

Influence of Different Natural Gas Blends on the Regulated Emissions, Particle Number and Size Distribution Emissions from a Refuse Hauler Truck

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ABSTRACT

Natural gas is a potential alternative to conventional liquid fuels for use in automotive internal combustion engines. The primary goal of this study is to understand how gas composition changes might impact the performance or emissions of a natural gas vehicle or engine. For this study, a waste hauler truck equipped with a 2001 Cummins 8.3L C Gas Plus lean burn spark ignited engine and an oxidation catalyst was operated on the William H. Martin Refuse Truck Cycle (RTC). This cycle was developed to simulate waste hauler operation and consists of a transport segment, a curbside pickup segment, and a compaction segment. The vehicle was tested on 7 different gases included two gases representative of Texas and Rocky Mountain Pipeline Gases, a Peruvian LNG, a Middle East LNG-Untreated with high Wobbe number (above 1400), two gases representative of those located within the state that have low methane number (MN) as well as varying hydrocarbon compositions, and a CNG blend produced from an LNG fuel tank with similar properties to the first two gases. The experimental results indicate the fuel composition had a noticeable effect on fuel economy and carbon dioxide (CO₂) emissions of the waste hauler, with the high energy content and higher hydrocarbons gases exhibiting higher fuel economy and CO₂ emissions. Emissions of nitrogen oxides (NO_x) were also influenced by fuel composition, and increased for gases with higher levels of heavier hydrocarbons. Total hydrocarbon (THC), nonmethane hydrocarbon (NMHC), and methane (CH₄) emissions were affected by the concentration of higher hydrocarbon molecules in the gases, with gases with higher levels of CH₄ showing high THC and CH₄ emissions and lower NMHC emissions. Decreases in particulate matter mass, particle number, and, in some cases, CO emissions were also found for the gases with more heavy hydrocarbons, while fuel quality had a minimal impact on particle size distributions.

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INTRODUCTION

In an effort to improve air quality, the US Environmental Protection Agency and the California Air Resources Board (CARB) have enacted increasingly more stringent emissions standards for light-duty and heavy-duty vehicles [1]. In order to achieve those goals, alternative fuels are being used and developed to replace traditional fuels. Because of its lower emissions potential compared to petroleum diesel fuel and availability, natural gas is one of the alternative fuels to petroleum diesel being considered for low emissions heavy-duty applications [2-3]. Natural gas is predominantly methane (CH₄) with smaller percentages of other gas including heavier hydrocarbons such as ethane (C₂H₆), propane (C₃H₈), and butane (C₄H₁₀), and inert diluents such as molecular nitrogen

(N₂) and carbon dioxide (CO₂). There are also trace levels of sulfur compounds and other hydrocarbon species. The levels of these species vary substantially with geographical source, time of year, and treatments applied during production or transportation [4-5]. As a result, natural gas does not describe a single type of fuel or a narrow range of characteristics, unlike gasoline or diesel fuel, which is manufactured within certain specifications.

While general supply and handling of natural gas is widespread, the refueling infrastructure for natural gas vehicles is still limited compared to petroleum fuels [5]. Therefore, it is difficult to regard a gaseous fuel as a complete replacement of gasoline and diesel-fueled vehicles for the near term. However, natural gas vehicles use in cities and suburban areas remains attractive. This is because travel

distances are relatively short, and for many fleets refueling is centralized. A number of studies have shown that natural gas vehicles can produce lower levels of carbon monoxide (CO), nitrogen oxide (NO_x) emissions, and non-methane hydrocarbon (NMHC) emissions [6-7], although in some studies increases in NO_x emissions and CO emissions with natural gas vehicles have been observed [1]. Natural gas vehicles also emit virtually no visible particulate matter (PM) or black soot at the tailpipe, and systematically show less PM emissions than diesel and gasoline vehicles [8-9]. However, there is still a concern about the particle number emissions and the size of these particles. Several studies have indicated that heavy-duty natural gas vehicles produced higher number of nanoparticles (particles smaller than 50 nm in diameter) compared to their diesel-powered counterparts [10-11]. A large body of epidemiological studies has shown that nanoparticles are especially important, as they can penetrate deep into the human lung and the respiratory tract and are more toxic than larger particles [12-13].

