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Abstract

The emissions of two ultralow NOx heavy-duty (HD) vehicles equipped with 0.02 g/bhp-hr low NOx natural gas (NG) engines were evaluated on a chassis dynamometer. This included a waste hauler and a city transit bus, each with a 0.02 g/bhp-hr NOx L9N near zero (NZ) natural gas engine. The vehicles were tested over a variety of different cycles, including the Urban Dynamometer Driving Schedule (UDDS), port drayage cycles, transit bus cycles, and a refuse truck cycle.

For both vehicles, the NOx emissions results were below the 0.02 g/bhp-hr level for most cycles, with the exception of some cold start tests. For the waste hauler, NOx emissions averaged between 0.014 and 0.002 g/bhp-hr for the hot start tests, and from 0.043 to 0.014 g/bhp-hr for the cold start tests. This represented NOx emissions reductions from 97%-100% of compared with previous ISL G 8.9 engines. For the transit bus, the NOx emissions ranged from 0.0007 g/bhp-hr to 0.0042 g/bhp-hr for the warm tests and up to 0.04 g/bhp-hr for the cold start tests. The NOx results for the warm tests are 99% lower than the existing 2010 NOx diesel standard (0.2 g/bhp-hr) and 90% lower than the optional low NOx standard (0.02 g/bhp-h). In contrast, some elevation of ammonia emissions was observed for both vehicles, due to reactions that occur over the three way catalyst. Overall, the results suggest that ultralow NOx NG engines could play an important role in reducing NOx emissions from heavy-duty vehicles towards near zero levels in urban areas.

The particle mass emissions were low and typically were more than 90% lower than the 2010 certification standard (10 mg/bhp-hr) for the L9N engine for both applications. Particle number (PN) emissions for the L9N (0.02 g/bhp-h) and other previous tests of ISL G 8.9 (0.2 g/bhp-h) engines both show higher PN emissions compared to diesel vehicles equipped with diesel particle filters (DPFs). Fuel economy, greenhouse gas and nitrous oxide (N_2O) emissions are also reported in this paper.

Introduction

Meeting regulations that control pollutant emissions and greenhouse gas (GHG) emissions has been a key topic worldwide for over twenty years. Currently, this issue is as important as ever in many regions of the world due to the steady growth in diesel-powered vehicles. Heavy-duty (HD) on-road vehicles represent one of the largest sources of GHG emissions and nitrogen oxides (NOx) emissions in North America. The latter pollutant is known to be an ozone precursor when it reacts with volatile organic compounds (VOCs) in the presence of sunlight to form photochemical smog [1, 2, 3, 4]. The United States (U.S.) has implemented more stringent and aggressive requirements for lowering NOx emissions from HD vehicles. With the introduction of 2010 0.2 grams NOx per brake horse power hour (g/bhp-hr) certification limit, NOx certification emission levels have dropped 90% for HD engines compared to 2002 levels [5], leading to the widespread introduction of selective catalytic reduction (SCR) systems.

While significant reductions in NOx are being achieved, additional reductions in NOx emissions for California are required to meet federal ambient ozone air quality standards in 2023 and 2031. Thirteen basins in California did not meet National Ambient Air Quality Standards (NAAQS) for ozone in 2013 [6, 7], and two of the nation's most polluted basins, in the greater Los Angeles area and the San Joaquin Valley, are far from making attainment. In the South Coast Air Quality Management District (SCAQMD), which represents the greater Los Angeles area, NOx reductions are considered to be the critical factor in lowering ambient ozone level, with estimates showing a 90% reduction in NOx emissions below 2010 levels is needed to meet 2031 standards. This has spurred interest in imposing more stringent legislation for NOx emissions from engines, and interest in near zero NOx emission combustion strategies [8]. This has led to the development of an optional 0.02 g/bhp-hr NOx emissions standard for California. There is also consideration of implementation the 0.02 g/bhp-hr NOx standard to all new HD engines as part of future regulations [9].

In addition to new and advanced vehicles and powertrains, alternative fuels have been viewed as viable solutions for reducing tailpipe emissions, including NOx emissions. Natural gas (NG) and natural gas-powered engines have been employed in some capacity in HD applications for several decades now. NG or compressed natural gas (CNG), which is primarily composed of methane (CH_4), has unique chemical properties with a high hydrogen to carbon (H/C) ratio and high research octane number (about 130). The low levels of carbon-carbon bonds in natural gas and the absence of aromatics compared to diesel fuel reduces soot formation in natural gas engines. Early natural gas vehicles (NGVs) were equipped with lean-burn engines and diesel oxidation catalysts (DOCs) to effectively control carbon monoxide (CO), total hydrocarbons (THC), and formaldehyde emissions. While lean burn NG engines met the initial market needs, more robust emission control was needed to achieve the 2010 0.2 g/bhp-hr standard. Current HD NGVs, equipped with spark-ignited stoichiometric combustion engines, with water cooled exhaust gas recirculation (EGR) technology, and three-way catalysts (TWCs), provide large reductions in NOx and THC emissions compared to lean burn strategies. Hajbabaei et al. [10] compared emissions of a bus equipped with lean burn combustion engine and a DOC and a bus equipped with a stoichiometric NG engine with a TWC and EGR. They found that the stoichiometric bus engine showed significantly reduced NOx and THC emissions compared to the lean burn engine, but did show higher levels of CO and ammonia (NH_3) emissions.

The focus of this study is the evaluation and characterization of a near zero NOx version of the stoichiometric ISL G natural gas engine, one of the most extensively produced and used HD NG engine platforms, which has undergone additional improvements to reduce NOx emissions down to the 0.02 g/bhp-hr level. This engine is being certified as a L9N near zero (NZ) engine platform and also meets the 2017 US Environmental Protection Agency (EPA) GHG emission requirements with a 9% GHG reduction from the current ISL G 8.9 NG engine. Early demonstrations of this engine technology in a vehicle include a waste hauler and a transit city bus operating in the greater Los Angeles area. This work examined the gaseous and particulate matter (PM) emissions from this engine in both the waste hauler and transit bus applications, with an emphasis on characterizing NOx emissions at and below the 0.02 g/bhp-hr level under a variety of operating conditions.

Experimental

Test Fuel

California pipeline natural gas was used as the test fuel for this study, which is typical of the natural gas available in Southern California. The fuel properties were measured during the emissions testing for the waste hauler and are presented in Table 1. This should be typical of the fuel used for the city bus as well. The gas composition is reported on a mole percent basis. The H/C ratio in the hydrocarbon portion of the gas blend was 3.905. Properties such as higher heating value, octane number, and methane number were evaluated at 60 °F (15.6 °C) and 14.73 psi (101.6 kPa), and calculated based on the fuel composition in Table 2. The higher heating value (HHV) is 1042.5 BTU/ft^3 and the lower heating value (LHV) is 939.9 BTU/ft^3. The fuel had a carbon weight fraction of 0.745 and a specific gravity (SG) of 0.58. Methane number was calculated to be 95.90, based on a California Air Resources Board (CARB) equation [11, 12], while the Wobbe number was 1363. Fuel samples were collected from the vehicle prior to testing.

