM.

## 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*

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

$FC_{NG}$= 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** | 98.42 | 1.26 | 0.05 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.747 | 0.747 | 0.801 | 19.195 | 905.0 |

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

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

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

**References**

1. Environmental Protection Agency, National Vehicle and Fuel Emissions Laboratory (NVFEL) Emissions Analysis, http://www.epa.gov/nvfel/testing/methods.htm

2. American Gas Association Report No.5, "Natural Gas Energy Measurement", AGA 5 Calculation Spreadsheet – Imperial Units of Measure, version 1.1, Feb 26, 2008

3. US Dept. of Energy, Argonne National Laboratory, GREET 1 2013, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, http://greet.es.anl.gov/, 2013

4. Code of Federal Regulations, Part 600, Subpart B- Fuel Economy and Carbon-Related Exhaust Emission Test Procedures, 2012.