In California, the use of natural gas has been increasing for a number of years, due predominantly to expanded power and home heating needs. As the demand for natural gas continues to grow, natural gas from a wider range of sources will be needed to meet the demand. It is also anticipated that the use of liquefied natural gas (LNG) globally and within California will increase over time, as greater emphasis is placed on low carbon fuels and as energy use continues to increase globally [14]. As new producing fields are developed in the western US, the composition of domestic NG supplies could also change in the future. These new sources of natural gas will likely differ in composition, leading to potential differences in the performance and exhaust emissions of natural gas powered vehicles. From a regulatory standpoint, it is especially important to ensure that new fuels with varying composition will not negatively impact the reductions already being achieved under existing regulations.

The goal of this study is to investigate the effect of different natural gas compositions on the criteria emissions, particle number and size distributions of a waste hauler. There has been fairly limited work on emissions from heavy-duty vehicles used for public waste collection, although the activity of these vehicles can be a significant contributor to urban air quality and create exposure risks for sanitation workers. Refuse trucks have unique operating characteristics because they have to start and stop frequently in between disposal bins. This results in numerous accelerations, decelerations, and idling for short intervals. The refuse trucks also travel to and from the service area and the dump site, which is more characteristic of typical driving patterns. For this study, a natural gas waste hauler was tested over the Refuse Truck Cycle on a range of 7 different test gases. The test gases included gases representative of those typically found in the marketplace and other gases with higher Wobbe

numbers that might provide insight into the impact of a wider range of compositions from different sources.

EXPERIMENTAL

Test Fuels and Vehicle

Seven different gases were tested in this study. Gases 1 and 2 were representative of Texas and Rocky Mountain Pipeline Gases and served as the baseline fuels. The third fuel was a Peruvian LNG, while the fourth fuel was an Untreated Middle East LNG with a high Wobbe number (above 1400). Gases 5 and 6 were representative of associated gases located within the state of California that have low methane numbers (MN) as well as hydrocarbon compositions that vary in terms of high ethane, low propane and butane for GNG5 or low ethane, high propane and butane for CNG6. Gases 5 and 6 are also designed to have Wobbe Numbers of 1385, which is the pipeline limit in California. Gas 7 was a CNG blend produced from a LNG fuel tank that had similar properties with gases 1 and 2, but does not have inerts. Selected properties of the test gases are presented in [Table 1](#).

For this study, a waste hauler with a 2001 Cummins 8.3L C Gas Plus lean burn spark ignited engine was used. This vehicle was fitted with an oxidation catalyst. The C Gas Plus engine was produced from 2001 to 2008 in the United States, and it represents one of the most common natural gas engine platforms currently used in refuse haulers in California. The main technical specifications of the C Gas Plus engine are given in [Table 2](#).

Test Cycle and Measurement Protocol

The waste hauler was tested on each fuel on the William H. Martin (WHM) refuse truck driving cycle. The test matrix was randomized to allow some measure of the experimental reproducibility. The test matrix for the heavy-duty chassis dynamometer testing is provided in [Table 3](#).

The William H. Martin Refuse Truck Cycle (RTC) was developed by West Virginia University to simulate waste hauler operation. The Refuse Truck Cycle is shown in [Figure 1](#). The cycle consists of a transport segment, a curbside pickup segment, and a compaction segment. The transport portion of the cycle includes a segment designed to represent a trip out to the service area (from 293 to 593 seconds) and a segment designed to represent the return trip from the service area (from 1128 to 1428 seconds). The curbside pickup portion of the cycle is the middle portion of the cycle with a series of small, low speed accelerations. The compaction portion of the cycle is the final 155 seconds. The compaction load is simulated by applying a load of approximately 80 horsepower (hp) to the drive axle while maintaining a fixed speed of 30 mph. The initial 293 second segment of the cycle is a warm-up period where no emissions are collected.