TABLE 1 Fuel properties for the local NG test fuels utilized.

Property	Molar %	Property	Molar %
Methane	94.65	Pentane	0.01
Ethane	3.87	Carbon dioxide	0.00
Propane	0.41	Oxygen	0.35
Butane	0.08	Nitrogen	0.63

TABLE 2 Test Cycle Characteristics.

Day	Distance (mi)	Average speed (mph)	Duration (s)
Near Dock	5.61	6.6	3046
Local	8.71	9.3	3362
Regional	27.3	23.2	3361
UDDS x2	11.1	18.8	2122
CBD	3.22	20.2	560
AQMD Refuse	4.30	7.31	2997
OCTA	6.54	12.4	1890

Test Vehicles, Cycles, and Test Protocol

Testing was conducted on two stoichiometric spark ignited L9N NZ Cummins Westport Inc. (CWI) natural gas engines. This engine is designed for use in a variety of applications, 1) waste haulers, 2) buses, and 3) goods movement vehicles. For this study, the applications included one engine in a waste hauler application and one in a city transit bus, which are two of the more common uses for the 8.9L engine. Cummins Westport Inc. (CWI) developed this engine as an ultra-low NOx demonstration engine where the NOx emissions were further reduced to 0.02 g/bhp-hr (90% lower than the 2010 NOx emissions standard). The engines both had a displacement of 8.9 L and rated horsepowers of 320 hp at 1800 rpm and 280 hp at 1300 rpm, respectively, for the waste hauler and city transit bus. The engines were equipped with EGR and a TWC. The waste hauler and transit bus had mileages of over 25,000 miles and 8,200 mi, respectively.

The waste hauler and transit city bus were tested over a range of different cycles. A summary of the characteristics of these cycles is provided in Table 2. Both vehicles were tested over the EPA Urban Dynamometer Driving Schedule (UDDS). Of the commonly available chassis dynamometer test cycles, this is the one that is considered to most closely represent the type of operation simulated in the Federal Test Procedure (FTP) engine test cycle used for engine certification. A double UDDS was conducted for the test vehicles to obtain sufficient PM mass for gravimetric analysis. The UDDS was conducted as a cold start and as a hot start test for both vehicles. The waste hauler and transit city bus were also both exercised over the Near Dock duty cycle (DPT1), the Local Haul duty cycle (DPT2), and the Regional Haul duty cycle (DPT3), which are segments of the drayage truck port cycle developed by TIAX LLC in conjunction with the Ports of Long Beach and Los Angeles. These are drayage cycles classified based on whether the cargo is being moved around in the port terminal or distributed to local or regional distribution centers. Although these vehicles are not designed for drayage operations, since a potentially important application of the ultralow NOx engine is in the drayage area, it was thought that it would be useful to understand how the engine would perform under these types of operating conditions. In addition to these cycles, the waste hauler was also tested over the Central Business District (CBD) cycle, and the WHM (William H. Martin) Waste Truck Cycle (RTC), while the transit bus was tested over the Orange County Transit Authority (OCTA) Bus cycle. The RTC was originally developed by West Virginia University to simulate waste hauler operation. The cycle has an average speed of 10.6 miles per hour (mph) and covers a total distance of 6.17 miles. The cycle consists of a transport segment, representing a trip out to the service area, a curbside pickup segment, with a series of small, low speed accelerations, and a compaction segment.

The compaction load is simulated by applying a load of approximately 80 hp (horsepower) to the drive axle while maintaining a fixed speed of 45 miles/hour. This load is typical of the loads applied to the engine during loading and packing operations. The RTC included an initial 293 second segment as a warm-up period where no emissions are collected. The CBD cycle has an average speed of 12.6 mph, a maximum speed of 20 mph, and covers a total distance of 2 miles. The CBD cycle used for this study consisted of a single CBD cycle as a warm-up, followed by three iterations CBD cycle to provide a sufficient PM mass sample for analysis. The CBD cycle was included in the waste hauler tests to provide added information as to how the engine would perform in bus applications. The OCTA cycle has an average speed of 12.4 mph, a maximum speed of 40.6 mph, and covers a total distance of 6.54 miles. The waste hauler and city bus were tested at weights of 56,000 and 34,500 lbs., respectively, comparable to typical values used in previous studies.

Emissions Testing

All tests were conducted at the University of California at Riverside's (UCR) College of Engineering-Center for Environmental Research and Technology's (CE-CERT's) Heavy-Duty Chassis Dynamometer facility. Emissions measurements were obtained using the CE-CERT Mobile Emissions Laboratory (MEL). The facility and sampling setup have been described in detail previously and are only discussed briefly here [13]. For all tests, emissions measurements of THC, NMHC, CH_4, CO, NOx, carbon dioxide (CO_2), and PM, were measured using standard instruments, as shown in the Figure A1. Measurements of NH_3 were also obtained on a real-time basis using a Unisearch Associates Inc. LasIR S Series tunable diode laser (TDL) near infrared absorption spectrometer.

PM mass emissions were characterized using gravimetric analysis of particulates collected on 47 mm diameter 2 μm pore Teflon filters (Whatman brand). The filters were measured for net gains using a UMX2 ultra precision microbalance with buoyancy correction following the weighing procedure guidelines in the Code of Federal Regulations (CFR).

Greenhouse gas emissions were also evaluated in this study. CO_2 and CH_4 measurements were collected as part of the MEL's normal operation. Nitrous oxide (N_2O) emissions were collected utilizing an off-line Fourier-Transform Infrared (FTIR) spectrometer. These samples were collected off the MEL CVS dilution tunnel using flow controllers and Tedlar bags. N_2O emissions were only measured for the waste hauler.

Additional measurements of particle number (PN) emissions and particle size distributions (PSDs) were also performed for the waste hauler. PN measurements were made with a TSI model 3776 ultrafine condensation particle counter (CPC), with a cut point of 2.5 nm. Particle size distributions were obtained using an Engine Exhaust Particle Sizer (EEPS) spectrometer. The EEPS (TSI 3090, MCU firmware version 3.05) provides real-time second-by-second size distributions between 5.6 to 560 nm. The PSD data was all post-processed under the newly released 'soot' matrix from TSI. The PN (CPC and EEPS) measurements were sampled from the MEL dilution tunnel.

Results and Discussion

The results of this study are presented on a g/bhp-hp basis, which is the same unit used during certification testing, for most of the pollutants to allow for comparisons to the regulatory limits. There is also some figures and discussion of emissions results in g/mi units throughout the text to allow comparisons with other studies. The results shown in the figures/tables represent the average of two or three test runs performed on each vehicle for each driving cycle. The error bars represent one standard deviation on the average value.

NOx Emissions

NOx emissions are presented in Figure 1 on a g/bhp-hr basis for both vehicles and for all the test cycles performed. Additional information on the NOx emission rates on a g/mi basis is provided in Appendix B. Overall, NOx emissions were at or below the optional NOx certification standard of 0.02 g/bhp-hr for most tests. The waste hauler NOx emissions were below the 0.02 g/bhp-hr emissions targets for the hot DPT1, RTC, and the CBD. NOx emissions were extremely low for the CBD cycle. The average value for the CBD cycle was about -0.0033 g/bhp-hr, or near zero. The negative emission rates for some tests were due to ambient bag concentrations that were higher compared to the dilute exhaust concentrations. It should be noted that the ultralow NOx emissions for the Near Dock duty cycle (DPT1) is particularly important, as diesel engines typically cannot achieve high enough exhaust temperatures for the SCR system to be effective under creep, low-speed transient, and short high-speed transient conditions [14, 15]. This may be partially accounted for by higher exhaust temperatures for the NG engine during lower load

FIGURE 1 NOx emissions for the waste hauler and city bus. The error bars represent one standard deviation of the average values.

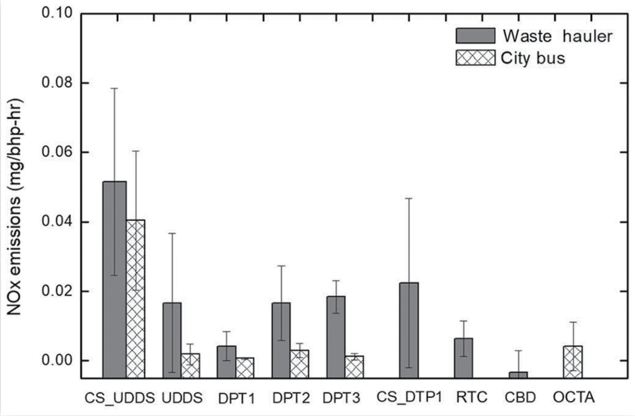


FIGURE 2 Real-time mass rate NOx emissions (g/s) UDDS cycles, waste hauler (full view).

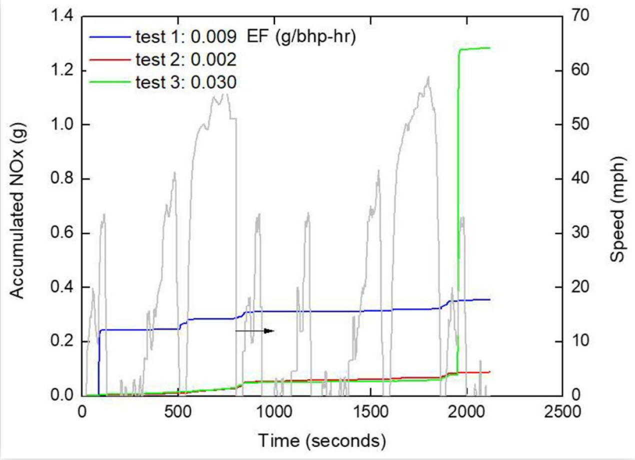
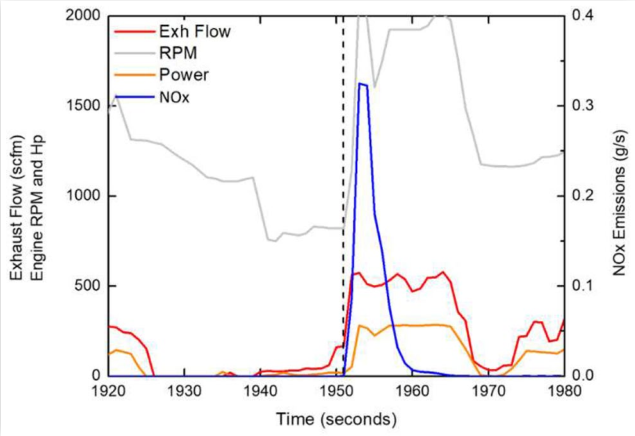


FIGURE 3 Real time NOx Accumulated mass emissions for the three UDDS hot cycle, waste hauler (detail view test #3).



duty cycles compared to typical diesel engines [13, 16]. Within the experimental variability, NOx emissions were either at or below the 0.02 g/bhp-hr level for the cold-start DPT1, the hot-start DPT2 and DPT3 cycles, and the UDDS. Cold-start emissions were higher than the hot tests when comparing between like cycles (i.e., UDDS cold vs. hot and DPT1 cold vs. hot). The cold-start UDDS showed the highest emissions of all cycles, ranging from 0.034 to 0.052 g/bhp-hr. The higher cold-start emissions were due to the TWC being below its light-off temperature.

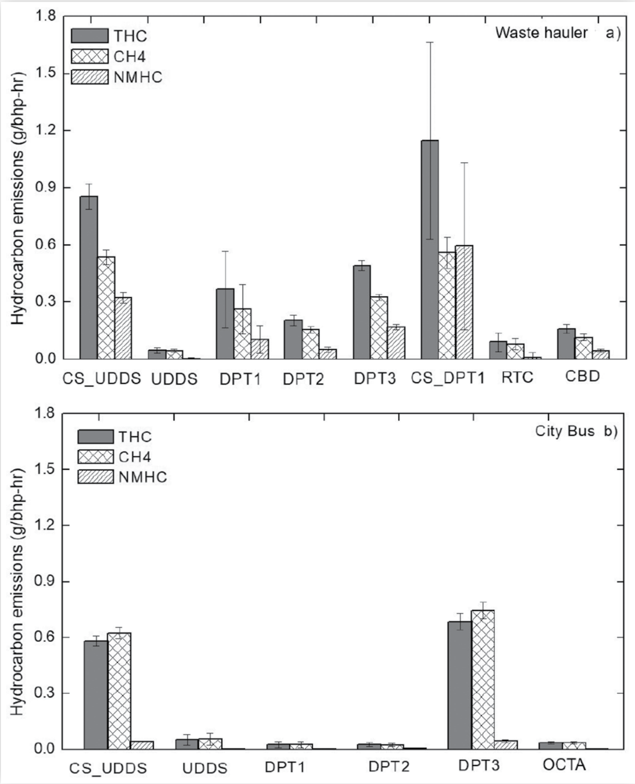
These results can be compared with those of late model diesel vehicles. Jiang et al. [17] evaluated the emissions from five SCR-equipped 2010+ diesel trucks. They observed that NOx emissions ranged from 0.5 to 1.36 g/mi over the UDDS cycle. They found considerably higher emissions for the Creep cycle, ranging from 2.13 to 9.47 g/mi. Researchers from CARB have found even higher NOx emissions for trucks tested as part of their Truck and Bus in-use surveillance program [18]. These results indicate that emissions from diesel trucks can be twenty to a hundred times higher than those observed in this study for the waste hauler and city bus in UDDS cycle, respectively. It should also be noted that even under conditions when NOx levels for heavy-duty diesel vehicles (HDDVs) meet the certification levels, these are still ten-times higher than the NOx emissions for both CNG vehicles.