The vehicle was preconditioned at the start of each test day by performing a power map. Between tests, there was a 'hot soak', where the engine was turned off for about 10-15 minutes. All tests were conducted as 'hot running' tests, with

Table 1. Main properties of the test fuels.

Gas #	Description	Methane	Ethane	Propane	I-butane	N ₂	CO ₂	MN	Wobbe #	HHV	H/C ratio
1	Baseline, Texas Pipeline	96	1.8	0.4	0.15	0.7	0.95	99	1339	1021	3.94
2	Baseline, Rocky Mountain Pipeline	94.5	3.5	0.6	0.3	0.35	0.75	95	1361	1046	3.89
3	Peruvian LNG	88.3	10.5	0	0	1.2	0	84	1385	1083	3.81
4	Middle East LNG-Untreated	89.3	6.8	2.6	1.3	0	0	80	1428	1136	3.73
5	Associated High Ethane	83.65	10.75	2.7	0.2	2.7	0	75.3	1385	1115	3.71
6	Associated High Propane	87.2	4.5	4.4	1.2	2.7	0	75.1	1385	1116	3.70
7	L-CNG fuel	98.4	1.2	0.3	0	0	0	103.1	1370	1029	3.96

MN = Methane Number determined via California Air Resources Board (CARB) calculations [15]; 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

Table 2. Technical specifications of the C Gas Plus engine.

Horsepower	187 kW at 2400 rpm
Peak Torque	1017 Nm at 1400 rpm
Governed speed	2400 rpm
Number of Cylinders	6
Engine Displacement	8.3 L
Compression Ratio	10:1
Bore and Stroke	114 mm X 135 mm
Fuel Type	CNG/LNG (methane number 65 or greater)

Table 3. Chassis dynamometer test matrix.

Test Day	Morning schedule (assumes 3 replicates)	Afternoon schedule (assumes 3 replicates)
Day 1	111	222
Day 2	222	333
Day 3	333	444
Day 4	444	555
Day 5	555	666
Day 6	666	777
Day 7	777	111

1 = Gas #1, 2 = Gas #2, 3 = Gas #3, 4 = Gas #4, 5 = Gas #5, 6 = Gas #6, 7 = Gas #7

a 293 second warm-up period. The road coefficients for the vehicle were determined by coasting down the vehicle from approximately 60 mph to approximately 10 mph on a local road. The vehicle was weighed on a scale to determine the test weight.

Emissions Testing

All tests were conducted at The University of California at Riverside (UCR) College of Engineering-Center for Environmental Research and Technology's CE-CERT's

Heavy-Duty Chassis Dynamometer facility. The CE-CERT heavy-duty chassis dynamometer is 48" Electric Chassis Dynamometer manufactured by Mustang Dynamometer with Dual Direct Connected, 300 Hp AC Motors individually attached to each roll set (model MD-AC/AC-300.48/300.48-45,000lb-HD-TANDEM) [16]. This dynamometer can continuously absorb/motor loads in excess of 600 HP from 45 to 80 mph and intermittently absorb/motor loads in the range of 1,200Hp. The dynamometer is able perform vehicle inertia simulation across a vehicle weight