The variability shown by the larger error bars for some of the waste hauler tests in Figure 1 was investigated further by evaluating the real-time NOx emissions. The real-time analysis suggests the variability was not from low-level measurement issues, but appears to be due to variability in the operation of the vehicle itself between different iterations of the same test cycle. Figure 2 shows the accumulated NOx emissions and engine speed for three UDDS tests. The real-time accumulated data shows that the majority of the higher NOx mass emissions resulted from two individual events in tests 1 and 3. These high NOx events were found to represent more than 80% of the total emissions for the different tests. Figure 3 shows real-time NOx emissions compared with real-time exhaust flow, engine horse power (hp) and engine revolutions per minute (RPM) speed. Closer inspection of these data shows that the NOx concentration and exhaust flow spikes occurred simultaneously, and were usually a result of a rapid acceleration from idle. This suggests that driven behavior and transmission type can influence emissions significantly.

THC, NMHC, and CH_4 Emissions

Hydrocarbon emissions (THC, CH_4, and NMHC) are presented for both vehicles and for all the test cycles performed in Figure 4. For the waste hauler (see Figure 4a), the CS_UDDS and CS_DPT1 showed the highest HC emissions. For the hot tests, the NMHC emissions were below the standard of 0.14 g/bhp-hr, which is the target that must be met during the certification testing, for all cycles except the regional cycle. NMHC emissions were much lower than the THC and CH_4 emissions, consistent with the HC emissions being primarily CH_4. This is consistent with other studies showing very low NMHC emissions for NG engines [19, 20, 21]. The CH_4 emissions were lower than the certification values for the engine (0.04 g/bhp-hr for chassis dynamometer testing vs the family emission limit (FEL) level of 0.65 g/bhp-hr). Also, the CH_4

FIGURE 4 Hydrocarbon emissions for (a) waste hauler and (b) city bus.



emissions for the waste hauler are significantly lower than previously tested NG waste haulers with the 2010 certified NG 8.9 liter engine (0.26 in g/mi units vs 6.4 g/mi) [22]. For the city bus, the THC and CH_4 are highest for the cold start and DPT 3 cycle, with the other cycles all having THC and CH_4 emissions below 0.1 g/bhp-hr.

The THC emissions levels for the waste hauler and transit bus (see Figure 4), are similar to those for earlier studies of stoichiometric NG engines, which are considerable lower than those for the older generation lean burn NG engines [20, 25, 26]. The lower emissions for the stoichiometric TWC NG engines compared to the older lean burn NG engines can be attributed to the more advanced aftertreatment and engine technology for the L9N, the larger size, higher precious metal loadings, and improved catalyst efficiency for the TWC[23, 26], and closed crankcase ventilation (CCV) improvements. Lean burn engines can also have higher engine-out THC emissions since they operate near the lean burn limit for HC formation.

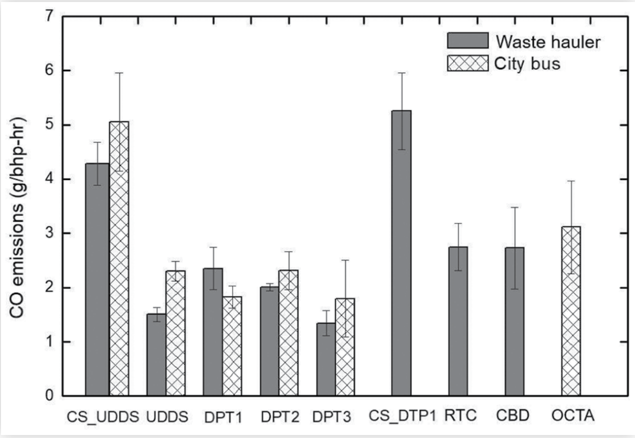
Comparisons of HC emissions can also be made with diesel HD vehicles from other studies. THC emissions of 2010+ diesel trucks with DOC/DPF/SCR systems were below 0.034 g/mile for five test vehicles over the UDDS [17]. Ayala et al. [27] found THC and NMHC emissions of 0.9 g/mile and 0.01 g/mile for an diesel vehicle equipped with a Catalyzed muffler and a continuously regenerating trap (CRT), respectively, over the UDDS cycle. It is evident that THC emissions for these diesel vehicles were five and ten orders of magnitude lower than CNG vehicles (e.g., 1.7 g/mile for both vehicles in this study) with the same test cycle, primarily due to the higher CH_4 emissions. If one considers only NMHC emissions, the waste hauler and city bus in this study have emissions comparable to those of HD diesel vehicles.

CO Emissions

CO emission results for the waste hauler and city bus are shown in Figure 5. For the waste hauler, CO emissions ranged between 1.3 to 5.3 g/bhp-hr, with the highest emissions for the cold start near dock (DPT1) and UDDS cycles and the lowest emissions for the regional (DPT3) test cycle. This corresponds to distance specific emissions from 4.2 to 24.3 g/mi for the regional (DPT3) and the cold start DPT1 test cycles, respectively. For the city bus, CO emissions were slightly higher than those of the waste hauler for most of test cycles, except for the DPT1. CO emissions ranged between 1.8 to 5.0 g/bhp-hr, with the lowest emissions for the DPT3 and the highest emissions for the cold start UDDS test cycle. CO emissions for these stoichiometric Cummins Westport L9N vehicles are comparable to those seen previously for regular Cummins Westport stoichiometric ISL G 8.9 engines, but are considerably higher than those for earlier generation NG lean burn engines [19, 20]. The lower CO emissions for the lean burn engines can be attributed to more available oxygen under the lean conditions to oxidize CO to CO_2 during combustion and over the catalyst.

Although CO emissions from HD vehicles are considered to be of less importance from an air quality standpoint, and are well below the certification standards for these NG vehicles, it is worth noting that these values are still higher than those of comparable HD diesel vehicles equipped with DOC [27] and OEM / CRT [21] systems. Jiang et al. [17] reported very low CO emissions below 0.2 g/mi for 5 2010+ HDDVs for most of the test cycles. Thiruvengadam et al. [28] found CO emissions that were below 1 g/mi for all cycles for three 2010+ SCR-equipped heavy-duty diesel trucks (HDDTs), while CO emissions for three stoichiometric ISL-G equipped NG HDDTs showed CO emissions ranging from 6.1 to 13.1 g/mi. Again, the high CO emissions measured from the CNG vehicles can be attributed to the fact that the CNG vehicles operate near stoichiometric conditions, while the diesel vehicles operate under lean conditions. Although the CO

FIGURE 5 CO emissions for waste hauler and city bus.



emissions for the L9N stoichiometric NG engine are higher than those for both older generation lean burn NG engines and diesel engines, the emissions are still well below the CO certification standard of 15.5 g/bhp-hr.