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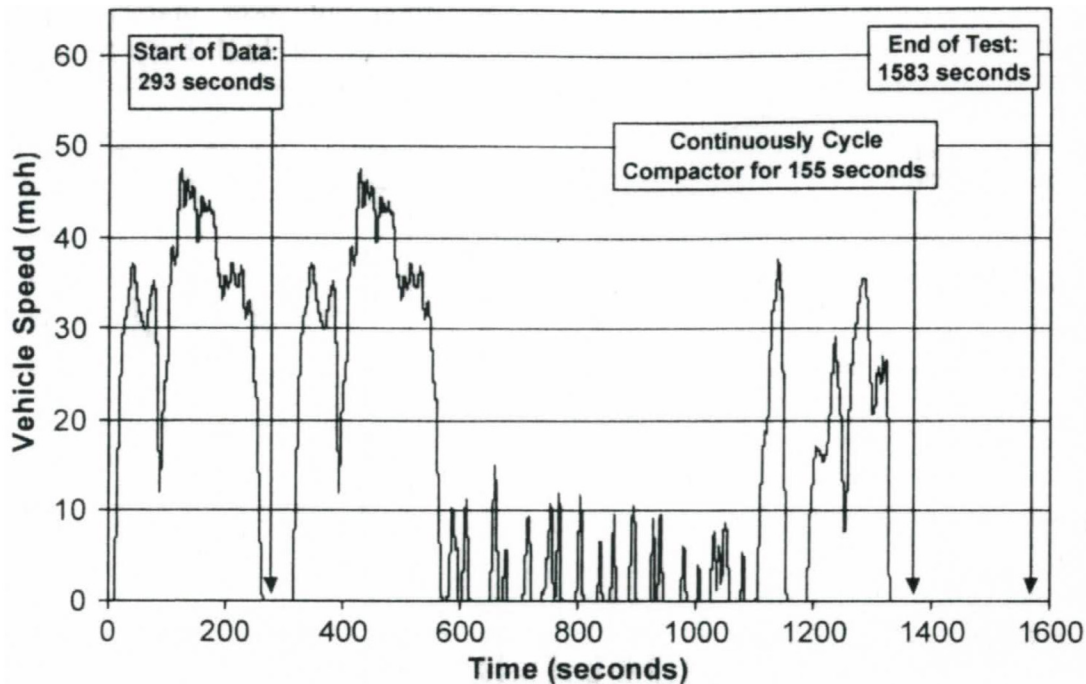


Figure 1. Refuse Truck Cycle speed-time profile.

range of 10,000 to 80,000 lb for a broad range of different drive cycles.

A power map was conducted prior to beginning testing on any new fuel or after refueling. The power map provides information on the differences between the vehicle power on the different blends. The power map consisted of maximum power readings at 4-5 different engine speeds, including a speed close to the intermediate speed where maximum power is seen and a speed close to the rated engine speed. The vehicle was also monitored throughout the course of testing to evaluate the operability of the engine on different blends, including characteristics such as knock.

Emissions measurements were obtained using CE-CERT's Mobile Emissions Laboratory (MEL) [17-18]. For all tests, standard emissions measurements of total hydrocarbons (THC), nonmethane hydrocarbons (NMHC), methane (CH₄), carbon monoxide (CO), oxides of nitrogen (NO_x), carbon dioxide (CO₂), and particulate matter (PM), were measured. Particle number counts were measured with the 3776 CPC (TSI) with a 2.5 nm cut point. Additionally, a nano scanning mobility particle sizer (nano-SMPS) was used to obtain information about how the particle size distributions differ between gas blends. The size range of the nano-SMPS was 4 to 70 nm in electrical mobility diameter and the total scan time was 120 seconds (60 seconds for up scan and 60 seconds for down scan).

RESULTS AND DISCUSSION

The figures for each emissions component show the results for each fuel tested on the waste hauler over the RTC

based on the average of all tests conducted on that particular fuel. The error bars represent the standard deviation for the average for each fuel. The figures show the emissions for the different segments of RTC, expressed in g/miles for the transport and curbside segments of the cycle, and in g/bhp-hr for the compaction segment of the cycle. For the purpose of this discussion, results are considered to be statistically significant for $p \geq 0.05$.