NH_3 Emissions

NH_3 emission results for the waste hauler and city bus are shown in Figure 6. For the waste hauler, NH_3 emissions for the hot test cycles ranged from 0.43 g/bhp-hr for the hot UDDS to 0.94 g/bhp-hr for the regional (DPT3) cycle. The distance specific emissions varied from 1.16 g/mi for the regional cycle to 5.27 g/mi for the CBD test cycle. The NH_3 emissions are slightly higher than those from earlier testing of an ISL G 8.9 vehicle, where the NH_3 ranged from 1.17 to 2.8 g/mi for the UDDS and RTC cycles [22], as compared to 1.19 and 4.09 g/mi for the L9N NZ, respectively. The NH_3 concentrations varied from 118 ppm (UDDS) to 305 ppm (CBD), as shown in Appendix B, which is considerably higher than the levels associated with SCR systems, which are designed to control NH_3 slip levels to 10 ppm or less. For the city bus, the NH_3 emissions are similar to those for the waste hauler for the cold start UDDS test cycle. For the hot start test cycles, on the other hand, NH_3 emissions for the city bus were lower than those the waste hauler for the UDDS and all of the drayage cycles, however. The trend of lower NH_3 emissions for the city bus compared to the waste hauler is in agreement with the NOx emissions trends, as shown in Figure 1, which could be attributed to similar NH_3 emissions spikes as seen for the NOx emissions for the waste hauler.

It is known that NH_3 emissions can form over TWCs as a byproduct of N in nitrogen oxide (NO) and hydrogen (H_2) in the exhaust [29, 30]. Hydrogen can be produced from water gas shift reactions (with CO and H_2O) or steam reforming reactions (with CH_4 and H_2O) [31, 32], and is more favorably formed under rich conditions [29]. Previous studies have shown very low NH_3 emissions for older lean burn NG engines by comparison with the stoichiometric L9N bus, because there is not a significant mechanism for NH_3 formation over a DOC, which is not designed for the reduction of nitrogen oxide species.

PM Emissions

PM mass emissions results for the waste hauler and city bus are shown in Figure 7. For both vehicles, the PM mass emissions for all the tests, including the cold start tests, were typically 90% below the certification standard and close to UCR tunnel blank value of 0.42 mg/bhp-hr (this tunnel blank value is based on a sample time and typical work for a UDDS cycle). For the waste hauler, the first PM filter weight for the regional drayage cycle was statistically higher than the other three (80, 21, 20 µg), suggesting that something may have burned off the exhaust system during that test that maybe an artifact from previous testing. If the PM result for the first UDDS test was eliminated, the DPT3 EF would be reduced from 1.01 mg/bhp-hr to 0.5 mg/bhp-hr. In either case, all the PM mass emission levels were well below the certification standard of 10 mg/bhp-hr. Low PM results are expected for NG fueled engines, as previous studies have similarly showed PM emissions well below 10 mg/bhp-hr [13]. The corresponding measured filter weights for the waste hauler were 13 µg with a single standard deviation of 3 µg, while the tunnel blank was measured at 5 µg (representative of 0.42 g/bhp-hr using the UDDS sample conditions). As such, the PM emission rates are very low and the shown variability may be a result of measurement limitations at such low levels more than vehicle performance between cycles.

Previous studies have typically shown low PM mass emissions for different NG engine applications [21, 25], although some studies have shown higher PM emission rates for some NG engine than others [20]. The low PM emissions for NG combustion can be attributed to the simple, low molecular weight structure of the main component of natural gas, CH_4 [33], which has less tendency to form localized areas of rich combustion than other hydrocarbon fuels. Instead, PM from NG engines has been more attributed to engine lubricating oil entering into the combustion chamber [33].

PN Emissions

The PN emissions (CPC 3772) for the waste hauler are shown in Figure 8 on a logarithmic scale for the test cycles performed. PN values were highest for the high speed regional cycle

FIGURE 6 NH_3 emissions for waste hauler and city bus.

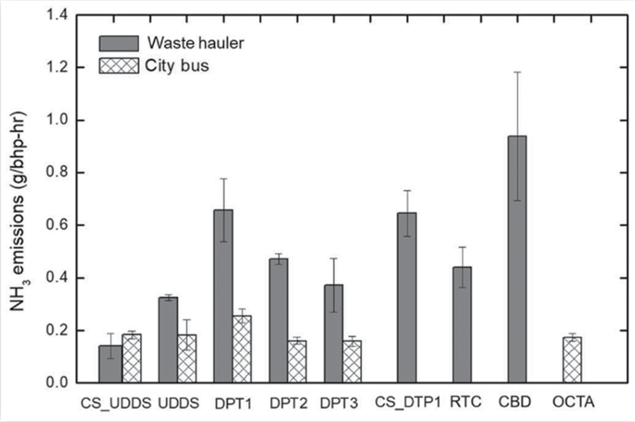


FIGURE 7 PM emissions for waste hauler and City bus.

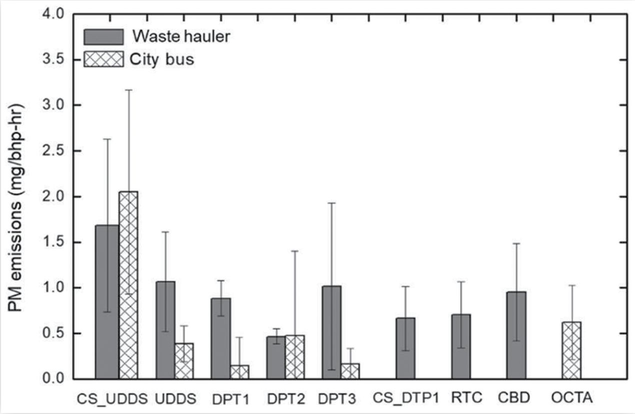


FIGURE 8 Particle number emissions for waste hauler.

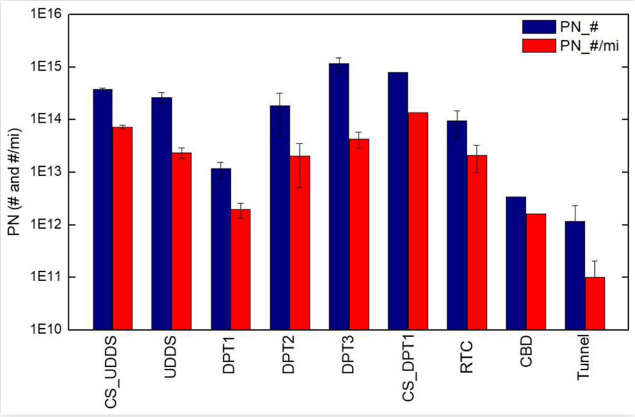
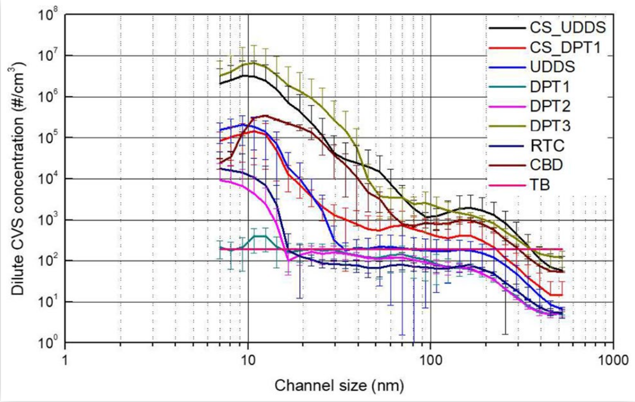


FIGURE 9 EEPS ultrafine PSD measurements for waste Hauler for each of the test cycles.



(DPT3) on a total # basis and the cold start near dock (DPT1) and cold start UDDS cycles on a #/mi basis, with PN emissions of 1.4 x10^{14} #/mi and 7.3 x10^{13} #/mi, respectively. The near dock port cycle (DPT1) and CBD cycle showed the lowest PN values of 1.0 x10^{13} #/mi and 1.6 x10^{12} #/mi, respectively. The UDDS, local drayage cycle, and RTC showed comparable PN levels in a range from 2.0 x10^{13} to 2.4 x10^{12} #/mi.

The PN results can be compared with results from other studies. In one study, a 0.2 g/bhp-hr certified NOx ISL G 8.9 engine equipped truck tested on the near dock port cycle, the PN emissions were 1.9x10^{12} ± 3.8 x10^{11} #/mi [35], which is comparable to the waste hauler results for the near dock port cycle. In a second study with a truck with a 2009 Cummins Westport ISL G 8.9 engine, the PN emissions were 4x10^{12} #/mi for the CBD test cycle [10], which agrees well with the results in this study for the near dock and CBD test cycles. In another study with a waste hauler with a standard ISL G 8.9 engine, the PN emissions for the RTC cycle were 2.5x10^{13}, 5.8x10^{12}, and 2.2x10^{12} #/mi for the curbside, transit, and compaction portions of the RTC test cycle, respectively [34], which compares well with the PN from the L9N NZ results. Late model diesel engines equipped with DPFs show PN emissions that range from 1.3x10^{11} to 0.7x10^{11} #/mi for on-road UDDS and cruise type of tests [36]. In general the PN emissions for the L9N NZ are mixed in comparison to the ISL G 8.9 with some higher and some about the same. The L9N NZ and ISL G 8.9 both show higher PN emissions compared to diesel vehicles equipped with DPFs.

Particle Size Distributions (PSDs)

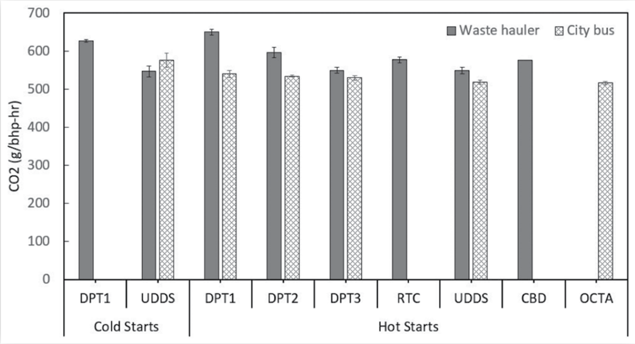
The particle size distributions (PSDs) for the waste hauler (as measured by the EEPS) are shown in Figure 9 on a log-log scale concentration basis as measured in the dilute CVS. The PSDs for most cycles show the highest concentrations in the 10-20 nm nucleation mode size range. The cold start UDDS and the regional (DPT3) cycles showed the highest particle concentrations at 10 nm diameter for all the traces. This is consistent with the results from previous studies reporting that the majority of particles from CNG buses were in the nucleation mode [37, 38, 39]. Since PM levels from NG combustion are very low, as discussed above, nucleation particles formed during combustion cannot readily agglomerate to form larger carbonaceous particles.

The higher PSDs concentrations for the cold UDDS and regional cycle are a result of PN spikes under different conditions. The PSD PN spikes occurred during the early part of the cold start UDDS and during the cruise part of the hot regional cycle (DPT3). The secondary peak at a particle diameter of approximately 105 nm was highest for the same two cycles and the CBD. DPT1 showed the lowest concentrations for the PSD, which were typically below the tunnel blank concentrations. During previous testing on a truck with a 2012 Cummins Westport ISL G 8.9 engine, PSDs showed a similar bi-modal PSD at 10 nm and 110 nm [10, 34, 35]. Diesel vehicles equipped with a DPF typically only show a single mode of operation (when not in a DPF regeneration) when tested over the UDDS and port cycles [40].

CO_2 Emissions and Fuel Economy

CO_2 emissions for the waste hauler and city bus are shown in Figure 10 in g/mi units. CO_2 emissions ranged from CO_2 emissions ranged from 2,000 g/mi (DPT3) to 5,300 g/mi (RTC) for the waste hauler and from 1,700 g/mi (DPT3) to 3,000 g/mi

FIGURE 10 CO_2 emissions from the waste hauler and city bus in g/mi units.



(DPT1) for the city bus over the various cycles. The high CO_2 emissions for the RTC cycle are due to the large fraction of stop and go driving during the curbside pickup portion of that cycle. The CO_2 emissions for the other cycles were largely less than 3,000 g/mi.

CO_2 emissions were also calculated on a g/bhp-hr basis. CO_2 emissions ranged from 548 g/bhp-hr to 649 g/bhp-hr for the waste hauler and from 516 g/bhp-hr to 576 g/bhp-hr for the city bus over the various cycles, as shown in Appendix B. These values are comparable to the 555 g/bhp-hr CO_2 standard for 2017+ HD diesel engines over the FTP. The brake specific CO_2 is regulated by EPA for the FTP, which is most comparable to the UDDS chassis dynamometer test cycle, and SET test cycles.

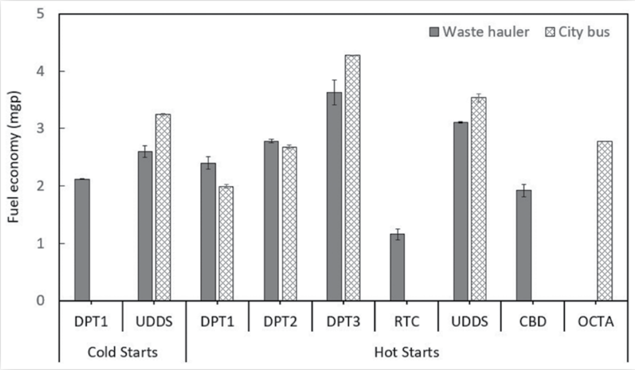
CO_2 emissions can be compared to values from previous studies. Karavalakis et al. [34] found CO_2 emissions of ~1300 g/mi and ~5,000 g/mi for a ISL-G equipped waste hauler for the transport and curbside portions of the RTC cycle, respectively. The higher CO_2 emissions for the curbside portion are consistent with those seen in the current study. Karavalakis et al. [41] also found CO_2 emissions of 2,123 g/mi for an ISL-G equipped goods movement vehicle over the DPT1 cycles and of 2,188 g/mi for an ISX12-G equipped goods movement vehicle over the DPT3 cycle. Hajbabaei et al. [10] found CO_2 emissions of ~1,700 g/mi for a ISL-G equipped transit bus over the CBD.