Fuel Economy and CO₂ Emissions

Fuel economy on a volumetric basis is probably the most important to the natural gas consumer, since fuel is distributed on a volumetric basis. For the waste hauler, fuel economy, on a gasoline equivalent gallon basis, is shown in Figure 2 (a-c). The effects of fuel composition were the strongest for the compaction phase, followed by the transport phase. The gases of CNG1, CNG2, and CNG7 exhibited lower volumetric fuel economy compared to the other gases, due to the lower energy content of these fuels. Specifically, statistically significant fuel economy increases were found for the CNG3, CNG4, and CNG6 fuels in comparison with CNG1, CNG2, and CNG7 for both the transport and compaction phases. For the curbside phase, the differences in fuel economy between the test fuels were marginal and cannot be considered as statistically significant. Compared to transport mode, the curbside mode is the most critical operation in terms of fuel consumption and CO₂ emissions, as most typical residential refuse trucks spend most of their time and consume most of their fuel in this mode. Note that for CNG5, the THC emissions were available only a single

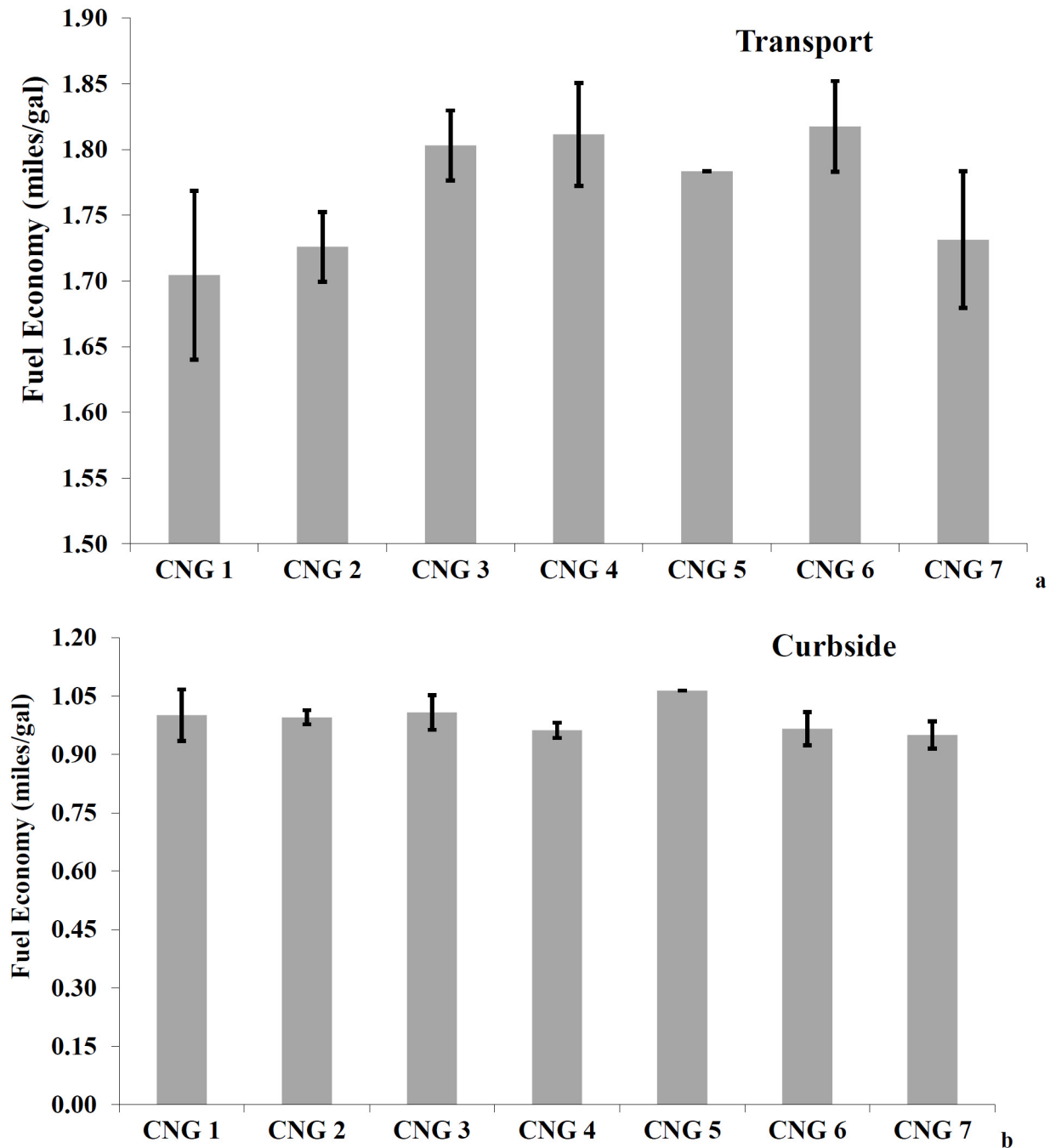