Fuel economy for the waste hauler and city bus are shown in Figure 11 in miles per gallon (MPG) units. Fuel economy was determined on a diesel gallon equivalent (MPGde) basis (assuming 2863 g NG/gallon diesel). Fuel economy for the waste hauler ranges from 3.6 MPGde for the regional port cycle (DPT3) to 1.2 MPGde for the RTC cycle. Fuel economy for the city bus ranges from 4.3 MPGde for the regional port cycle (DPT3) to 2.0 MPGde for the near dock prot cycle (DPT1).

Greenhouse Gases and Global Warming Potential (GWP)

The greenhouse gases include CO_2, CH_4 and N_2O and are reported here to characterize the vehicles global warming potential (GWP). It should be noted that N_2O emissions were only available for the waste hauler, but comprised much less than 1% of the total GWP. The GWP for CO_2, CH_4, and N_2O are presented in Appendix B for the waste hauler and the city bus in CO_2 equivalent g/bhp-hr units. The GWP calculations are based on the intergovernmental panel on climate change (IPCC) values of 28 times CO_2 equivalent for CH_4 and 265 times CO_2 equivalent for nitrous oxide (N_2O) [42]. The GWP varied from 550 g/bhp-hr (hot UDDS) to 667 g/bhp-hr (cold start DPT1) for the waste hauler and from 517 g/bhp-hr (OCTA) to 594 g/bhp-hr (cold start UDDS) for the city bus. CO_2 represented the primary contribution to the GWP, ranging from 94% to 99%.

FIGURE 11 Fuel economy for the waste hauler and city bus.



Conclusions

Emissions for a waste hauler and city bus equipped with an L9N NZ NG engine were evaluated on a chassis dynamometer. This engine is certified at the 0.02 g/bhp-hr NOx level, which represents a 90% reduction in NOx emissions from the current standard for HD engines. The emissions collected in this study include NOx, PM, PN, NO_x, HC, CO, and NH_3.

The main conclusions can be summarized as follows:

In general, the L9N engine NOx emissions were at or below the optional NOx standard of 0.02 g/bhp-hr, and these emission levels were achieved for a wide range of duty cycles.

The L9N liter NG engine showed NOx emissions below the proposed 0.02 g/bhp-hr emission target and averaged between 0.014 and 0.002 g/bhp-hr for waste hauler and between 0.0007 g/bhp-hr to 0.0042 g/bhp-hr for city bus for all hot start cycles. For both vehicles, NOx emissions were significantly reduced by 97%-100% compared with the standard ISL G 8.9 engine. A larger TWC, a slightly different air-fuel ratio, and an improvement in the crankcase ventilation system (CCV) all contribute to the ultra-low NOx emissions.

NOx emissions did not increase with the low duty DPT 1 cycle for both vehicles. The low NOx emissions under low duty conditions are different from diesel engines, which typically cannot achieve high enough exhaust temperatures for the SCR system to work at low loads.

The results suggest that NG vehicles could play a role in the reduction of NOx inventories in areas with severe air quality problems.

The NOx emissions showed relatively large variability from test to test for the waste hauler. The real-time analysis suggests the variability is not from low-level measurement issues, but appears to be due to variability in the operation of the vehicle itself between different iterations of the same test cycle during rapid tip-in events from an acceleration. This suggests driver behavior may impact overall in-use NOx emissions from a vehicle, with more gradual accelerations providing lower emissions.

The CO emissions ranged between 1.3 to 5.3 g/bhp-hr for waste hauler and ranged between 1.8 to 5.0 g/bhp-hr for city bus over all test cycles, with the highest emissions for the cold start near dock cycles (DPT1). This is solidly below 15.5 g/bhp-hr certification standard. For CO emissions were in a similar range to those for conventional ISL-G 8.9 engines, but there is a 14% to 90% increase for the CBD and DPT1 cycles and a 43%-83% decrease for RTC and UDDS cycles compared to previous ISL G 8.9 engines. The increases in CO emissions suggest a richer air-fuel ratio maybe being used to increase the TWC efficiency for reducing NOx emissions for the L9N NZ engine, although it is not consistent over all cycles.

The NH_3 emissions for the L9N NZ were relatively high, ranging from 0.19 to 0.94 g/bhp-hr. This can be attributed to reactions on the TWC, which are more prevalent for richer air-fuel ratios. The TWC is a catalyst that reduces NOx to N_2, which can react with the hydrogen from H_2O and CH_4 to produce NH_3. In contrast, older lean burn NG engines with DOCs show much lower NH_3 emissions, since the DOC is not designed for NOx reduction reactions.

THC/CH_4 emissions were lower than those for the older ISL G 8.9 NG engines. For the RTC cycle, for example, CH_4 emissions were 0.18 g/mi for the L9N NZ engine compared to 6.8 g/mi for an older ISL G 8.9 NG engine. This could be due to an increase in the efficiency of the larger catalyst in reducing CH_4 or to improvements in the CCV system.

The PM/NMHC emissions were very low, which is consistent with the results from previous studies of NG fueled HDVs.

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Appendix A. Experimental Procedures

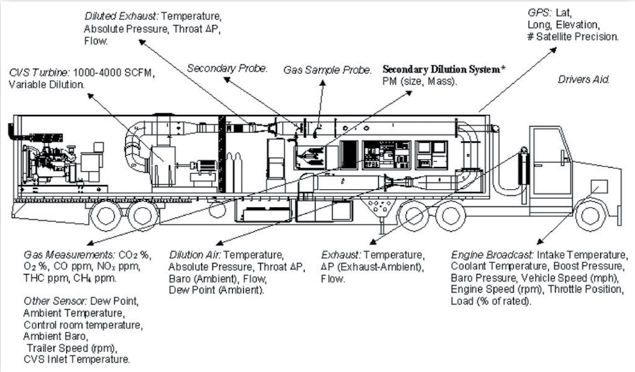
Emissions Sampling

The approach used for measuring the emissions from a vehicle or an engine on a dynamometer is to connect UCR's heavy-duty mobile emission lab (MEL) to the total exhaust of the diesel engine, see Appendix C for more details. The details for sampling and measurement methods of mass emission rates from heavy-duty diesel engines are specified in Section 40, Code of Federal Regulations (CFR): Protection of the Environment, Part 1065. UCR's unique heavy-duty diesel MEL is designed and operated to meet those stringent specifications. MEL is a complex laboratory and a schematic of the major operating subsystems for MEL are shown in Figure A1 Figure . The accuracy of MEL's measurements has been checked/verified against ARB's[1] and Southwest Research Institute's heavy-duty diesel laboratories. MEL routinely measures Total Hydrocarbons (THC), Methane (CH_4), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NOx), and Particulate Matter (PM) emissions from diesel engines. Design capabilities and details of MEL are described in Cocker et al. Samples can be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

The dilution based NOx measurements include a 600 heated chemiluminescent detector (HCLD) from California Analytical Inc. (CAI) configured to sample from the CVS tunnel during real time and ambient and dilute bag measurements following automated routines of the MEL laboratory. The samples are collected from the CVS dilute tunnel through an acid treated filter to prevent measurement interferences from ammonia (NH_3) concentrations. The acid treated filters were replaced daily.