Figure 2 (a-c). Average fuel economy for the waste hauler over the RTC. CNG1: Texas (1339 WI), CNG2: Rocky Mtn (1361 WI), CNG3: Peruvian LNG (1385 WI), CNG4: Middle East LNG (1428 WI), CNG5: Associated Hi Ethane (1385 WI), CNG6: Associated Hi Propane (1385 WI), CNG7: L-CNG (1370 WI)

test. As such, fuel economy was calculated for a single test on CNG5, and no statistical comparisons of fuel economy were made for this fuel.

CO₂ emissions for the waste hauler are shown for the transport, curbside, and compaction phases of the Refuse Truck Cycle, in Figure 3 (a-c). The compaction phase showed the most consistent trends, with CO₂ emissions peaking for fuels CNG4, CNG5, and CNG6. Compared to the baseline

CNG1 and CNG7, all of the fuel gas blends exhibited statistically significant increases in CO₂ emissions. These trends show increases in CO₂ emissions with increases in levels of heavier hydrocarbons and decreases in H/C ratios, as seen in Table 1. This is consistent with a great fraction of the energy for the combustion process coming from C-C bonds for the fuels with lower H/C ratios. For the curbside phase, gases CNG4 and CNG6 showed higher CO₂ emissions, with

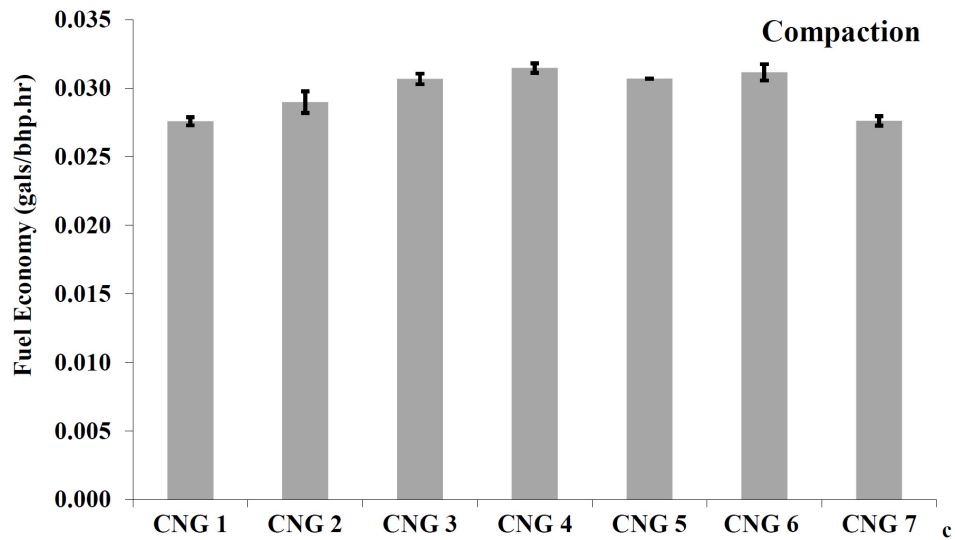


Figure 2 (a-c). (cont.) Average fuel economy for the waste hauler over the RTC. CNG1: Texas (1339 WI), CNG2: Rocky Mtn (1361 WI), CNG3: Peruvian LNG (1385 WI), CNG4: Middle East LNG (1428 WI), CNG5: Associated Hi Ethane (1385 WI), CNG6: Associated Hi Propane (1385 WI), CNG7: L-CNG (1370 WI)