In addition to the regulated emissions, the laboratory was equipped to measure particle size distribution (PSD) with TSI's Engine Exhaust Particle Sizer 3090 (EEPS). Particle number (PN) with a TSI 3776 condensation particle counter (CPC), soot PM mass with AVL's Micro Soot Sensors (MSS 483), NH_3 emissions with an integrated real-time tunable diode laser (TDL), and a batched low level nitrogen dioxide (N_2O) emissions with a Fourier Transform Infrared Spectrometer (FTIR) configured for low concentrations.

FIGURE A-1 Major Systems within UCR's Mobile Emission Lab (MEL).



Work Calculation

The reported emission factors presented are based on a g/bhp-hr and g/mi basis. The engine work is calculated utilizing actual torque, friction torque, and reference torque from broadcast J1939 ECM signals. The following two formulas show the calculation used to determine engine brake horse power (bhp) and work (bhp-hr) for the tested vehicle. Distance is measured by the chassis dynamometer and the vehicle broadcast J1939 vehicle speed signal. A representative L9N engine lug curve is provided in Figure A2

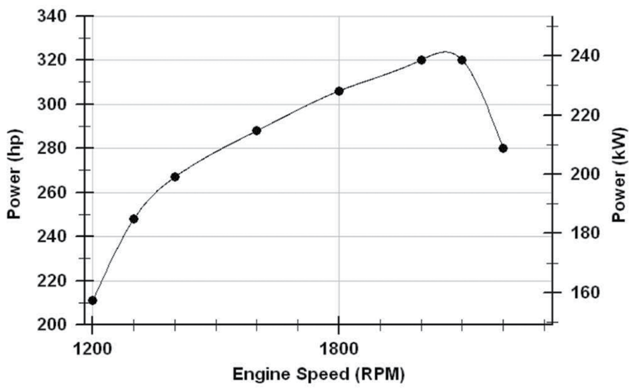
$$Hp_{\_i} = \frac{RPM_{\_i}\left(Torque_{actual\_i} - Torque_{friction\_i}\right)}{5252} * Torque_{reference}$$

Where:

- *Hp_i* - instantaneous power from the engine. Negative values set to zero
- *RPM_i* -instantaneous engine speed as reported by the ECM (J1939)
- *Torque_actual_i* -instantaneous engine actual torque (%): ECM (J1939)
- *Torque_friction_i* - instantaneous engine friction torque (%): ECM (J1939)
- *Torque_reference* - reference torque (ft-lb) as reported by the ECM (J1939)

$$Work = \sum_{i=0}^{n} \frac{Hp_{\_i}}{3600}$$

FIGURE A-2 Published ISLG 8.9 320 HP engine power curve.



Appendix B. Additional Results

NH_3 measurements for the cold UDDS test stopped working during the first hill where the system may have over ranged. The cold start UDDS NH_3 results are estimated at 20% higher than the hot-UDDS test.

FIGURE B-1 NOx emissions on a g/mi basis for the waste hauler and city bus. The error bars represent one standard deviation of the average values.

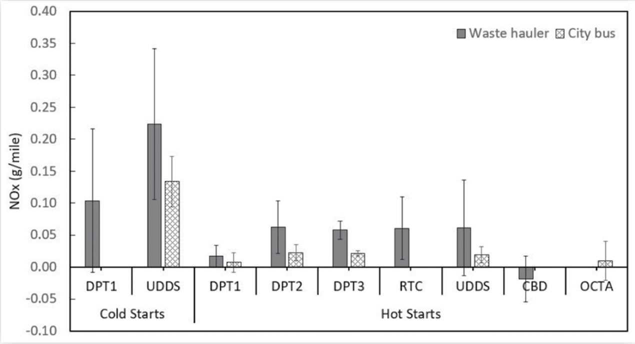


FIGURE B-2 Ammonia measured tail pipe concentration (ppm).

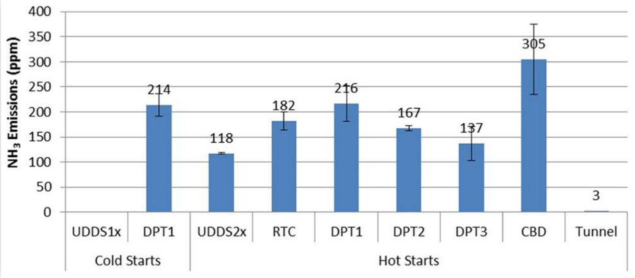


FIGURE B-3 CO_2 emissions from the waste hauler and city bus on a g/bhp-hr basis.

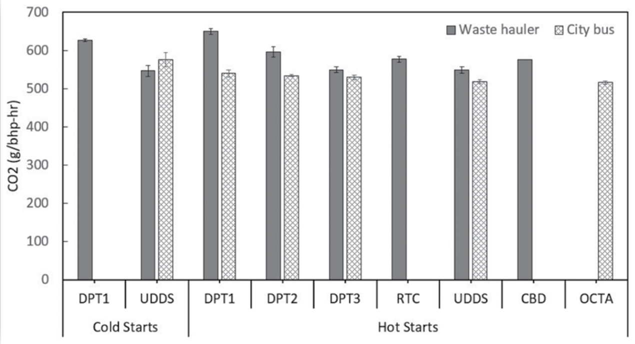


TABLE B-1 Global warming potential for the waste hauler and city bus tested (g/bhp-hr).

	Condition	Trace	CO_2	CH_4	N_2O	GWP ($CO_{2\,eq}$)	CO_2 /GWP
Waste hauler	Cold start	UDDS1x	546.8	0.53	0.062	578.3	0.95
		DPT1	627.0	0.56	0.09	666.8	0.94
	Hot start	UDDS2x	548.9	0.04	-	550.0	0.99
		RTC	577.0	0.08	-	579.2	0.99
		DPT1	649.8	0.26	-	657.1	0.99
		DPT2	597.0	0.16	0.027	608.7	0.98
		DPT3	549.3	0.33	0.024	564.9	0.97
		CBD	576.1	0.11	0.034	588.3	0.98
		OCTA	-	-	-		
City Bus	Cold start	UDDS1x	576.4	0.624	-	593.9	0.97
		DPT1	-	-	-	-	-
	Hot start	UDDS2x	518.9	0.056	-	520.5	0.99
		RTC	-	-	-	-	-
		DPT1	539.7	0.027	-	540.5	0.99
		DPT2	534.6	0.026	-	535.3	0.99
		DPT3	530.0	0.746	-	550.9	0.96
		CBD	-	-	-	-	-
		OCTA	516.4	0.037	-	517.4	0.99

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