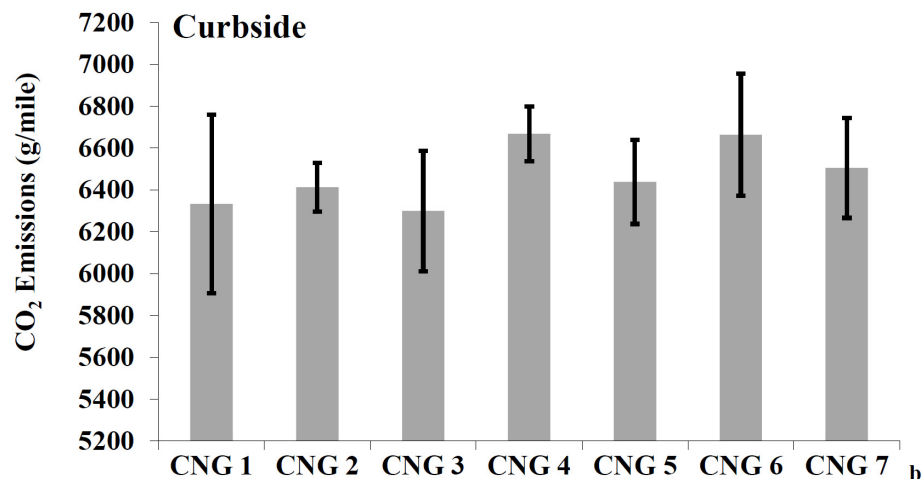
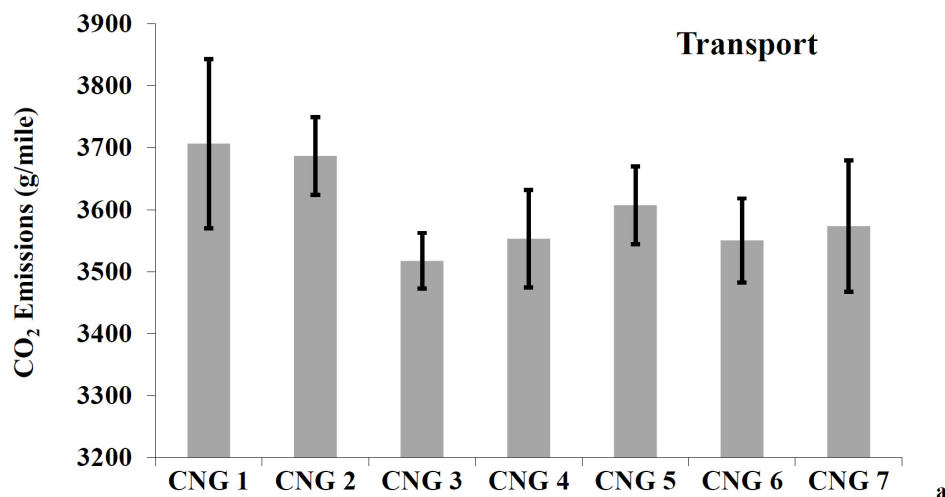


Figure 3 (a-c). Average CO₂ emissions for the waste hauler over the RTC. CNG1: Texas (1339 WI), CNG2: Rocky Mtn (1361 WI), CNG3: Peruvian LNG (1385 WI), CNG4: Middle East LNG (1428 WI), CNG5: Associated Hi Ethane (1385 WI), CNG6: Associated Hi Propane (1385 WI), CNG7: L-CNG (1370 WI)